https://doi.org/10.5194/egusphere-2025-5542
Preprint. Discussion started: 25 November 2025

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

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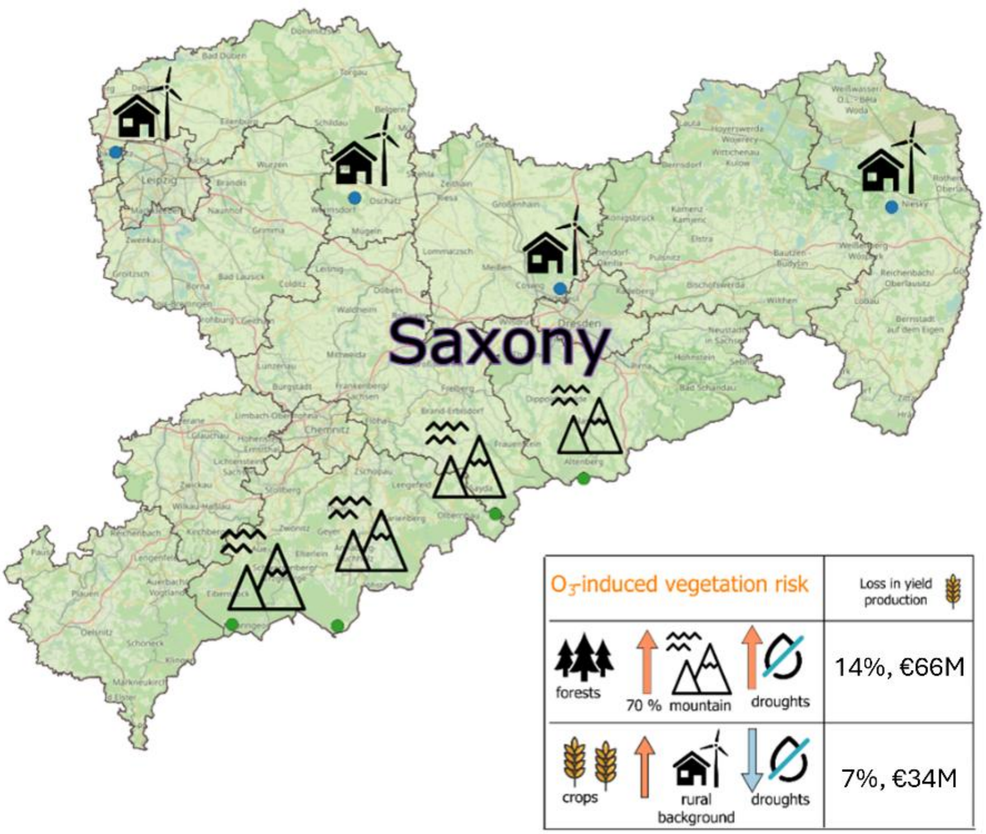
Graphical abstract. Overview of ozone-induced vegetation risks in Saxony. Basemap: © OpenStreetMap contributors 2023. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.



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Preprint. Discussion started: 25 November 2025

Abstract.

Tropospheric ozone (O_3) at ground level is a phytotoxic pollutant that affects vegetation and reduces crop productivity, with implications for forest ecosystems, agriculture, and food security. The present study presents a 15-year assessment (2006-2020) of O_3 risk in Saxony, Germany, using the stomatal flux-based metric PODySPEC. 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). Given Saxony's extensive forest cover and the sensitivity of high-elevation ecosystems, a detailed forest evaluation was performed. POD_1SPEC in spruce and beech frequently exceeded critical levels, with values up to 70% higher at mountain than rural sites. While stomatal O_3 uptake declined in dry years at rural sites, likely due to drought-induced closure, forests at mountain sites sustained O_3 stomatal uptake even during prolonged droughts, reflecting deeper rooting and higher drought tolerance. The number of dry days, used as a proxy for drought duration, helped explain these contrasting responses. Grasslands were also consistently in the high-risk zone, with POD_1SPEC exceeding critical levels throughout the time series. Under worst-case assumptions, potential reductions reached ~9% for above-ground biomass and ~16% for flower numbers, with impacts about 20% higher at mountain than rural sites. These findings suggest that meteorological conditions strongly modulate O_3 uptake in grassland systems. For wheat, estimations under worst-case conditions indicate yield reductions of up to 14% at mountain sites and 7% at rural sites, corresponding to average annual economic losses of about €66 million and €34 million, respectively, based on the 2016-2020 producer price. Assuming similar losses under the 2025 wheat price, the economic loss increases by 13%. These results highlight the importance of site-specific, flux-based O_3 risk assessments for guiding air quality and land-use policies in Saxony. More broadly, the approach offers a framework for evaluating O_3 impacts in other mountain regions where agriculture is essential and adaptive capacity is limited.

1. Introduction

Tropospheric ozone (O_3) has been a central subject of atmospheric chemistry research for decades due to its decisive role for atmospheric oxidation capacity but also as a short-lived climate forcer (SLCF) (Donzelli and Suarez-Varela, 2024; Forster et al., 2023). It regulates the formation of hydroxyl radicals (OH), which control the atmospheric lifetime of key greenhouse gases such as methane (Fiore et al., 2024). Beyond its chemical significance, tropospheric O_3 exposure poses adverse effects on human health, contributing to increased respiratory morbidity and mortality worldwide (Pozzer et al., 2023; World Health Organization, 2021). Tropospheric O_3 is also widely recognized as a major phytotoxic pollutant that disrupts essential ecological functions, including the water cycle and carbon sequestration through its direct damage to vegetation (Grulke and Heath, 2020; Juráň et al., 2021; Mills et al., 2018b). This vegetative damage substantially reduces crop yields, leading to significant economic losses and decreased food availability that pose serious threats to global food security (Emberson, 2020).

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The issue has become particularly pressing for wheat crops in India and China, which have recorded the highest yield losses globally in recent decades (Feng et al., 2019; Pei et al., 2023; Sharma et al., 2019; Ramya et al., 2023).

In 2019, Germany experienced the second-highest wheat yield loss in Europe, amounting to 1.6 million tonnes or 280 million euros (€175/t) (Schucht et al., 2021). Valued at the current farm wheat price in Germany for 2025 (€189/t) (Dairy and Agricultural Economic Analysis Centre, 2025), the same loss would correspond to approximately €302 million, underscoring the growing economic significance of O_3-induced crop damage (European Commission Directorate General for Agriculture and Rural Development, 2025). 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., 2018c), Understanding current O_3 impacts on vegetation is therefore essential for sustainable forest management, climate adaptation strategies, and ensuring food security (Emberson, 2020).

Ozone's phytotoxicity varies among plant species and depends on several factors, including the plant's physiology, sensitivity to O_3, detoxification capacity, and adaptive responses (Grulke and Heath, 2020). Since O_3 enters plants through stomatal pores, realistic impact assessment requires considering the actual O_3 uptake rather than just ambient concentrations. In this context, flux-based approaches like the accumulated stomatal O_3 uptake over a threshold for specific plant receptors (POD_YSPEC) offer a more physiologically accurate perspective compared to concentration-based metrics like accumulated Ozone exposure over a threshold of 40 ppb (AOT40) (Lefohn et al., 2018; Pleijel et al., 2022; Proietti et al., 2020). The POD_YSPEC considers environmental variables and is particularly suitable for assessing O_3 impact on crops (Pleijel et al., 2022) and forests (Proietti et al., 2020) at local and regional scales, as well as estimating economic losses in terms of biomass or yield (Mills et al., 2018a).

O_3 enters plants through stomatal pores, and its uptake is influenced by environmental parameters that regulate stomatal aperture. Factors promoting maximum stomatal aperture can increase the risk of O_3 damage, while conditions causing stomatal closure, such as water stress and droughts, limit O_3 uptake, even at high O_3 concentrations (Buckley, 2019; Pirasteh-Anosheh et al., 2016) Understanding this modulation effect is essential for realistic risk assessment, as explored in this study. By studying the relationships and variability between the O_3 stomatal flux and environmental factors using multiannual estimates of POD_YSPEC, valuable insights into the influence of these factors on O_3-induced damage to vegetation have been achieved (Watanabe et al., 2016). For example, studies in Switzerland revealed that the meteorological conditions lead to more considerable variations in soil water content (SWC) and in the POD_YSPEC values for wheat as compared to potato crops (Schneuwly and Ammann, 2020). In forest sites of Western Germany (Rhineland Palatinate), correlations between O_3 concentrations, daytime O_3 (for the hours with global radiation exceeding 50 W m^{-2}), POD_YSPEC, global radiation, vapor pressure deficit, air temperature and SWC were found, emphasizing the role of SWC in the O_3 stomatal uptake (Eghdami et al., 2020; Eghdami et al., 2022a). It was also found that years with fewer droughts and moderate O_3 concentrations led to higher stomatal O_3 flux, and hence higher potential risk of physiological damage, than dry years with higher O_3 concentrations, where stomatal closure limited O_3 uptake (Eghdami et al., 2022b).

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However, most current risk assessments for vegetation using POD_YSPEC metrics assume a worst-case scenario, neglecting the influence of SWC on stomatal O_3 uptake and assuming unrestricted plant irrigation (German Institute for Standardization, 2020). Considering that under low SWC, the lower O_3 uptake results in a possible lower risk of vegetation damage due to O_3, a worst-case scenario setting in models can be less realistic. Recent studies show that including SWC and analysing droughts in the estimations of O_3 fluxes would allow for more reasonable O_3 stomatal uptake model outputs (Eghdami et al., 2022a; Schneuwly and Ammann, 2020).

O_3 risk assessment studies that include Germany often employ models with coarse spatial resolutions (Schucht et al., 2021; Mills et al., 2018b) frequently done at regional scales unable to resolve scale differences in meteorology, soil water properties, and crop phenology (Mills et al., 2017). Such studies mainly focus on rural and forested areas with low and mid-elevation (Eghdami et al., 2020). At the same time, mountain sites have been underrepresented in such assessments despite experiencing higher O_3 concentrations and being areas of essential conservation (Ehlers et al., 2016). The vegetation working group from the Tropospheric Ozone Assessment Report (TOAR) community recommends that assessments of the O_3 effects on vegetation should be developed for mountain sites (Mills et al., 2018a). To our knowledge, very few studies have explicitly assessed O_3 effects on vegetation at high-altitude forest sites in Germany based on field measurements. One such example is (Baumgarten et al., 2009), who investigated O_3 risk on Bavarian mountain forests between 2002 and 2005 using exposure and flux-based approach.

Around 27% of the land in the state of Saxony is covered by forests (Saxon Statistical Office, 2020) characterized by coniferous and deciduous trees (e.g. spruce and beech) in a varied topography, including higher elevations of up to 1200 m in the Ore Mountains, where vegetation has been heavily impacted by air pollution, with visible O_3 damage (Kupková et al., 2018; Šrámek et al., 2008). Land use in Saxony also includes permanent grassland and cropland, representing a case of highly intensive industrial agriculture in Eastern Germany and Europe (Beleites, 2012; Dietze et al., 2019). Approximately 54% of the state's area is devoted to agriculture (Saxon Statistical Office, 2020) with wheat (27%), barley (16%), and maize (11%) as the main crops.

Based on this distribution, the present study investigates O_3-induced damage to the dominant forest species (beech and spruce), permanent grasslands, and the most economically important crop, wheat. Forests and grasslands are included due to their extensive land coverage and ecological significance, while wheat is analysed as the predominant crop for which robust O_3 dose-response relationships estimates are available at the European scale. 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. In addition, the study compares flux-based (PODySPEC) and concentration-based (AOT40) metrics, and extends the assessment to grassland and croplands (wheat). This approach aims to provide a comprehensive understanding of O_3 impacts on different vegetation groups under changing environmental conditions, supporting future land and forest management strategies (Emberson, 2020; Fuhrer et al., 2016).

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2. Materials and methods

The following provides a brief overview of the study areas and a description of the dataset.

2.1 Study area and selected sites

The Federal State of Saxony covers an area of about 18500 km^2. Located in eastern Germany, it borders the German states of Bavaria, Thuringia, Saxony-Anhalt, and Brandenburg, and the countries of Poland and the Czech Republic. Saxony topography is characterized by varied elevations, lower (100 m) in the northern parts and higher (up to 1200 m) in the southwest (the Ore Mountains). Prevailing colder climatic conditions make forests dominate the vegetation at elevated sites. In comparison, warmer conditions make them agriculturally dominant in lower sites (Saxon State Office for Geoinformation, n.d.).

Land in Saxony is used mainly for intensive industrial agriculture and forests. Agriculture is managed using approximately 704,000 hectares (ha) of croplands and 183,700 ha of permanent grassland (Saxon Statistical Office, 2020; Van Der Ploeg et al., 2015). The predominant crops are wheat, barley, and maize, which account for 27%, 16%, and 11% of the cultivated area, respectively. Forests cover about 521,500 ha, representing 28% of Saxony's land area. Coniferous species dominate, with spruce and pine covering 35% and 31% of the forested area, respectively, while deciduous species such as birch, oak, and beech account for 7%, 6%, and 3% (Saxon State Office for Environment, n.d.; Saxon Environment and Agriculture Ministry, n.d.)

In this study, we focus on those vegetation groups that are both central to Saxony's land use and of particular relevance for O_3 risk assessment. For forests, we selected spruce and beech as representative coniferous and deciduous species. For agriculture, we included permanent grasslands and wheat as the dominant and economically most relevant crop. While barley and maize are also widespread, they were not considered because species-specific flux-response functions and long-term parameterisation data are lacking for Saxony. This scope ensures that the analysis addresses the most representative vegetation types while allowing a robust, physiologically based assessment of ozone risk.

The air quality monitoring network operated by the Saxon State Office for the Environment, Agriculture, and Geology (LfULG) provides long-term ground-based measurements from various station types across Saxony, including mountain sites (Ore Mountains), rural background, urban background, and traffic stations (Pausch and Mühlner, 2020). For this study, eight stations were selected, four located in the Ore Mountains and four at rural background sites (Figure 1) to capture the variability in elevation and climate of Saxony, particularly across key forested and agricultural areas. Site selection also considered data completeness and consistency over a 15-year period, enabling the annual calculation of species-specific PODySPEC values and their interannual comparison.

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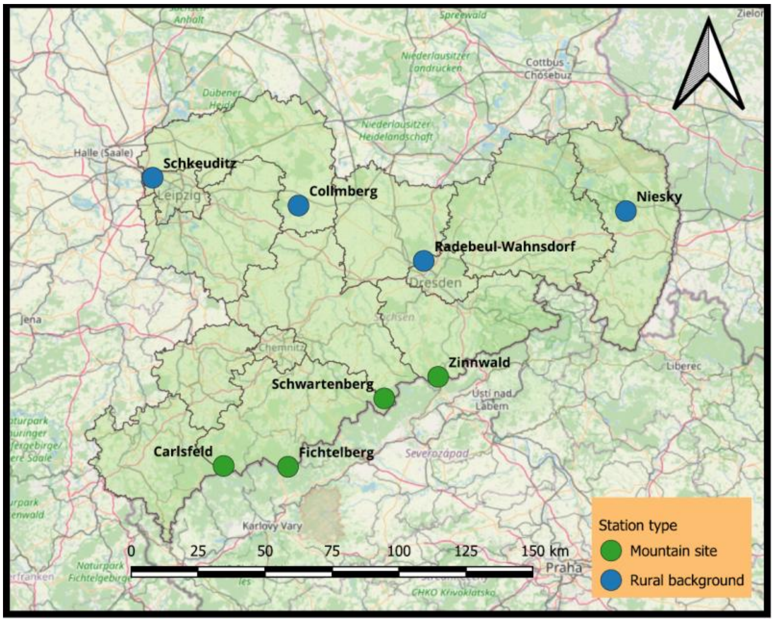

Figure 1: Map of Saxony, Germany, showing the location of the selected station types. Mountain sites are shown as green circles and rural background sites as blue circles. The map was created using QGIS 3.40 with administrative boundaries from GADM (2023) and site coordinates compiled by the authors. Basemap: © OpenStreetMap contributors 2023. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

Ozone concentrations were highest at mountain sites, with 2006-2020 one-hour median values ranging from 66 µg m^{-3} at Carlsfeld to 77 µg m^{-3} at Fichtelberg. The highest single hourly concentration recorded up to 2020 was 282 µg m^{-3} at Schwartenberg. In contrast, rural background sites showed lower median values, between 46 and 58 µg m^{-3}. A summary of site characteristics, measurement details, and geographical locations is provided in Table 1, and additional information can also be found in (Wang et al., 2025).

Table 1. Main characteristics of selected study sites in Saxony, Germany

Station type	**Station**	**Land cover type**	**Predominant representative specie**	**Longitude**	**Latitude**	**Elevation (m.a.s.l.)**
Rural background	Collmberg	cropland, evergreen needle-leaved, deciduous broadleaved	wheat, beech, spruce, grassland	51°18'13"	13°00'33"	312
	Niesky	evergreen needle-leaved, cropland	wheat, grassland, beech, spruce	51°17'07"	14°44'59"	172
	Radebeul-Wahnsdorf	cropland, herbaceous wetland, deciduous broadleaved, evergreen needle-leaved	wheat, beech, spruce, grassland	51°07'10"	13°40'30"	131
	Schkeuditz	cropland, deciduous, broadleaved, herbaceous vegetation	wheat, beech, spruce, grassland	51°23'45"	12°14'02"	111

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Mountain sites	Carlsfeld	herbaceous, evergreen needle-leaved	beech, spruce, grassland	50°25'52"	12°36'40"	837
	Fichtelberg	herbaceous, evergreen broadleaved	beech, spruce, grassland	50°25'42"	12°57'12"	1215
	Schwartenberg	evergreen needle-leaved, deciduous broadleaved, deciduous needle-leaved, cropland	wheat, beech, spruce, grassland	50°39'32"	13°27'54"	789
	Zinnwald	cropland, evergreen needle-leaved	wheat, beech, spruce, grassland	50°43'53"	13°45'05"	807

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) open data centre. All data are given in Central European Time (CET) with no daylight saving considered.

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 %.

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 Buuren S, 2011) 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 may become more critical when dealing with larger gaps or less complete datasets.

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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 O3-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.

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

In Eq. 1, POD_YSPEC is the accumulated phytotoxic O_3 dose above a 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 $TV_{PODySPEC}$.

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

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)

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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).

2.4 Economic loss

Based on the estimated crop relative yield loss (RYL) from wheat with the POD_6SPEC metric, the crop production loss (CPL) and economic cost loss (ECL) can be calculated with Eq. 3 and Eq. 4, as in (Avnery et al., 2011; Sinha et al., 2015) and (Hu et al., 2020).

$$CPL = CP * \frac{RYL}{1 - RYL} \qquad \text{Eq. 3}$$

$$ECL = CPL * MPP \qquad \text{Eq. 4}$$

Where CP corresponds to the amount of crop production obtained from 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) (German Ministry of Food and Agriculture, 2020; German Agricultural Market Information Company (Ami), 2020). For policy context, an additional evaluation is done using the farm prices for the year 2025, (€189/t) (Dairy and Agricultural Economic Analysis Centre, 2025).

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 O_3 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 O_3, 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).

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., 2022b), 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 (Donald, 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.

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

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).

2.7 Statistical analyses

The 15-year time series of the environmental data set used for the present study follows a non-normal distribution and has extreme values; therefore, non-parametric statistical tests with a 5% significance level ($p < 0.05$) were applied to analyse it

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and were performed with R software. To compare the distributions of the observations from the two case scenarios (best and worst) for beech and spruce, the non-parametric statistical goodness-of-fit Kolmogorov-Smirnov (KS) two-sample test was used (Massey, 1951; Teegavarapu, 2018). The assessment of short-term trends for different variables (PODySPEC, AOT40, and droughts) was done with the Mann-Kendall test and Sen's slope estimator (Teegavarapu, 2018). To determine significant differences in the AOT40 for the protection of forests and vegetation for mountain and rural background sites, the Mann-Whitney U-test was used (Teegavarapu, 2018).

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 POD_1SPEC, 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.

3. 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.

3.1 Risk assessment for coniferous and deciduous forests

A summary of the accumulated POD_1SPEC 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

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is presented in Figure 2. The time series of POD_1SPEC 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

POD_1SPEC 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).

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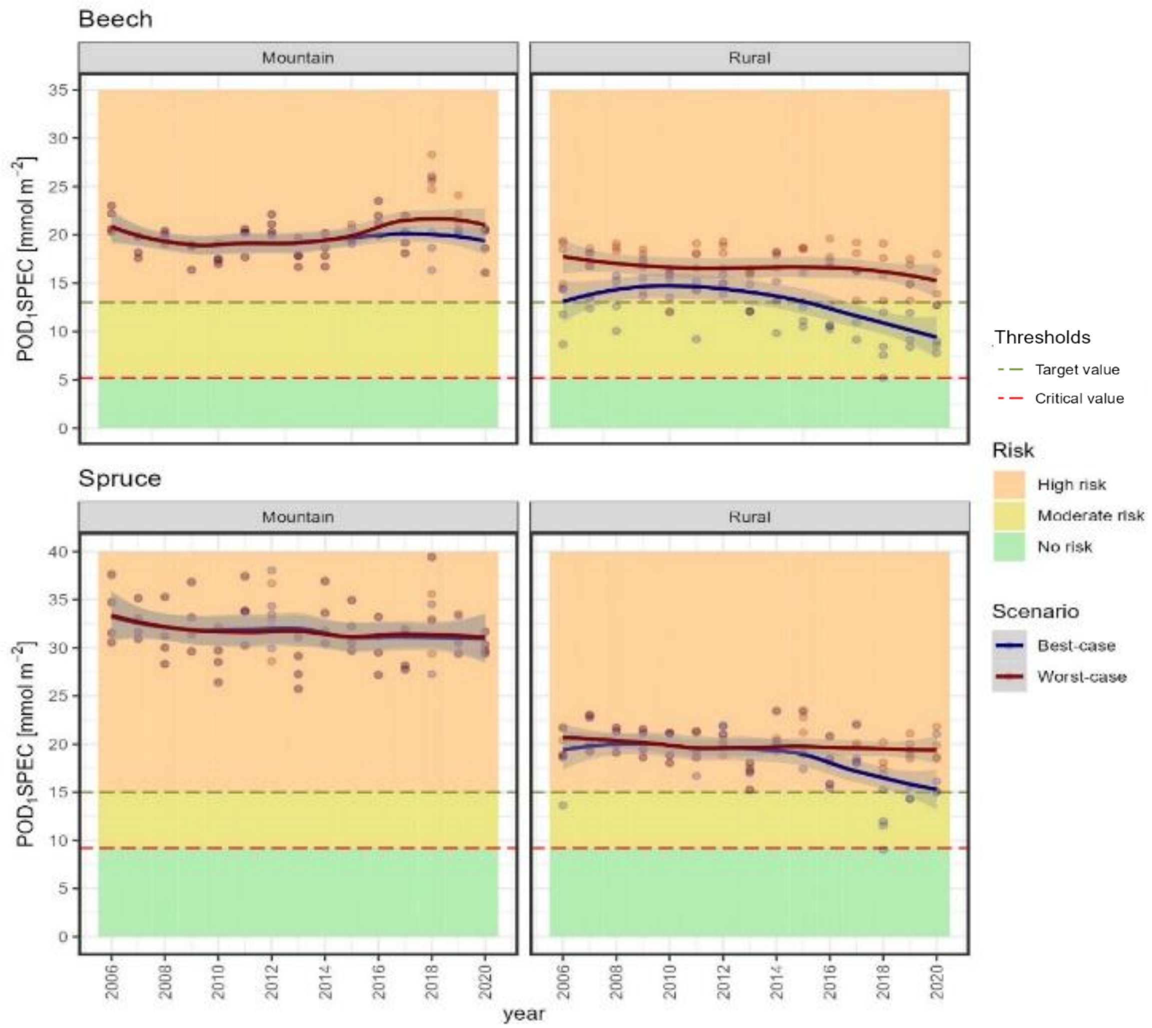

Figure 2: Accumulated POD1SPEC (mmol O3 per m-2 leaf area, PLA) per year for the time frame (2006-2020) at the mountain and rural sites in Saxony, Germany, with and without plant-available water approach (best-case and worst-case scenarios), for beech and spruce in the upper and lower panel, respectively. Dots represent individual station values, and lines are LOESS smothers to indicate the trend across all stations.

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).

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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

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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.

Decreasing trends are observed at rural background sites for the best-case scenarios of both representative species (Sen's slope ≤ -0.34) and for spruce at mountain sites (Sen's slope ≤ -0.16) (Table S4). Furthermore, 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

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(CL) for forest protection is defined for the accumulation period April-September, while the target value (TV); for vegetation protection is defined for May-July. For POD_1SPEC, both CL and TV are specified for all receptor species (forests, crops, and grasslands). As noted in Section 2.3, the species-specific accumulation periods for POD_1SPEC, applied in this study are April 1-October 30 for beech, year-round for spruce, and June 14-August 26 for wheat.

A comparison in the evolution of the mean accumulated for the two O_3 risk indexes POD_1SPEC (for beech and spruce; best-case scenario) and AOT40 per day of the year during the accumulation period for mountain and rural background stations tells about possible differences in their behaviours (Figure 3).

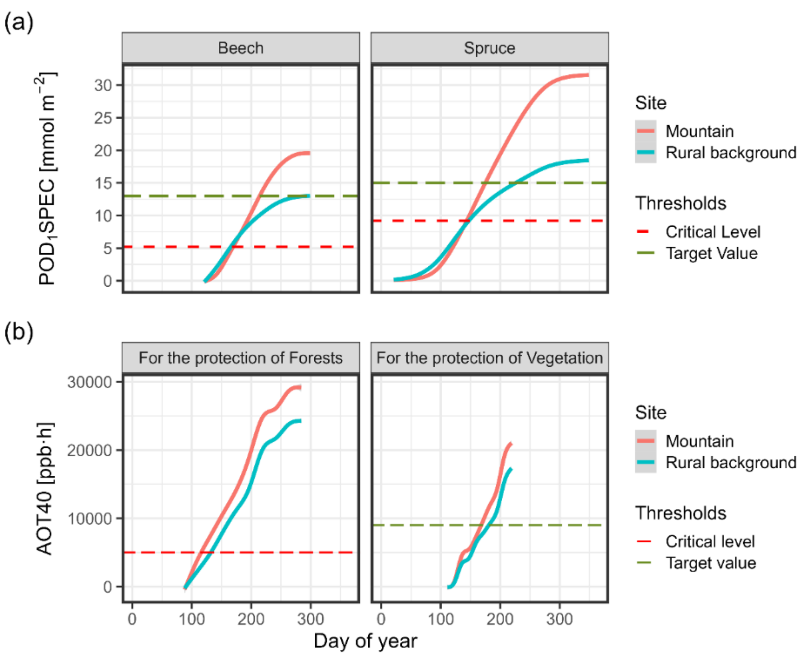

Figure 3: Evolution of the mean accumulated (a) POD1SPEC for the best-case scenario of beech and spruce, and (b) AOT40, per day of the year (DOY) during the accumulation period at mountain and rural background stations in Saxony from 2006 to 2020.

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.

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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 (30th 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 17th), 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 14th) and 180 (~June 29th), 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).

3.1.2 Environmental drivers of POD_1SPEC variability (POD_1SPEC drivers)

To study the main environmental drivers of POD_1SPEC variability in coniferous and deciduous forests across Saxony, a principal component analysis (PCA) and a Pearson correlation matrix were performed. These analyses were based on monthly

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averages of environmental and atmospheric variables, including the mean and daytime O_3 concentrations, POD_1SPEC, environmental variables, season, and elevation across all sites. Pearson correlation coefficients are shown in Figure 4, while factor loadings of four extracted principal components after Varimax rotation are shown in Table 3.

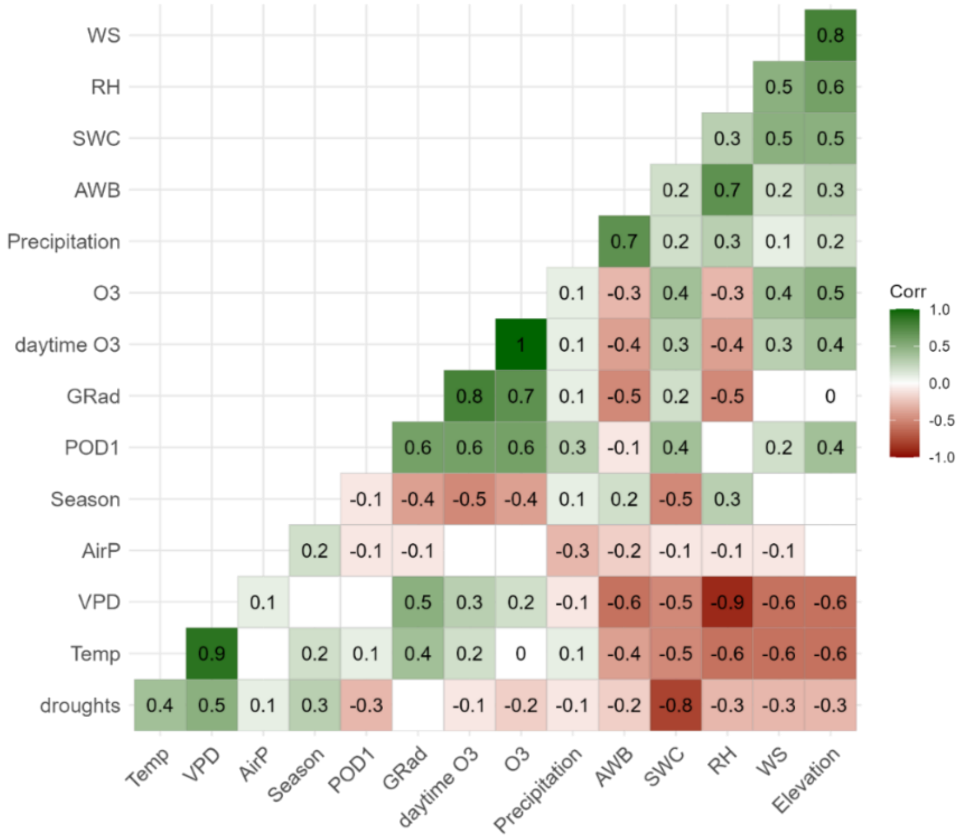

Figure 4: Pearson correlation coefficients for monthly data at the studied sites in Saxony from 2006 to 2020 for coniferous and deciduous forests.

Global radiation, O_3 concentrations, SWC and season

POD_1SPEC correlated with daytime O_3, mean O_3, global radiation and SWC, highlighting the importance of both, O_3 exposure and favourable meteorological conditions for stomatal uptake. These relationships were confirmed in the PCA (Table 3.), where POD_1SPEC loaded significantly only on the second principal component (RC2). RC2 also included strong positive loadings from daytime O_3 (p= 0.95), O_3 (p=0.93), and global radiation (p=0.82), and a moderate loading from SWC (p=0.29), alongside a negative loading for season (p=-0.43), directly reflecting the phytotoxicity of O_3 and the O_3 concentration load on POD_1SPEC for the entire growing season, being higher during spring than later in summer and autumn. Notably, POD_1SPEC

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showed a moderate loading and correlation with SWC, supporting previous findings on the influence of soil moisture on stomatal O_3 uptake (Eghdami et al., 2022a; Gerosa et al., 2022). However, the strength and direction of this relationship varied across elevations, being stronger at lowland rural background sites and turning mildly negative at the highest mountain sites, such as Carlsfeld (837 m a.s.l.) and Fichtelberg (1215 m a.s.l.) (Table S5).SWC was negatively correlated with season and temperature, indicating that SWC was generally higher in spring and also at lower temperature on higher altitude sites, allowing for a higher POD_1SPEC accumulation. Moreover, SWC was also negatively correlated with VPD, consistent with previous findings that elevated vapour pressure deficit can reduce stomatal O_3 uptake (Gerosa et al., 2022). Together, these results emphasize the dual role of SWC, and the control in season and elevation on O_3 uptake.

Table 3

Factor loadings of four principal components after varimax rotation at the studied sites in Saxony from 2006 to 2020, based on monthly data. Loadings with absolute values < 0.2 are considered insignificant and omitted; loadings > 0.5 are considered highly significant and are printed in bold. Season was treated as a numeric variable ranging from 1 (winter) to 4 (autumn).

Variable, (units)	RC1	RC2	RC3	RC4
Precipitation, (mm)			**0.94**	
Air pressure, (kPa)			- 0.45	0.26
POD_1SPEC, (mmol O_3 m^{-2})		**0.73**		
Daytime O_3, (hours with global radiation exceeding 50 W m^{-2})		**0.95**		
Global radiation, (W m^{-2})	- 0.31	**0.82**		
Wind speed, (m s^{-1})	**0.82**	0.27		
Air temperature, (∘C)	**- 0.65**	0.24		**0.61**
Relative humidity (%)	**0.79**	- 0.36	0.28	
O_3, (ppb)		**0.93**		
Vapor pressure deficit, (kPa)	**- 0.68**	0.31		**0.54**
Elevation (m)	**0.87**	0.41		
Season	0.33	- 0.43		**0.68**
Droughts, (mm)	- 0.24			**0.72**
SWC, (%)	0.37	0.29		**- 0.74**
AWB, (mm)	0.26		**0.87**	

Elevation and climate

Elevation had a high loading on RC1 (p=0.87), which also included wind speed and relative humidity, while temperature and VPD loaded negatively. This pattern reflects the typical higher altitude site conditions: lower temperature, higher relative humidity, and higher wind speed. Although elevation did not load significantly on RC2, it was moderately correlated with both POD_1SPEC and SWC, specifically at mountain sites where higher O_3 concentrations and moisture level contribute with higher O_3 stomatal uptake (Figure 2 and Figure 4). Additionally, elevated sites tend to experience higher daytime O_3 levels and more favorable environmental conditions for stomatal O_3 uptake, especially during spring. Additional correlations between environmental parameters were captured in RC3, which included strong loadings from precipitation

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(0.94) and atmospheric water balance (0.87), and a mild association with relative humidity. However, these factors showed no significant relationship with POD_1SPEC and likely reflect background hydrometeorological variability rather than direct drivers of stomatal O_3 uptake.

In summary, the second principal component (RC2) captures the key environmental and atmospheric conditions that drive POD_1SPEC variability: high radiation, O_3 concentrations, and sufficient soil moisture, especially during the growing season on spring. RC1, in contrast, reflects topographic and climatic background conditions associated with elevation, which modulate but do not directly drive POD_1SPEC accumulation.

3.1.3 Effects of droughts and O_3 concentrations on stomatal O_3 uptake

Understanding the variability in stomatal O_3 uptake (POD_1SPEC) requires an integrated assessment of both atmospheric O_3 exposure and plant water stress. While elevated O_3 concentrations can increase POD_1SPEC, drought conditions can suppress stomatal O_3 uptake, leading to complex, and sometimes opposing, effects. This section explores how environmental drought signals, the frequency of dry days, and daytime O_3 concentrations interact to influence POD_1SPEC in beech and spruce forests across Saxony. By combining statistical and temporal analyses, we aim to better understand how these factors jointly modulate vegetation risk under changing climate conditions.

Influence of drought conditions on POD_1SPEC variability

Drought variability is expressed in the fourth PCA factor (RC4), correlating with season, temperature, VPD, and a negative correlation to SWC (Figure 4 and Table 3). Droughts are more intense during summer months, when temperature and VPD are higher, and loss of water content in soil is increased due to evaporation. This seasonal drought signature is further reflected in the Pearson correlation matrix (Figure 6), where drought was negatively correlated with SWC and mildly negatively correlated with POD1SPEC. Although POD1SPEC did not load significantly on RC4, these drought-related variables likely influence stomatal O_3 uptake indirectly by reducing SWC and promoting stomatal closure, particularly during dry summer periods. This is consistent with previous findings that increased VPD limits O_3 stomatal uptake (Gerosa et al., 2022). Site-specific analysis revealed strong negative correlations between POD_1SPEC and droughts at rural background sites and mildly negative at mountain sites (Table S5), indicating that water stress may limit O_3 stomatal uptake more efficiently at rural sites.

From section 3.1, the analysis of the temporal variation for the yearly accumulated POD_1SPEC of coniferous and deciduous trees shows that POD_1SPEC accumulation was generally higher at mountain sites than at rural background stations in Saxony, attributing these to the usual higher O_3 concentrations at higher elevation sites, which is confirmed through the PCA and correlation matrix analysis. Nevertheless, the role of drought has not yet been explicitly considered in this interpretation. While in the current subsection droughts are first explored as a broader environmental signal using monthly-scale variables (e.g. temperature, VPD, SWC) captured in the PCA and correlation matrix, the following subsection goes further by examining the number of dry days as a more precise, temporal site-level indicator of drought stress. This approach

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provides additional insight into how interannual drought duration affects POD_1SPEC accumulation, particularly under high O_3 conditions.

Number of dry days as a key modulator of stomatal O_3 uptake

Overall, the number of dry days was higher for rural background sites than at mountain sites in Saxony between 2006 and 2020 (Figure S4). Years with a higher number of dry days are observed during the entire time series at rural background sites, except for the year 2007. On the other hand, years with dry days at mountain sites happened seldom, observed only during 2013 and from 2015 to 2019 (Figure S4). These observations help understand the strong negative correlations between POD_1SPEC and droughts at rural background sites and mildly negative at mountain sites (Table S5). At rural background sites, years with more dry days show lower yearly accumulation of POD_1SPEC for coniferous and deciduous forests during their growing seasons, with a higher impact for beech trees, e.g., in 2018. These results indicate that the more extended droughts are, the more restricted O_3 stomatal uptake is for coniferous and deciduous forests in Saxony, which has been reported extensively in the literature (Buckley, 2019; Pirasteh-Anosheh et al., 2016).

However, this pattern seems less pronounced at mountain sites. Despite prolonged dry periods, POD_1SPEC remained high for spruce and beech, especially at elevated locations like Fichtelberg. This may be explained by the cooler temperatures, lower vapour pressure deficit, and generally higher soil moisture availability at high-altitude sites, which reduce drought stress and allow stomata to remain more open. Species-specific tolerance traits may also contribute. Similar behaviour has been reported for mountain forests elsewhere, suggesting a complex stomatal response under drought conditions.

Although drought usually limits stomatal conductance, the results suggest that at higher elevations stomatal activity may be partly maintained due to species-specific tolerance traits, cooler temperatures, lower vapour pressure deficit, and potentially greater soil water availability. Similar behaviour has been reported for mountain forests elsewhere, pointing to a complex stomatal response under drought conditions. By contrast, at rural background sites the higher number of dry days in recent years (2018, 2019; Figure S4) coincides with decreasing PODySPEC accumulation, reflecting stronger drought limitation of O_3 uptake. This is consistent with previous reports showing reduced stomatal O_3 uptake under prolonged drought and high O_3 concentrations (Gerosa et al., 2022). To further explore these interactions, we analysed yearly accumulated POD_1SPEC and the number of dry days grouped by 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 (see Figure 5 and Figure S5).

Interactions between daytime O_3 concentrations and drought duration

Generally, the years with a high daytime O_3 concentration have more dry days, which is more relevant for rural background sites. In contrast, drought duration is also low in years with low daytime O_3 concentration. Under high and medium daytime O_3 concentrations (percentiles 75 and 50), droughts increase by 37% and 95 %, respectively. At high daytime O_3 concentrations (percentile 75), POD_1SPEC for beech and spruce decreases in rural sites by 25% and 14 %, respectively. At mountain sites, the opposite occurs, increasing by 4 and 7 %. Under low and medium daytime O_3 concentrations (percentiles

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25 and 50), the POD_1SPEC for beech and spruce trees keeps a regular accumulation pattern, without differences among them, even when at medium daytime O_3 concentrations (percentiles 50), the number of dry days is increasing.

The evolution in the accumulation of POD_1SPEC under the best-case scenario for years with high daytime O_3 concentrations (percentile 75) is low for beech and spruce. POD_1SPEC accumulation does not reach the target level for beech, positioning in a moderate risk level. These results indicate that for rural background sites in Saxony, the daytime O_3 concentrations directly impact the O_3 risk for forests (beech and spruce). Considering that in years with high O_3 daytime concentration (percentile 75), the number of dry days is higher, an exacerbating effect of the atmospheric O_3 concentrations can be assumed. During droughts, plants close their stomata to reduce water loss under drought stress, consequently limiting the O_3 stomatal uptake by vegetation, as it has been reported for overall Europe, where such vegetation feedbacks worsen peak O_3 episodes during droughts (Lin et al., 2020). As the frequency of hot and dry summers is expected to increase over the coming decades, the results presented for Saxony indicate that the damage to vegetation due to O_3 could be severe and, therefore, needs to be considered when designing clean air policy in the European Union.

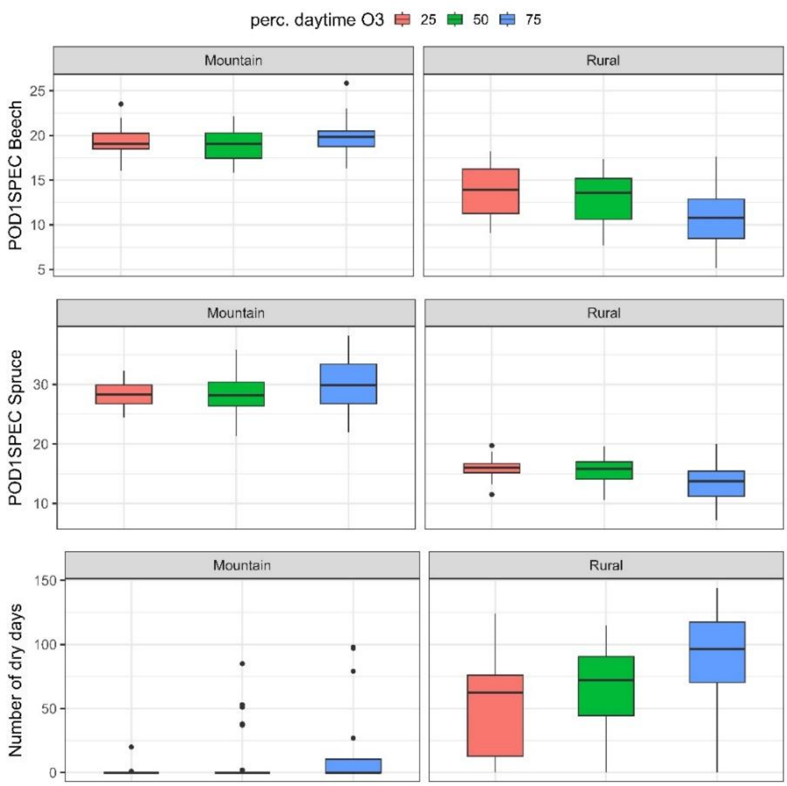

Figure 5: Box plot of the yearly accumulated POD_1SPEC and number of dry days grouped by percentiles 25, 50, and 75 of the daytime O_3 concentrations for rural background sites in Saxony from 2006 to 2020 for coniferous and deciduous forests.

In summary, the discussion in this section shows that both drought and O_3 concentrations influence the POD_1SPEC of beech and spruce trees across Saxony. At rural background sites, years with low daytime O_3 concentrations (25th percentile) were associated with fewer dry days and higher POD_1SPEC accumulation. In contrast, years with high O_3 concentrations (75th percentile) coincided with more frequent and prolonged droughts, reducing POD_1SPEC due to stomatal closure, similar to patterns observed in Rhineland-Palatinate forests (Eghdami et al., 2020; Eghdami et al., 2022a).

These results suggest that at rural background sites, O_3 risk is highest in years with moderate O_3 levels and sufficient soil moisture, when stomatal uptake is maximised. At mountain sites, however, high POD_1SPEC accumulation was maintained even in dry years. This can be explained by the cooler temperatures, lower vapour pressure deficit, and generally higher soil moisture availability at higher altitudes, which mitigate drought stress and allow stomata to remain open longer. Species-specific physiological tolerance at mountain ridge sites may further contribute. As a result, drought periods did not limit stomatal conductance to the same extent as at rural lowland sites, pointing to a higher and more consistent O_3 risk for mountain forests under dry conditions. Similar patterns were observed in a mountainous Norway spruce forest in the Czech Republic, where sap flow and eddy covariance data confirmed that physiological activity and O_3 uptake persisted during the extreme 2018 drought, despite expectations of stomatal closure at high elevations (Zavadilova et al., 2023). As hot and dry summers become more frequent, these findings highlight the importance of considering site-specific interactions between drought and O_3 uptake when assessing forest health and designing air quality policies.

3.2 Risk assessment for grassland and croplands

3.2.1 Assessment for grassland

Accumulated POD_1SPEC for grassland under the worst-case scenario (simulating full irrigation) can be seen in Figure 6, grouped and discriminated by mountain and rural sites in Saxony. With regards to the risk assessment from grassland, mountain and rural sites are in the high-risk zone during the entire time series, exceeding the recommended target and critical values for grassland. It is estimated that the above-ground biomass, total biomass, and flower numbers at mountain sites in Saxony have a mean potential maximum reduction rate (%) of 9.16, -0.08, and 16.02, respectively, for a worst-case scenario, with those biological endpoints being ~ 20 % higher than at rural background sites (Table 2.). While some studies have shown variable sensitivity of grassland species to elevated O_3, with certain species displaying tolerance under controlled conditions (Hayes et al., 2007); the high POD_1SPEC values observed in this study suggest a considerable risk. This implies that additional factors, such as meteorological conditions may influence O_3 uptake in grassland systems.

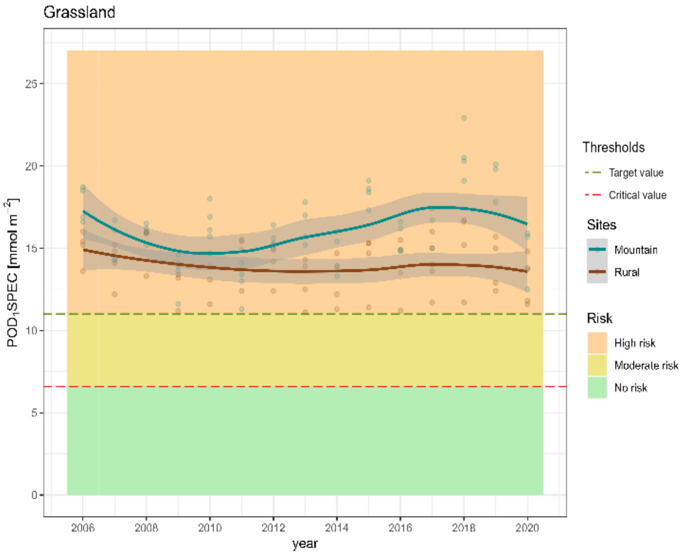

Figure 6. Accumulated POD_1SPEC (mmol O_3 per m^{-2} leaf area, PLA) for grassland per year, for the time frame (2006-2020) without plant available water approach (worst-case scenario), at the mountain and rural sites in Saxony, Germany. Dots represent individual station values, and lines are LOESS smothers to indicate the trend across all stations.

The mean of the accumulated POD_1SPEC for grassland was higher at the mountain sites (16.14 ± 2.27 mmol O_3 m^{-2}) than at rural background sites (13.97 ± 1.58 mmol O_3 m^{-2}) (Figure 6 and table S4), showing no significant trends. Given the growing season for grassland species, the results found in this study can be compared to the POD_1SPEC observations for the period April 1st to September 30th reported for central European forests at mid-range altitudes. The results for grassland are slightly below the ones reported by the author, with an average for all sites in the accumulated POD_1SPEC of 19,84 mmol O_3 m^{-2} (Eghdami et al., 2022a). An increment of ~ 30 % was observed for the years 2018 and 2019 when compared to the overall mean from the full-time series, except for the rural background station Collmberg, which had the most monotonic inter-yearly POD_1SPEC changes (Figure S2). As seen for beech and spruce, grassland also had lower POD_1SPEC values for Collmberg.

3.2.2 Assessment for croplands

The POD_6SPEC estimations for wheat under a worst-case scenario (simulating full irrigation) show that this representative species is in the high-risk zone at mountain sites, exceeding both the recommended target value (TV) and critical level (CL) (Figure 7). The potential maximum reduction rate estimates for grain yield indicate a mean of ~7% at rural background stations, and around twice as much at mountain sites (Table 2). A decreasing trend (Sen's slope = -0.1) was observed for POD_6SPEC at mountain sites (Table S4), pointing to a decline in risk over time. On average, wheat crops in Switzerland show about 6.7% higher O_3 uptake and related yield losses under worst-case assumptions than those estimated here for Saxony (Schneuwly and Ammann, 2020).

https://doi.org/10.5194/egusphere-2025-5542
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From 2015 to 2020, mean POD_6SPEC for rural background sites decreased by ~14%, reaching 3.10 ± 0.98 mmol O_3 m^{-2}, placing this representative species in a moderate risk category, below the TV (Figure 7). The highest POD_6SPEC values during the entire time series were observed at the mountain site Schwartenberg (789 m a.s.l.), where the mean was 5.46 ± 0.77 mmol O_3 m^{-2}. Among rural background stations, Collmberg and Niesky showed the lowest values, about 32% below the overall mean for wheat, and contributed most to the decreasing trend seen at rural sites (Figure S3 and Table S4). Interestingly, despite having higher average O_3 concentrations (~60 µg m^{-3}), both stations showed low risk. These two sites are located at higher elevation and farther from urban areas compared to Radebeul-Wahnsdorf and Schkeuditz, which are closer to Leipzig and showed higher POD_6SPEC values.

A comparison with wheat scenarios in Switzerland suggests that under low O_3 and low SWC conditions, differences between best- and worst-case scenarios are small (Schneuwly and Ammann, 2020). Therefore, high O_3 concentrations alone do not necessarily imply high risk if water availability limits uptake. In Saxony, while the same cannot be assumed for all sites, the higher POD_6SPEC observed at Schwartenberg may indicate that this mountain site regularly experiences both high O_3 concentrations and sufficient SWC to allow continued stomatal uptake. As mountain areas typically receive more rainfall and have lower temperatures, they may support prolonged stomatal activity even under regional drought conditions.

Currently, the fraction of irrigated crops in eastern Germany is very low, and arable farming generally depends on rainfall directly (German Institute for Standardization, 2022) (Zinke, 2019); thus, the calculated reduction in grain yield for sites in Saxony using a worst-case scenario (simulating full irrigation) may overestimate actual risk, particularly at rural sites. However, for mountain sites, the persistence of stomatal uptake observed in forests during drought suggests that this scenario could approximate real exposure levels more closely than expected. Because O_3 stomatal uptake is limited under low soil water conditions, a realistic O_3-induced risk to wheat would be low, even at high O_3 concentrations (Buckley, 2019; Pirasteh-Anosheh et al., 2016). During the last years, a lack of precipitation has resulted in droughts starting from the beginning of every spring in Germany, further reducing water availability for crops.

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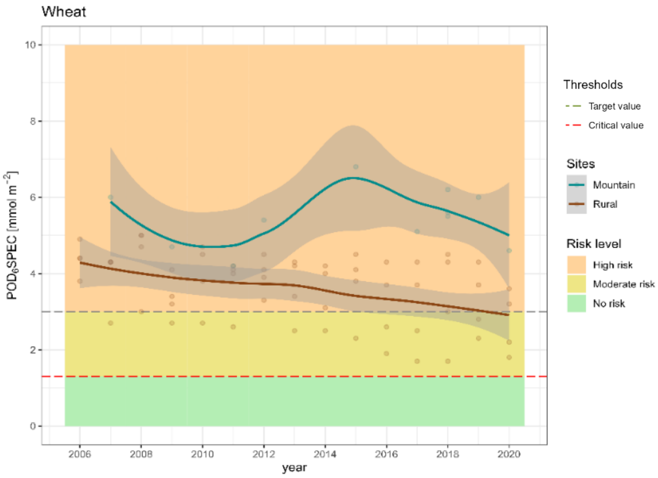

Figure 7: Accumulated POD_6SPEC (mmol O_3 per leaf area, PLA) for wheat, per year, for the time frame (2006-2020) without plant available water approach (worst-case scenario), at the mountain and rural sites in Saxony, Germany. Dots represent individual station values, and lines are LOESS smothers to indicate the trend across all stations.

At the same time, if irrigation becomes more widespread in the future, it could increase O_3 uptake and, therefore, the associated risk. Intense droughts like the one observed during the summer of 2022, and projected climate changes for Germany, such as rising temperatures, less summer rain, and more winter precipitation, suggest that irrigation may become necessary to maintain yields (German Institute for Standardization, 2022). However, this would also make crops more vulnerable to O_3 damage. In addition, drought conditions can enhance vegetation feedbacks that worsen O_3 extremes (Lin et al., 2020), adding complexity to future projections.

Although no best-case scenario was evaluated for wheat, the forest risk assessment offers useful physiological context for interpreting crop risk estimates. Forests at mountain sites showed sustained stomatal conductance during drought, contributing to higher POD_1SPEC values. In contrast, wheat typically reduces stomatal conductance under water stress, especially at rural sites with lower water availability. However, mountain environments often experience cooler temperatures and higher rainfall, which may reduce drought severity. If such conditions, or future increases in irrigation, help maintain stomatal activity in wheat during dry periods, POD_6SPEC values at mountain sites could remain elevated. In this case, the worst-case estimates may represent plausible upper-bound risks rather than clear overestimations. Still, caution is warranted when extrapolating drought responses from forests to annual crops, as physiological differences are substantial.

These findings are not only relevant for Saxony but also for other mountain farming systems, particularly in regions like the Andes, Himalayas, or East Africa, where upland agriculture plays a vital role in food security and economic stability. The combined use of flux-based metrics and environmental indicators, as demonstrated here, can support O_3 risk assessments in regions where data are limited but vulnerability is high. Based on the results for this representative species, an evaluation of the economic losses for Saxony is presented in Section 3.2.3.

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.

Despite an increase of approximately 7% in wheat production from 2015 to 2020 reported for the federal state of Saxony (German Ministry of Agriculture, 2021), These losses correspond to around 13% and 25%, per site type, of the German wheat yield loss in 2019, estimated at 1.6 million tonnes (valued at €280 million using €175/t) due to tropospheric O_3 (Schucht et al., 2021).

These estimates are based on a worst-case scenario assuming unrestricted irrigation and may therefore overestimate actual risk, especially at rural background sites where drought is more likely to limit O_3 stomatal uptake. However, as shown in the forest results, mountain sites may sustain stomatal conductance during dry periods. If wheat behaves similarly under drought conditions, the losses estimated under worst-case assumptions might reflect realistic risk levels for crops at mountain sites. Under the current price and cost ratios, economic losses in Saxony are already evident (German Institute for Standardization, 2022).

A reevaluation considering the current farm wheat price in Germany for 2025 (€189/t (Dairy and Agricultural Economic Analysis Centre, 2025), the same losses would correspond to approximately €38.0 million at rural background sites and €75.0 million at mountain sites, assuming the same average wheat losses as observed during 2016-2020. This represents an increase of about 13% compared to the 2016-2020 average.

A decreasing trend observed for POD_6SPEC and its associated risk suggests a a possible decline in Saxony's maximum yield reduction for wheat grain in the coming years. Nevertheless, drought conditions in eastern Germany have increasingly affected crop quality and yield, potentially amplifying losses beyond those attributed to O_3 alone (German Institute for Standardization, 2022; Zinke, 2019). In the future, O_3 damage may require higher wheat prices to offset both reduced yields and the rising costs of irrigation (German Institute for Standardization, 2022).

4. Conclusions

The present study used 15 years of PODySPEC 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.

By comparing best- and worst-case scenarios, the influence of soil water content on stomatal O_3 uptake could be identified. For beech, the risk was found to be overestimated under worst-case conditions that assume full irrigation, highlighting the importance of considering soil moisture when evaluating O_3 risk. The number of dry days appeared as a key variable for O_3 stomatal uptake. While uptake decreased during dry years at rural sites, high stomatal activity was still observed at mountain sites, even when water availability was limited. This likely reflects deeper rooting and species-specific tolerance to drought. These findings illustrate the advantage of using flux-based metrics such as PODySPEC, as opposed to concentration-based approaches like AOT40. PODySPEC accounts for physiological and environmental controls on O_3 uptake and allows for a more accurate representation of species and site differences.

For grasslands, POD_1SPEC values placed both mountain and rural sites consistently in the high-risk zone. Under worst-case assumptions, potential reductions reached ~9% for above-ground biomass and ~16% for flower numbers, with effects about 20% higher at mountain sites. These results suggest that grasslands, like forests, are sensitive to O_3, although responses may be further shaped by local meteorological conditions.

For wheat, worst-case POD_6SPEC estimates indicated potential yield losses of up to 14% at mountain sites, corresponding to annual economic losses of around €66 million when valued at the mean producer price for 2016-2020 (€166.67/t). At rural background sites, mean losses amounted to about €34 million. Assuming the same losses under the 2025 wheat price (€189/t), economic costs would rise by approximately 13%, to €38 million at rural sites and €75 million at mountain sites. Although no best-case scenario was evaluated for crops, the results from forest sites offer interpretive context: if local conditions or irrigation allow wheat to maintain gas exchange during drought, O_3 uptake may remain high. However, since wheat tends to reduce stomatal conductance under drought stress, particularly when irrigation is not available, the crop risk estimates presented here should be considered conservative upper limits. The actual risk may be lower in most cases.

These insights are not only relevant for Saxony but may also apply to other mountain regions where agriculture and grasslands play an important role. In areas such as the Andes, Himalayas, and East Africa, upland farming systems are essential for food production and local economies. The approach presented here, which combines flux-based risk metrics with drought indicators, can support better assessments of O_3 impacts in places where monitoring is limited. As dry and hot seasons become more frequent, the combination of drought, air pollution, and limited adaptive capacity could increasingly threaten yields and food security in vulnerable regions.

5. Data availability

The measurement data used in this study is freely available from the LfULG (https://www.umwelt.sachsen.de/umwelt/infosysteme/luftonline/recherche.aspx) or can be made available upon request to the corresponding author.

6. Supplement

The supplement related to this article is available online at:

7. Author contribution

VE, DvP, and HH conceptualized the study. VE, with support from DvP, curated the raw data. VE performed the modelling, formal analyses, and visualization of the results. DvP and HH supervised the study. VE drafted the manuscript, and all authors contributed to the review and editing of the final version.

8. Competing interests

The contact author has declared that none of the authors has any competing interests.

9. Acknowledgements

We gratefully acknowledge the Saxon State Office for the Environment, Agriculture, and Geology (LfULG) for providing the long-term ozone and meteorological datasets used in this study. We also thank the German Weather Service (DWD) for access to precipitation data.

10. Financial support

This research has been funded through the project grant no. 51-Z266/20, by the Saxonian State Office for the Environment, Agriculture and Geology (LfULG).

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