

Comparing absolute and standardized drought indices for modelling tree mortality of spruce, beech, pine, and oak based on the Crown Condition Survey in Germany

Laura-Marie Schotte^{*} , Angelika Olesch , Sebastian Fuchs , Luca Smekal ,
Bernd Ahrends

Northwest German Forest Research Institute (NW-FVA), Department of Environmental Control, Grützstraße 2, Göttingen 37079, Germany

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ABSTRACT

Increasing drought frequency and intensity driven by climate change have severely impacted tree vitality and contributed to rising mortality across Europe. To quantify and compare the intensity and regional extent of droughts, a variety of indices have been developed. Consequently, different methodological approaches are currently used in research to explain drought-induced tree mortality. The aim of this study was to evaluate the extent to which aridity (Climatic Water Balance, CWB; Site Water Balance, SWB) and drought indices (Standardized Precipitation Evapotranspiration Index, SPEI; CWB anomalies) were associated with tree mortality. The study used data from the German Crown Condition Survey (1990–2022) to derive mortality rates for four major tree species (Norway spruce, European beech, Scots pine, and oak). Using correlation analyses and generalized additive models (GAMs), we retrospectively quantified how aridity and drought indices, particularly the SPEI, explained tree mortality by comparing modelled mortality probabilities with observed rates. The results revealed distinct species-specific responses. For spruce, beech, and pine, SPEI and CWB anomalies showed the strongest links to mortality, with effects increasing over longer aggregation periods of up to five years. For oak, which exhibited lower mortality rates, the SPEI-based models did not adequately explain mortality, indicating the need for additional predictors. Overall, the results indicated that in Germany the mortality of the most common tree species was better described by relative deviations from long-term averages than by absolute aridity measures. The study shows that the SPEI is a robust indicator for predicting drought-related mortality across dominant tree species in Germany and contributes to improved tree species selection under climate change.

1. Introduction

Climate change is leading to an increase in global air temperatures, altered precipitation patterns as well as a growing frequency and intensity of drought events worldwide (IPCC et al., 2023). These changes directly affect the vitality and survival of forest trees across different climatic regions (Allen et al., 2015; Hartmann et al., 2022; Neumair et al., 2022; Schuldt et al., 2020). Tree mortality events related to climate change have been reported in various biomes, including temperate (Obladen et al., 2021; Schuldt et al., 2020; Senf et al., 2020), boreal (Liu et al., 2023), and tropical forest (Bauman et al., 2022), indicating that climate-induced stress is a global ecological phenomenon and will increase due to the projected future warming and drought (Adams et al., 2009; van der Wiel et al., 2023). A recent study indicates

that droughts leading to tree mortality are becoming longer, more intense, and more complete in dry biomes, particularly in angiosperm-dominated forests (Gazol et al., 2025). Models predicting the risk of tree mortality caused by drought stress contain large uncertainties (Hartmann et al., 2022). A variety of studies identify climatic variables as key predictors of the recently increased mortality rates of European tree species (Anders et al., 2025; Brandl et al., 2020; Neumair et al., 2022; Neumann et al., 2017) as well as tree species in tropical forest ecosystems (Bauman et al., 2022). Warmer winters and droughts in the summer months contribute significantly to the rising mortality risk of trees (Brandl et al., 2020; Neumann et al., 2017). Between 2018 and 2020, Central Europe experienced prolonged drought periods, which led to a substantial increase in crown damage and tree mortality in Germany (Schuldt et al., 2020; Thonfeld et al., 2022).

^{*} Corresponding author.

E-mail address: Laura.Schotte@nw-fva.de (L.-M. Schotte).

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Drought-induced water deficits impair key physiological processes such as xylem water transport and photosynthesis, increasing the vulnerability to pests and ultimately resulting in tree death (Adams et al., 2017). As forests cover roughly one-third of Germany's land area (BMEL, 2024), evaluating the effects of rising temperatures, shifting precipitation, and recurring droughts on tree vitality and mortality is essential.

In Germany, the Crown Condition Survey (Waldzustandserhebung, WZE) provides annually collected data since the early 1980s (Wellbrock et al., 2018). Although the WZE represents a decades-long national forest monitoring programs, its dataset are not yet integrated into the International Tree Mortality Network, which globally highlights the need for consistent, annual mortality monitoring (International Tree Mortality Network, 2025). Systematic assessment of crown condition in the WZE allows precise quantification of tree vitality, contributing to improved accuracy of tree mortality prediction models (Dobbertin and Brang, 2001). Recent results from 2024 indicate that crown condition deteriorated across all most common species during the consecutive extreme drought years 2018–2020, with many cases still showing substantial defoliation (BMELH, 2025). Norway spruce was particularly affected, with stand area declining by approximately 17% due to drought and subsequent disturbance events in Germany (BMEL, 2024). Beech, pine, and oak also showed significant losses in vitality, reduced growth, and increased susceptibility to secondary stressors such as insect or fungal infestations during the extreme years, which increased the risk of mortality over several years (Bigler and Vitasse, 2021; BMEL, 2024; Gentilesca et al., 2017; Haberstroh et al., 2022; Leuschner, 2020; Rukh et al., 2023; Schuldt et al., 2020). Because the risk of tree mortality is depending on tree species (Petit-Cailleux et al., 2021), there is a strong need for species specific analysis.

Drought is a complex natural phenomenon that can be characterized by climatological and hydrological parameters (Mishra and Singh, 2010). Currently, a wide range of indices has been developed and applied to compare the intensity, duration, and spatial extent of drought under varying climatic and hydrological conditions at regional scales (Speich, 2019; Stagge et al., 2015). Moreover, these indices make it possible to relate observed tree mortality events to drought conditions and to analyse potential links between water deficits and tree vitality losses. Several studies have compared different indices used to quantify drought stress in forests (Braun et al., 2015; Habel et al., 2023; Speich, 2019). For instance, Speich (2019) differentiates between drought and aridity indices: while the former describe deviations from climatological norms, the latter are based on absolute threshold values.

There is currently no generally accepted standard in forest science for assessing drought, resulting in the use of various methodological approaches to explain drought-induced tree mortality. Some studies employ standardized drought indices, such as the *Standardized Precipitation Evapotranspiration Index* (SPEI; Vicente-Serrano et al., 2010), to quantify drought periods and model tree mortality probabilities (Zhang et al., 2017). The SPEI widely used in studies to investigate the impact of drought on tree mortality across different climatic regions (Gazol et al., 2025; Hammond et al., 2022). In contrast, the *Site Water Balance* (SWB) is commonly used in northwestern Germany as an absolute aridity index for species suitability screening under climate change, as it integrates both climatic and site-specific factors (Grier and Running, 1977; Spellmann et al., 2020). Current mortality-modelling studies based on WZE data in Germany also apply aridity indices such as the *climatic water balance* (CWB), which is used in both absolute (Knapp et al., 2024) and standardized form (Anders et al., 2025). These studies achieved the best results using CWB-derived metrics such as rolling means and minimums or anomalies. Nevertheless, Anders et al. (2025) emphasize the need for further research to determine whether the SPEI can capture relationships between drought and tree mortality as effectively as the CWB. A key advantage of such standardized drought indices is their large-scale comparability, which is ensured by uniform scaling. This allows different regions, time periods, and climatic conditions to be systematically compared (Stagge et al., 2015; Vicente-Serrano et al., 2010).

Considering the increasing of drought events and the variety of methods to explain tree mortality, identifying the most suitable index for future modelling is of crucial importance (Senf and Seidl, 2021).

This study examines which absolute aridity (CWB, SWB) and standardized drought (SPEI) indices are stronger associated with tree mortality of the four most common tree species (Norway spruce, European beech, Scots pine, and oak) in Germany. The data were based on the WZE from 1990 to 2022. First, correlation analyses were used to identify which indices and climatic or site-specific predictors exert the strongest influence on tree mortality. Since previous studies (Anders et al., 2025; Knapp et al., 2024) using also WZE data have already modelled tree mortality based on various forms of the CWB, this study focuses on the SPEI to test whether it provides a comparable capacity to describe mortality rates. Different aggregation periods were considered to capture both short-term and cumulative drought effects. Using GAMs, species-specific mortality probabilities were modelled as a function of the SPEI and were compared with observed mortality rates based of the WZE. Accordingly, the study addresses the following hypotheses: (1) Absolute aridity and standardized drought indices differ in their ability to explain tree mortality, with standardized indices expected to provide a better representation of mortality responses due to their characterization of relative deviations from long-term climatic means. (2) The strength of the relationship between drought conditions and tree mortality depends on the aggregation period, with the expectation that longer drought aggregation periods exert a stronger influence on tree mortality. (3) Drought-mortality-relationships vary among tree species.

2. Material and methods

2.1. Tree mortality data

The analysis of tree mortality for Norway spruce (*Picea abies* (L.) H. Karst.), European beech (*Fagus sylvatica* L.), Scots pine (*Pinus sylvestris* L.), and oak (*Quercus robur* L. and *Quercus petraea* (Matt.) Liebl.) was based on data from the WZE covering the period 1990–2022. The WZE is an annual, nationwide forest monitoring program conducted since 1984 on a 16×16 km grid across Germany (Fig. 1) to systematically record and evaluate the vitality status of forests based on a standardized evaluation of 24 reference trees per plot (Wellbrock et al., 2018). In advance, the database was harmonized and merged across states by the Thünen Institute of Forest Ecosystems. As data collection is organized independently by federal states, minor methodological differences and

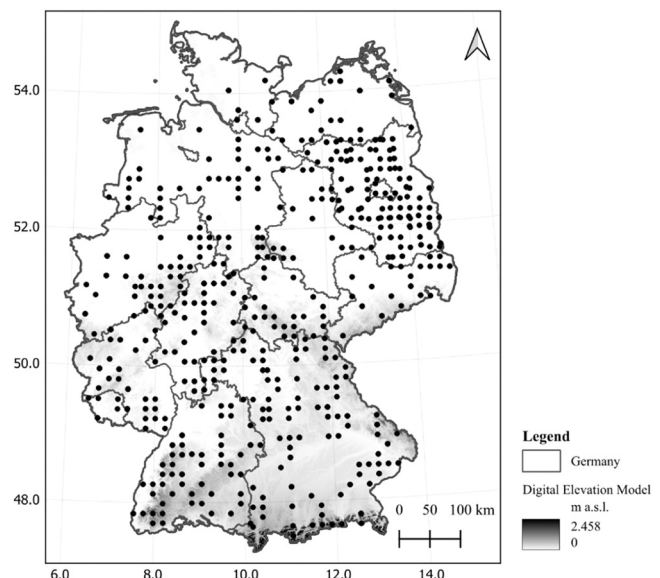


Fig. 1. WZE-Plots (n = 481) on a 16×16 km grid across Germany.

documentation inconsistencies may occur (Fig. A 1). For example, the WZE in Bavaria was systematically revised in 2006 to align its sampling grid with the National Forest Inventory (Bundeswaldinventur, BWI) and the National Forest Soil Inventory (NFSI II; Wellbrock et al., 2019). This adjustment came with a change in methodology and grid density. Thus, WZE data collected in Bavaria before 2006 were excluded at the expense of an abrupt increase in sample size in the year of 2006 (Fig. A 2).

In this study, the response variable *mortality* was coded as binary: 0 = alive and 1 = mortality event. The first observation of a complete needle or leaf loss (100%) in the time series of a tree or specific plot or tree statuses indicated mortality (Tab. A1) were classified as mortality events. This included cases such as tree removal due to biotic or abiotic stress factors. Methodologically, tree death in the WZE is recorded with a delay of up to 12 months because the survey is conducted annually. Trees affected by windthrow events or regular harvest without complete defoliation excluded from the dataset to ensure the focus on drought-related mortality (cf. Anders et al., 2025; Knapp et al., 2024). The final dataset comprised 481 plots, 16473 individual trees, and a total of 237558 observations from 1990 to 2022 (Table 1).

The annual mortality rate per tree species was calculated by dividing the number of mortality events in a given year by the total number of observed trees in that year:

$$\text{Mortality rate [\%]} = \frac{\text{Number of mortality events per year}}{\text{Total number of observed trees per year}} * 100 \quad (1)$$

Data processing and calculation of the annual mortality rate were performed using the R package *dplyr* (Wickham, 2015), and visualization was conducted with the *ggplot2* package (Wickham, 2016) in R (version 4.5.0, R Core Team, 2024).

2.2. Climate data

Daily climate data were regionalized from climate stations of the German Weather Service (DWD) to the respective WZE plots. Further methodological information and evaluation of the model performance for regionalized climate data can be found in Ahrends et al. (2018). Potential evapotranspiration (PET) was calculated according to the FAO standard (Food and Agriculture Organization of the United Nations) for consistent grass cover (Allen et al., 1998). The temperature data were first aggregated to monthly means, while precipitation and evapotranspiration were aggregated to monthly sums. Based on these data, the mean temperatures for the entire year and for the growing season (May to September) were calculated at plot level. In addition, the 30-year temperature average (1991–2020) was determined in order to analyse possible correlations with tree mortality.

2.3. Soil data

The soil data were taken from the second National Forest Soil Inventory (NFSI II) in Germany, covering the organic layer and mineral soil to a depth of 90 cm. Details on sampling procedure are given in Wellbrock et al. (2019). Missing soil bulk density in some horizons were filled with the pedotransfer function (PTF) for German forest soils from Steinicke et al. (2016). The Available Water Capacity (AWC) of the soil

was deduced from soil texture, bulk density, stone content and soil organic matter using the PTF from Dehner et al. (2015). The soil data, in particular the AWC, were used to calculate the SWB based on a subset of 413 plots where corresponding information from both the WZE and the NFSI II database was available.

2.4. Drought and aridity indices

This study tested aridity indices (CWB, SWB) as well as a drought index (SPEI) according to Speich (2019). While aridity indices are based on absolute thresholds and therefore account for both spatial and temporal components, the SPEI represents relative deviations from the long-term climatic mean of a site, thus capturing only the temporal dimension (Speich, 2019; Vicente-Serrano et al., 2010). The CWB and SPEI are purely climatic indices, whereas the SWB integrates both climate and soil variables (Fig. 2).

The CWB was calculated based on monthly sums (Eq. 2) and aggregated over 3, 12, 24, 36, and 60 months. July was selected as the reference month for calculating aggregation periods for the CWB and subsequently the SPEI, as the WZE is typically conducted during this month, allowing a complete growing season to be represented. Based on Knapp et al. (2024), rolling annual means of the CWB were calculated for each aggregation period, both for the entire year and for the growing season from May to September, complemented by rolling minimum values. In addition, CWB anomalies were calculated as in Anders et al. (2025) by subtracting the 30-year mean (1991–2020) of the CWB for the respective aggregation periods (3, 12, 2, 36, 60 months) from the corresponding CWB values. These anomalies can be interpreted as a standardization of CWB, but differ from SPEI in that they represent the deviations in absolute form.

$$\text{CWB} = P - \text{PET} \quad (2)$$

P = precipitation [mm]

PET = potential evapotranspiration [mm]

The SWB extends the purely macroclimatic CWB by additionally capturing mesoclimatic and soil physical aspects. First, the CWB was adjusted for local slope aspect by modifying the PET according to incoming insolation using functions based on the modular hydrological and water balance model WaSiM-ETH (Schulla, 2025). Second, the CWB was aggregated over the growing season (May-Sep) and added to the soil AWC, assuming water saturation at field capacity at the beginning of the growing season (Eq. 3). Soil physical properties were only available for WZE plots that were also part of the NFSI II, thus the SWB was just calculated for this sub-dataset (n = 413 plots). In addition, SWB anomalies were calculated by subtracting the long-term mean (1991–2020) from the current SWB values for each plot and year.

$$\text{SWB} = \text{CWB}_{\text{aspect}} + \text{AWC} \quad (3)$$

$\text{CWB}_{\text{aspect}}$ = aspect-corrected Climate Water Balance [mm]

AWC = Plant Available Water Capacity of the soil [mm]

The SPEI according to Vicente-Serrano et al. (2010) was used as the drought index. The SPEI is a standardized form of the CWB and defines drought as a negative deviation from the site-specific climatic normal. Its use allows aggregation over variable time periods, which makes it possible to examine the effects of the duration and intensity of previous climatic conditions. Therefore, drought is defined as a continuous period during which the SPEI remains below a specified threshold (≤ -1). Positive values indicate wet anomalies, while negative values correspond to dry anomalies (Table 2).

The calculation of the SPEI was based on the aggregated CWB. Therefore, the CWB data were first tested for their statistical distribution, which showed that they followed a normal distribution (Fig. A 3). The SPEI was then calculated for each plot over 3, 12, 24, 36 and 60 month periods using the R package *SPEI* (Beguería et al., 2014; Vicente-Serrano et al., 2010). To limit sensitivity to extreme values

Table 1

Overview of sample size (n) of plots, trees and mortality events, and mortality rate, for the whole period from 1990 to 2022.

Species	n plots	n trees	n mortality events	mortality rate [%]
Norway Spruce	224	5699	1139	19.99
European Beech	199	3106	52	1.67
Scots Pine	266	6010	273	4.54
Oak	149	1658	67	4.04
Sum	481	16473	1531	9.29

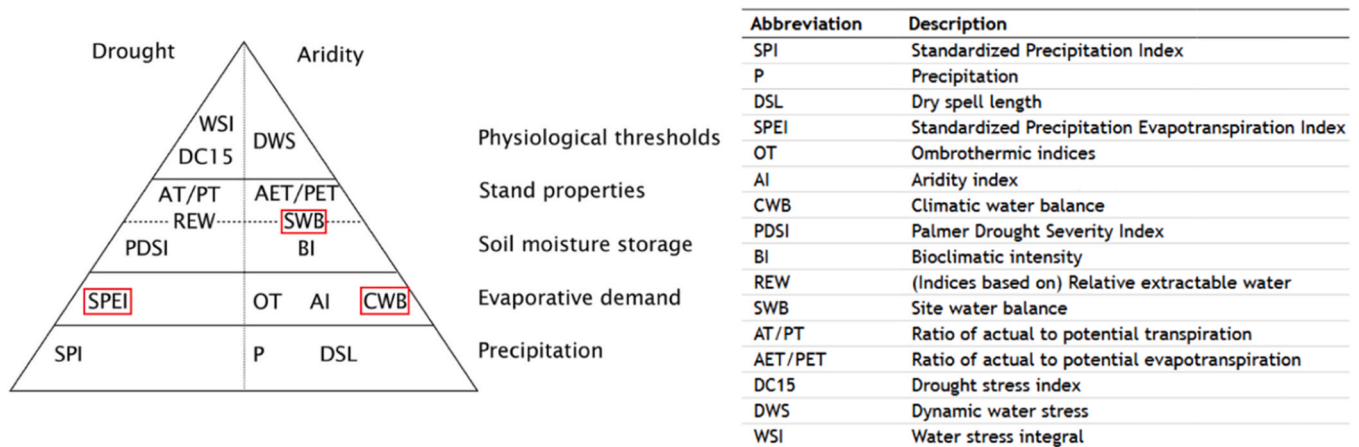


Fig. 2. Classification of drought and aridity indices. The pyramid levels represent the information layers considered by each index. Indices on the left side are used to quantify drought, whereas those on the right describe aridity. Indices highlighted in red are those analysed in this study. The table on the right provides descriptions of the indices pictured in the pyramid on the left. Taken and modified from [Speich \(2019\)](#).

Table 2

Classification of the value ranges of the drought index SPEI (according to [DWD, 2025](#); [Vicente-Serrano et al., 2010](#)).

Classification	Value range
Extremely wet	> 2
Significantly wet	1.5 to 2
Moderately wet	1 to 1.5
Normal range	0 to 1
Normal range	-1 to 0
Moderate drought	-1.5 to -1
Severe drought	-2 to -1.5
Extreme drought	< -2

while retaining meaningful drought signals, the standardized values were capped at ± 4 ([Stagge et al., 2015](#)). [Fig. 3](#) shows the temporal patterns of the SPEI for the different aggregation periods from 1960 to 2022. As the aggregation period increases, short-term fluctuations are smoothed, and longer-term drought periods become more pronounced.

2.5. Descriptive statistics

First, a descriptive analysis was conducted for each species to assess the relationships and effect sizes between the considered indices, drought-related variables, and tree mortality. Given the species-specific differences in mortality frequency and spatial distribution, point-biserial correlations were performed individually for each species. This is a special case of Pearson's correlation, in which a binary variable (mortality: 0/1) is correlated with continuous predictors ([Tate, 1954](#)). To account for additional site-specific factors beyond drought and aridity indices, the AWC was included as a proxy for soil properties. Also, tree age was included because age is a natural driver of mortality risk, as tree vitality generally declines with increasing age, while vulnerability to drought-induced hydraulic failure and pest infestations tends to increase ([Overbeck and Schmidt, 2012](#); [Thiele et al., 2017](#)). [Staupendahl and Zucchini \(2011\)](#) showed that the survival probability of the four most common tree species in Germany decreases with increasing age. Additional variables, including topographic factors, site index, and soil type, were pre-tested using correlation analyses and preliminary GAMs.

However, these variables did not show a strong significant effect on tree mortality and were therefore not included in the following analyses ([Fig. A 4](#) and [Tab. A 2](#)).

2.6. Generalized additive models

Based on the results of the correlation analyses, only the SPEI with different aggregation periods and tree age were included in the mortality modelling. In contrast to comparable studies ([Anders et al., 2025](#); [Knapp et al., 2024](#)), this study assumes a nonlinear relationship between the drought index and tree mortality probability. Therefore, generalized additive models (GAMs) following [Wood \(2017\)](#) were applied. Separate GAMs were fitted for each tree species and each SPEI aggregation period, using a binomial error distribution and a logit link function. The dependent variable was binary mortality (0 = alive, 1 = mortality event). The model predicts the probability of mortality for each annual observation $P(Y_i = 1)$, with β_0 representing the intercept, $s(\text{SPEI}_i)$ a smooth nonlinear function of the SPEI for observation i and $s(\text{tree age}_i)$ a smooth nonlinear function of tree age for observation i . To account for unexplained heterogeneity between WZE plots, a random effect for the plot ID u_{plot} was also included ([Eq. 4](#)).

$$\text{logit}(P(Y_i = 1)) = \beta_0 + s(\text{SPEI}_i) + s(\text{tree age}_i) + u_{\text{plot}} \quad (4)$$

In the following, the model predictions were averaged for each year and each SPEI aggregation period in order to enable a direct comparison

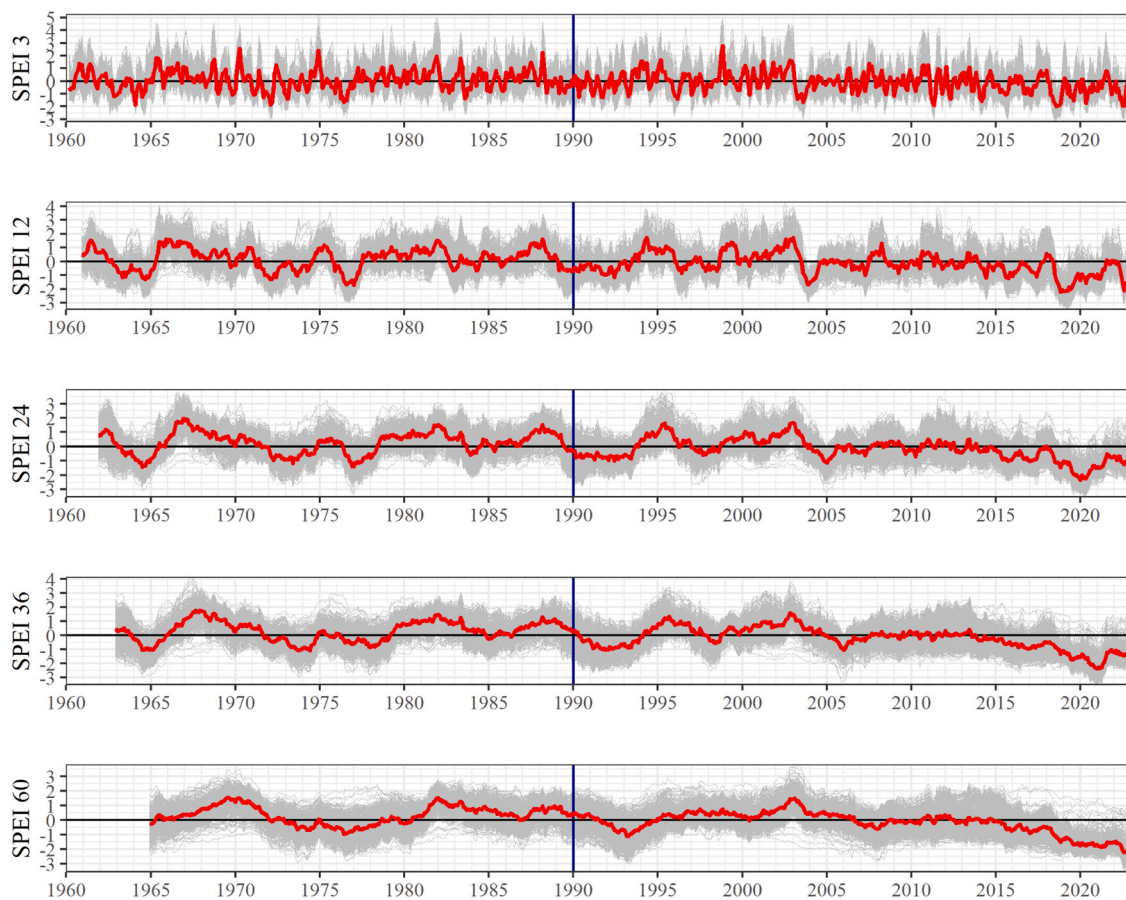


Fig. 3. Time series of the climatic drought index SPEI with different aggregation periods (3, 12, 24, 36, and 60 months) for the WZE plots considered (grey = individual plots, red = mean) from 1960 to 2022. The vertical blue line marks 1990, the start of the present WZE dataset, from which both WZE data and the corresponding mortality data are available.

between observed annual mortality and predicted mortality probability. To evaluate the model performance, the Akaike Information Criterion (AIC) according to Akaike (1974) was calculated to assess model fit while accounting for model complexity. Additionally, the Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) to evaluate classification performance (Hanley and McNeil, 1982), and McFadden's pseudo R^2 (McFadden, 1972) was calculated as an additional goodness-of-fit measure. The models were parameterized using the *gam* function from the *mgcv* R-package (Wood, 2017). To assess the accuracy of mortality predictions at the aggregated level, the estimated annual mortality rates were compared with the observed mean annual mortality rates. For this graphical evaluation and to detect systematic deviations, a linear model was fitted.

3. Results

3.1. Observed tree mortality

All four species showed increased mortality rates during and after the extreme drought years 2018–2020. However, the species differed in terms of temporal (Fig. 4a) and spatial patterns (Fig. 4b) of mortality. Spruce exhibited by far the highest mortality, reaching 10% in 2020 (Fig. 4a) and up to 65 mortality events per plot over 32 years, particularly in the German low mountain ranges: Harz, Sauerland, and southern Thuringia (Fig. 4b). For the other tree species, annual mortality rates remained low between 0% and 1% (Fig. 4a), and absolute mortality was also much lower than for spruce, with maximum values of 15 mortality events per plot for pine, 10 for beech, and 12 for oak (Fig. 4b). The spatial distribution of mortality events per plot in the period from 1990

to 2022 revealed that the four tree species have different distribution patterns (Fig. 4b). Spruce and pine showed pronounced spatial concentrations of mortality, whereas beech and oak did not exhibit clear spatial clustering. Accordingly, species-specific differences in mortality levels and regional concentrations of occurrence can be identified across the various climatic regions of Germany.

3.2. Descriptive analysis of tree mortality-related variables

The results of the correlation analyses revealed species-specific differences in the effects of the considered variables on tree mortality (Fig. 5). Overall, correlation coefficients were relatively low across all species. For spruce, beech, and pine, the CWB anomalies and SPEI aggregations in particular showed the strongest and most similar influence on mortality. Since these were relative deviations from the long-term average (1991–2020), a negative value of the CWB-anomalies or SPEI indicated conditions are drier than normal, which were associated with higher mortality. In contrast, absolute CWB aggregations as well as their rolling mean and minimum values had only minor effects on mortality, particularly for beech. In general, the strength of the correlations generally increased with longer aggregation periods. This was especially evident for spruce, beech, and pine, where the SPEI over 60 months (SPEI₆₀) showed the strongest association with mortality, followed by the CWB₆₀ anomaly. The 3-month SPEI (SPEI₃) was only significantly associated with mortality in spruce and pine, whereas for the other tree species, longer aggregation periods were more relevant. A similar pattern to the CWB was observed for the SWB. SWB anomalies were more strongly related to mortality in spruce, beech, and pine than absolute SWB values. In contrast, oak exhibited a distinctly different

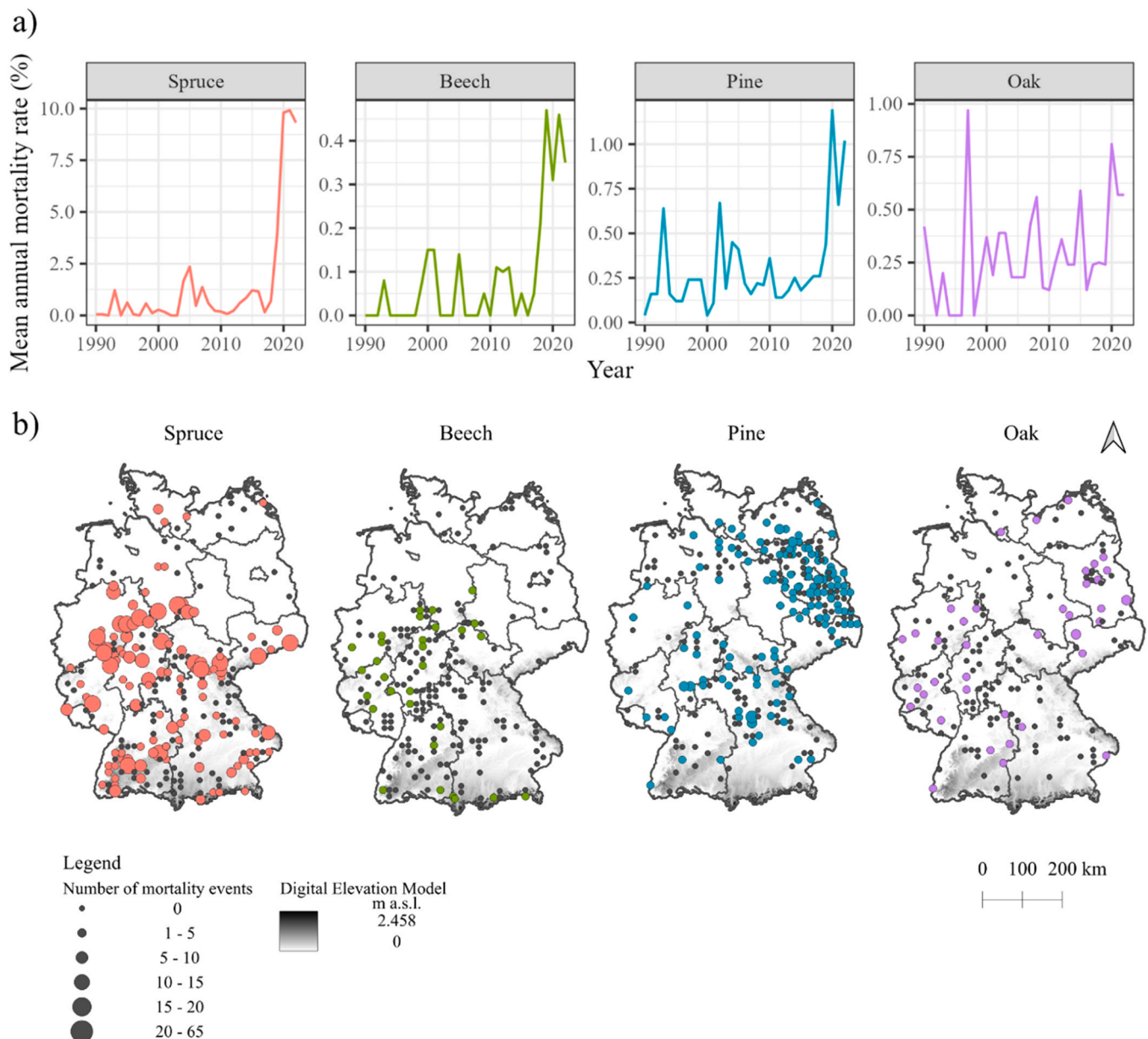


Fig. 4. a) Observed annual mortality rate of the four main tree species in the period from 1990 to 2022. b) Spatial distribution of the absolute number of mortality events per WZE plot for the four main tree species (spruce, beech, pine, oak) in Germany in the period 1990–2022. The size of the dots corresponds to the number of mortality events per plot.

response pattern. Oak mortality was most strongly associated with absolute SWB, as well as with moving averages and minimum values of the CWB and temperature-related variables, whereas standardized CWB anomalies and SPEI showed only weak correlations. Tree age is particularly correlated with mortality in spruce. Temperature-related variables generally indicated increasing mortality with rising temperatures across all species, with the exception of spruce, for which this relationship was less consistent (Fig. 5).

3.3. Species-specific model results and performance for SPEI

Based on the correlation analysis, the SPEI was identified as the strongest predictor and was therefore used in the subsequent modelling. The modelling results of tree mortality dependence on different SPEI aggregation periods showed clear species-specific relationships between intensity and duration of the drought and tree mortality (Fig. 6). Among the species, spruce consistently exhibited the highest predicted

mortality rate. The maximum mortality rate of spruce was associated with $SPEI_{60}$ and reached values of 6%. In contrast, predicted mortality rates of the other species did not exceed 1% across any aggregation period, with pine showing the strongest response to drought. Overall, beech and oak exhibited only minor changes in their responses to varying aggregation periods. For the 60 months aggregation period, the model indicated a slight increase in oak mortality under extremely wet conditions (Fig. 6). In total, SPEI-based predicted mortality rates closely reflected the observed mortality rates and tree mortality tended to be stronger correlated with longer SPEI aggregation periods.

The evaluation of the GAMs for the different SPEI aggregation periods showed distinct differences in model performance between tree species and aggregation periods. According to the AUC statistics, all models exhibited high statistical power ($AUC > 0.8$) across all species and SPEI aggregations, indicating a good ability to distinguish between surviving trees and mortality events under dry and non-dry conditions. Furthermore, the AIC-based evaluation indicated that models using the

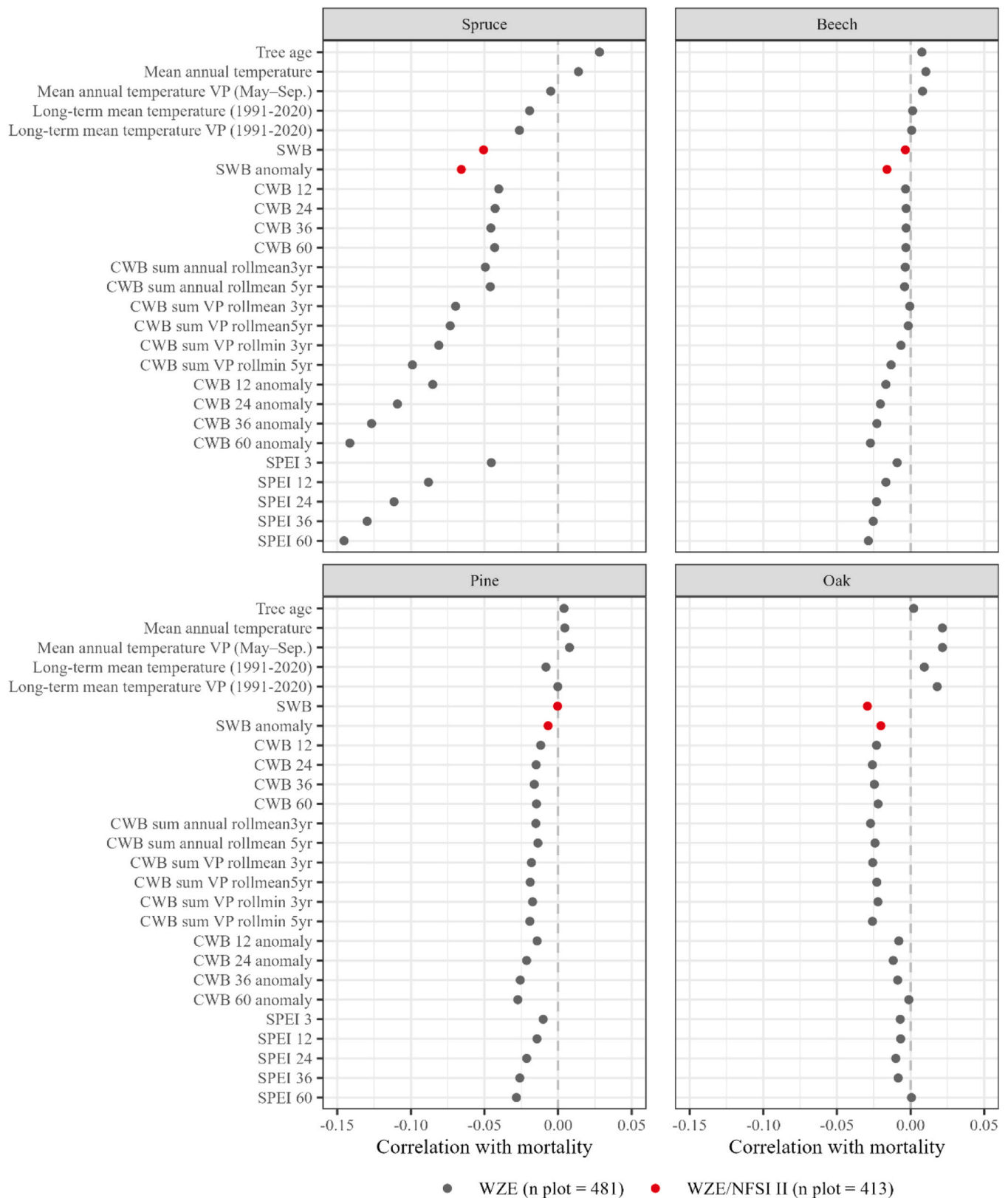


Fig. 5. Correlation coefficients between selected climate variables, drought indices, aridity indices, tree age and binomial mortality (0 = alive, 1 = mortality event) based on point-biserial correlations, separately for each tree species. The climate variables are derived for the complete WZE dataset (grey dots), while the SWB is only available for a subset where WZE and NFSI II grids overlap (red dots). Abbreviations of the indicators are explained in the text. Negative correlation values indicate that decreasing values of the variables or indices are associated with increasing mortality.

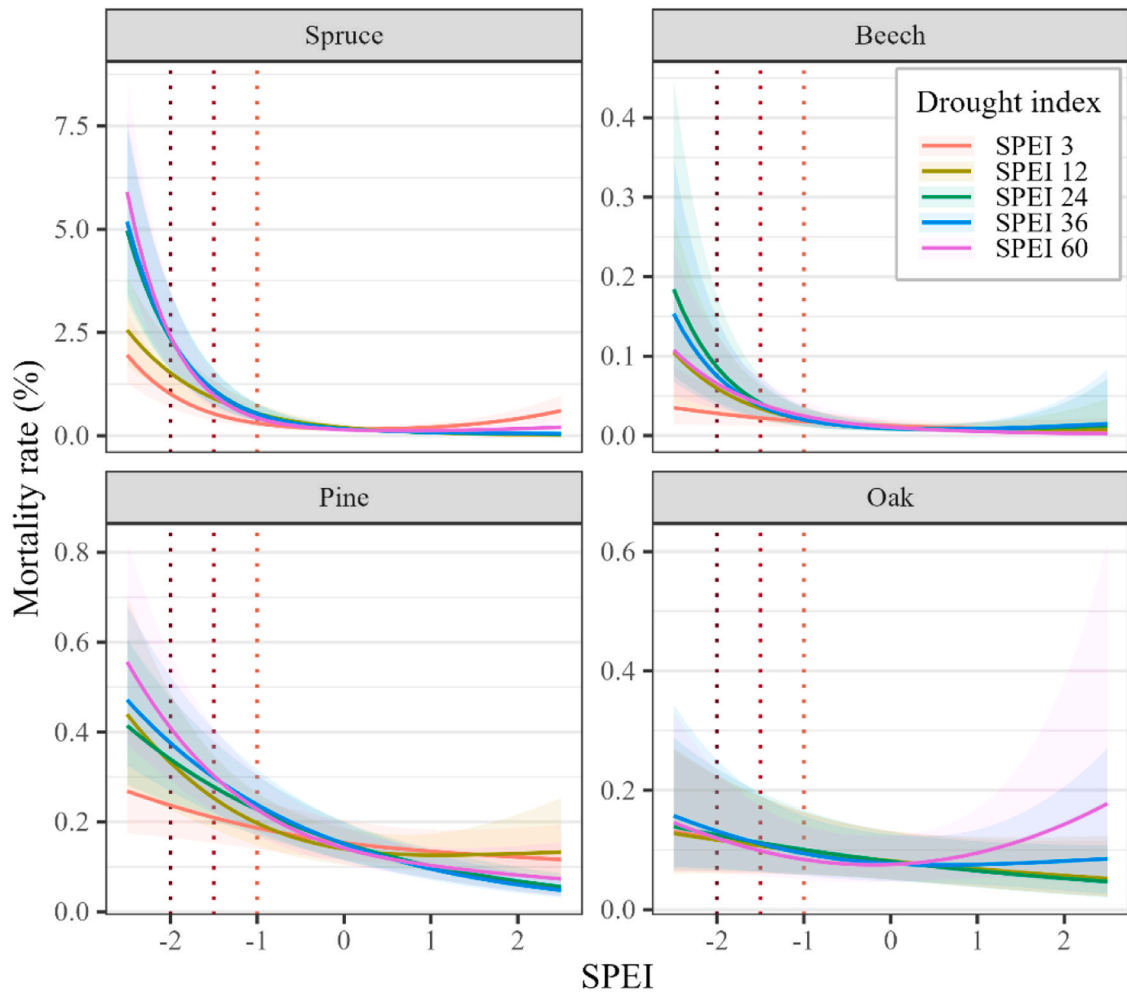


Fig. 6. Predicted mortality rates of the four main tree species in Germany based on the German Crown Condition Survey (1990–2020), modelled with GAM and arranged by SPEI aggregations periods (3, 12, 24, 36 and 60 months), including 95% confidence intervals. Vertical lines mark the thresholds for moderate to extreme drought (see Table 2).

60-month SPEI (SPEI₆₀) provided the best balance between model fit and complexity, resulting in the highest overall model performance for spruce, beech, and pine. In contrast, for oak, none of the tested models showed a clearly superior goodness of fit (Table 3).

The results for Norway spruce mortality showed that the predicted mortality rates closely follow the observed annual rates (Fig. 7a). However, differences were observed between SPEI aggregation periods. The strongest correspondence between predicted and observed mortality rate was found for the SPEI₆₀. This was further confirmed by the model evaluation: the AIC value was lowest for SPEI₆₀, while the AUC reached its highest value at 0.914 (Table 3). The linear comparison also highlighted that the model using SPEI₆₀ came closest to the observed mortality rate (Fig. 7b).

In contrast to spruce, the mortality rate of European Beech was only partially captured by the SPEI. Consequently, substantial deviations existed between the predicted mortality probabilities and the observed mortality rates, even though the SPEI partly reflected the general trend in mortality over the years. This was particularly in the predicted increase in mortality between 2018 and 2020 (Fig. 8a). The response curves of SPEI₃₆ and SPEI₆₀ showed a similar linear relationship, comparable to the observed mortality rates (Fig. 8b). Overall, beech exhibited lower sensitivity to drought, which was reflected in a weaker response to the drought index SPEI. Due to the general low mortality rate, the SPEI only explained the variability in beech mortality to a limited extent. Nevertheless, the model based on the SPEI₆₀ achieved the

Table 3

Model evaluation of the GAMs for the different SPEI aggregation periods, separate by tree species. The Akaike Information Criterion (AIC), McFadden's Pseudo-R², and the Area Under the Curve (AUC) are shown. The best model values for each tree species and indicator are highlighted in bold.

Species	Aggregation period	AIC	McFadden's R ²	AUC
Spruce	SPEI ₃	9410	0.229	0.878
	SPEI ₁₂	9155	0.251	0.890
	SPEI ₂₄	8804	0.280	0.900
	SPEI ₃₆	8396	0.315	0.911
	SPEI₆₀	7946	0.354	0.916
Beech	SPEI ₃	777	0.189	0.937
	SPEI ₁₂	766	0.206	0.932
	SPEI ₂₄	748	0.227	0.936
	SPEI ₃₆	743	0.233	0.938
	SPEI₆₀	743	0.235	0.941
Pine	SPEI ₃	3516	0.111	0.837
	SPEI ₁₂	3501	0.115	0.837
	SPEI ₂₄	3482	0.119	0.840
	SPEI ₃₆	3462	0.125	0.840
	SPEI₆₀	3455	0.128	0.834
Oak	SPEI ₃	890	0.095	0.856
	SPEI ₁₂	890	0.095	0.851
	SPEI ₂₄	892	0.096	0.848
	SPEI ₃₆	889	0.097	0.839
	SPEI₆₀	889	0.094	0.848

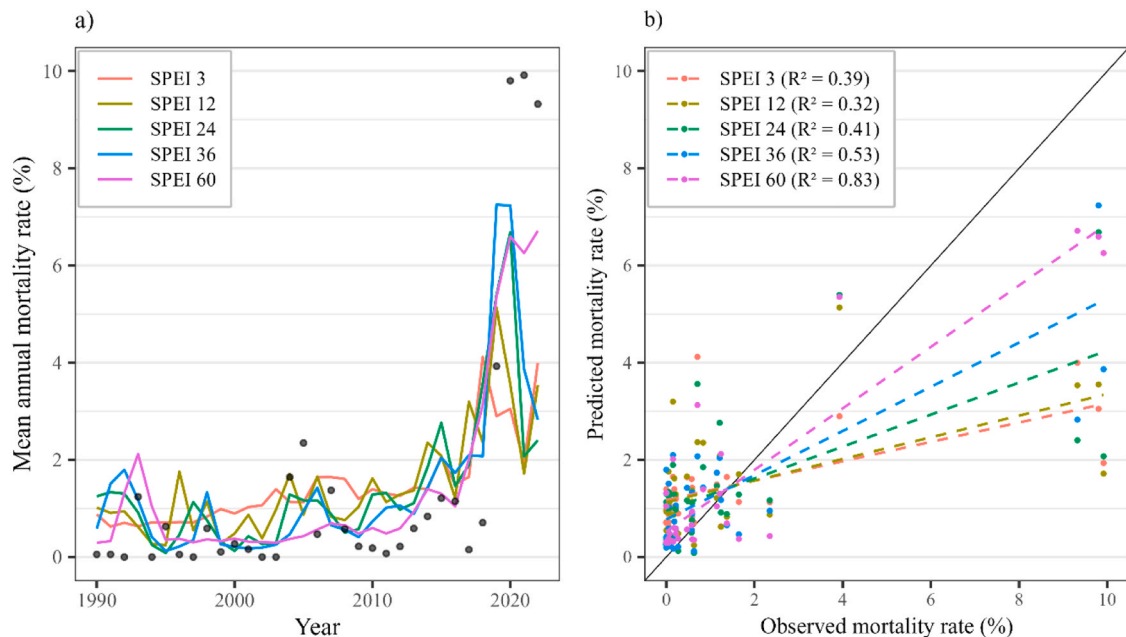


Fig. 7. a) Annual mean drought-related mortality rate of **Norway spruce** based on German Crown Condition Survey (WZE, black dots) compared to the predicted annual mean mortality rate for different SPEI aggregation periods (coloured lines) for the period from 1990 to 2022. b) Comparison between observed (black line) and predicted annual mortality rates (coloured lines). R^2 shows the correspondence between the observed and predicted drought-related mortality rates.

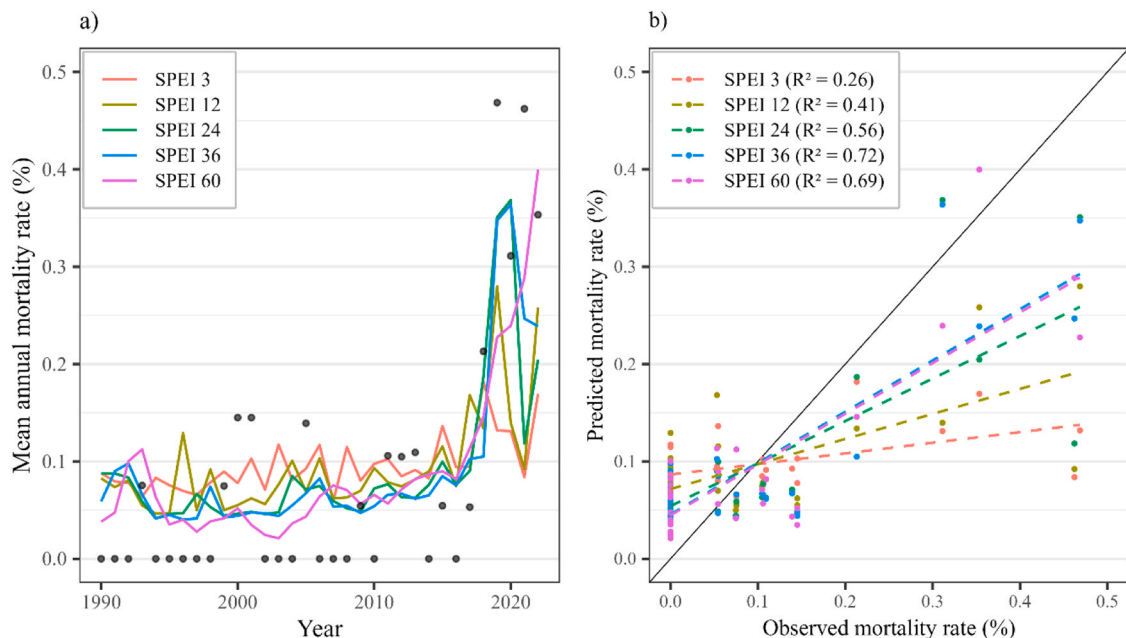


Fig. 8. a) Annual mean drought-related mortality rate of **European beech** based on German Crown Condition Survey (WZE, black dots) compared to the predicted annual mean mortality rate for different SPEI aggregation periods (coloured lines) for the period from 1990 to 2022. b) Comparison between observed (black line) and predicted annual mortality rates (coloured lines). R^2 shows the correspondence between the observed and predicted drought-related mortality rates.

highest model performance ($AUC = 0.942$), surpassing the models with shorter aggregation periods, similar to spruce (Table 3).

Scots pine showed a clear discrepancy between the observed and predicted mortality rates (Fig. 9). However, the increase in mortality between 2018 and 2020 was relatively well captured by the predicted mortality rate. Similar to beech, the observed mortality rate was in general low, meaning that individual outliers could have a disproportionate impact on the results. Nevertheless, the SPEI was able to adequately capture the general temporal trends of mortality rates over the years. The model based on the SPEI₆₀ provided the best fit, with the

lowest AIC value and the highest agreement between observed and predicted mortality (Table 3).

In contrast to the other tree species, no clear pattern could be identified between the SPEI and the observed mortality for oak. Distinct deviations existed between the predicted and observed mortality rates, which was also evident in the linear comparison (Fig. 10). The model based on SPEI₆₀ had the lowest AIC value, the SPEI₁₂ achieved the highest AUC value (0.844, Table 3). According, no model showed a clearly superior goodness of fit. Overall, the models failed to adequately reproduce the observed mortality dynamics of oak.

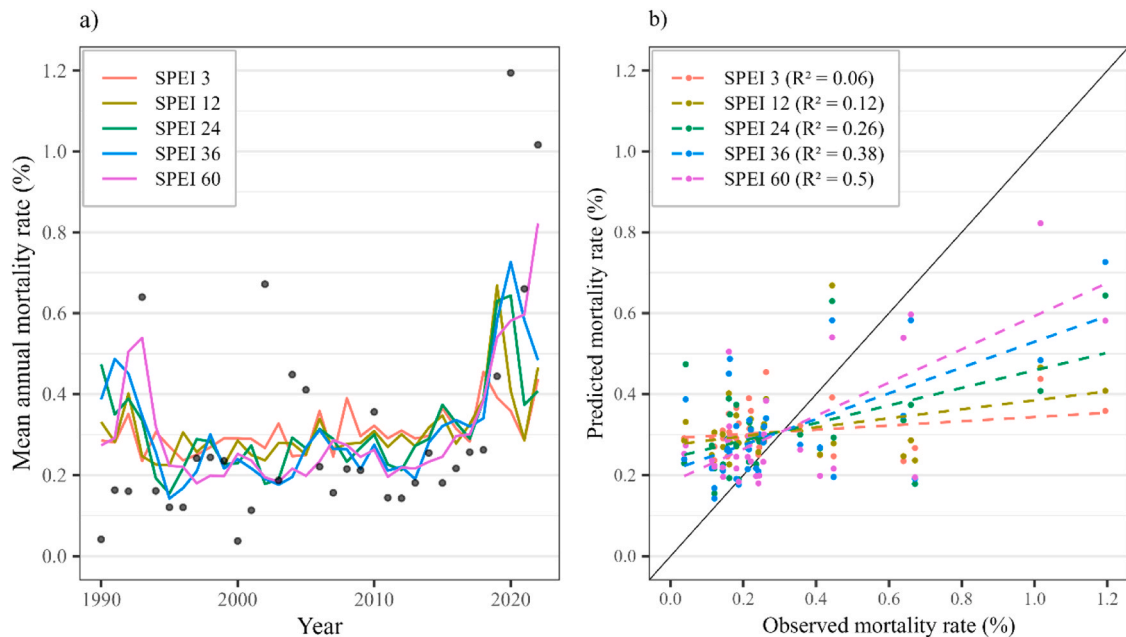


Fig. 9. a) Annual mean drought-related mortality rate of **Scots Pine** based on German Crown Condition Survey (WZE, black dots) compared to the predicted annual mean mortality rate for different SPEI aggregation periods (coloured lines) for the period from 1990 to 2022. b) Comparison between observed (black line) and predicted annual mortality rates (coloured lines). R^2 shows the correspondence between the observed and predicted drought-related mortality rates.

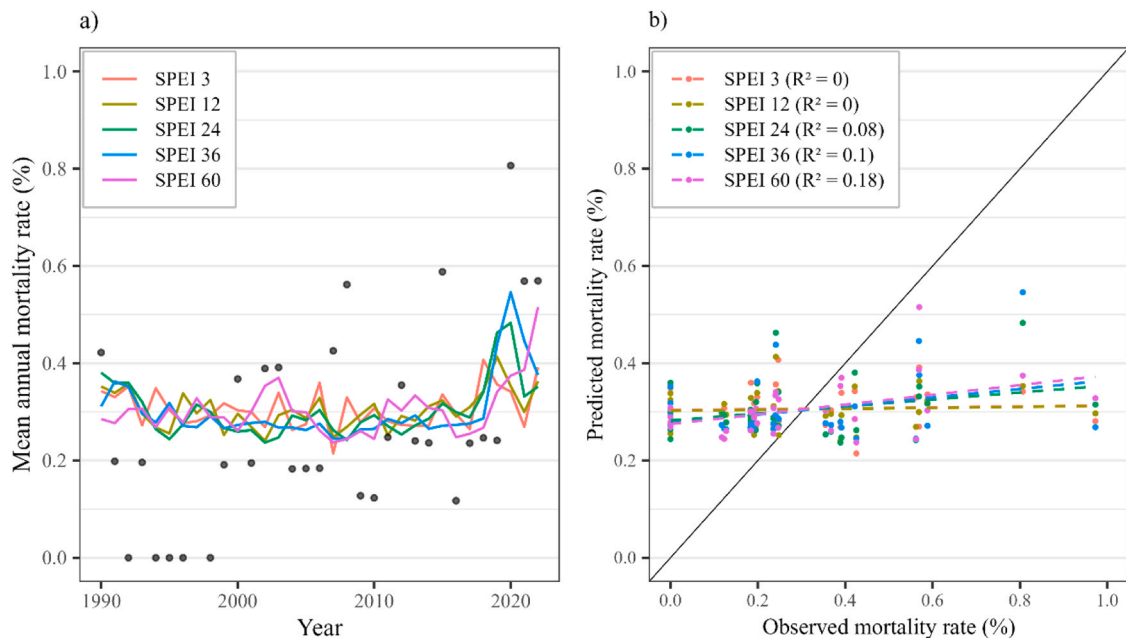


Fig. 10. a) Annual mean drought-related mortality rate of **Oak** (*Quercus robur* and *Quercus petraea*) based on German Crown Condition Survey (WZE, black dots) compared to the predicted annual mean mortality rate for different SPEI aggregation periods (coloured lines) for the period from 1990 to 2022. b) Comparison between observed (black line) and predicted annual mortality rates (coloured lines). R^2 shows the correspondence between the observed and predicted drought-related mortality rates.

4. Discussion

4.1. Comparison of absolute aridity vs. standardized drought indices

Regarding the first hypothesis, the results suggest that aridity and standardized drought indices differ in their ability to explain mortality. The findings indicate that tree mortality of Norway spruce, European beech, and Scots pine is primarily driven by relative deviations from long-term climatic means (1991–2020) rather than by aridity indices.

Consequently, absolute aridity and standardized drought indices differ in their predictive power for mortality. Aridity indices such as the CWB can be affected by spatial variability (e.g., lowlands vs. highlands) that may overlay temporal variability. This is particularly evident for Norway spruce, whose mortality is higher at high altitudes, as the species mainly occurs in elevated and generally humid regions with higher CWB values. Higher spruce abundance typically corresponds to extensive and homogeneous stands, which increases both the risk and potential rate of bark beetle spread (Fig. A 5). The effect is particularly strong during

extreme drought periods, such as the 2018–2020 event, when climatic conditions surpassed thresholds that promote bark beetle mass reproduction across large areas. Temporally, spruce mortality increases in years with low CWB values. Spatial effects partially offsetting the temporal effects weaken the influence of the absolute aridity indices. Due to the spatial concentration of mortality events in regions with a high occurrence of a given tree species, aridity indices such as CWB and SWB have a reduced capacity to explain mortality.

In contrast, standardization or the use of relative deviations from the long-term mean eliminates spatial variability, provide a much more effective explanation of tree mortality. This allows the indices to focus on temporary periods of drought, as each site is considered individually (Vicente-Serrano et al., 2010). Choat et al. (2012) also suggest that deviations from the long-term climatic norm are a key determinant of stand-specific drought risk for trees. Furthermore, trees on sites with high water availability are often adapted to these conditions, so slight deviations from the long-term mean can cause stress and increased mortality, even when the absolute water supply is sufficient. Aridity indices capture such relative changes only to a limited extent. The SPEI, by accounting for deviations from normal conditions, better reflects site-specific differences and adaptations.

Studies using drought indices in the context of drought prediction and characterization show that the SPEI most reliably captures drought events in European forests (Bachmair et al., 2018; Bhuyan et al., 2017; Blauhut et al., 2016). Both Bhuyan et al. (2017) and Blauhut et al. (2016) identified the SPEI as a suitable index for detecting drought events in temperate climate zones, with its highest predictive power observed for medium to long aggregation periods. Furthermore, numerous studies demonstrate that using the SPEI as a covariate in regressions models improves estimates of vitality loss and mortality probabilities under extreme conditions (Bhuyan et al., 2017; Greenwood et al., 2017; Pohl et al., 2023), which underlines the results of the present study. For instance, using the SPEI in mortality models achieve results for Norway spruce comparable to those reported by Knapp et al. (2024) and Anders et al. (2025), who used the CWB in combination with a wide range of additional predictors, including temperature and radiation anomalies, as well as soil physical and chemical parameters. Also regarding to the first hypothesis, the SPEI provides a good predictive power for spruce mortality, comparable to that of the aridity indices, whereas its model performance is considerably lower for the other tree species. At the same time, criticisms of the exclusive use of the SPEI have been raised. Some studies indicate that the SPEI does not always adequately reflect actual water availability, and standardized values calculated over different reference periods are only partially comparable (Schwarz et al., 2020; Zang et al., 2020). Consequently, it is increasingly recommended to complement standardized indices with soil hydrological parameters (Schwarz et al., 2020). The approach was tested using the AWC under the assumption that soils are saturated to field capacity at the beginning of the growing season, meaning that actual water availability is not represented. The AWC from the NFSI II does not appear to improve model performance, which may explain why the SWB (based on the AWC) shows only a weak correlation with mortality of spruce, beech and pine. Furthermore, for oak, it appears that either the absence of overlapping spatial and temporal variability or species-specific adaptations, such as deep root systems and a higher tolerance to deviations from the long-term average, may explain why absolute aridity indices has a stronger correlation with oak mortality. This suggests that the choice of suitable indices depends on the ecological characteristics of tree species (Chapter 4.3).

Nevertheless, current research emphasizes that the use of standardized drought indices is essential for a consistent characterization of drought events (Slette et al., 2019). In addition to reporting average and minimum values during the analysed drought period, it is recommended to clearly define the thresholds that separate normal conditions from drought and indicate drought severity (Slette et al., 2019). The consistent application of standardized indices is advised to enhance

comparability between studies and to improve the interpretability of ecological analyses. Besides the SPEI, there are other standardized indices, such as the Standardized Soil Moisture Index (SSMI) (Carrão et al., 2016; Xu et al., 2018), which explicitly considers soil moisture. In this context, further research is needed to determine whether such an index, similar to the SPEI or the SWB, exhibits a comparable effect on mortality as the aridity indices used so far.

4.2. Influence of different SPEI aggregations

Both the results of the correlation analyses and the modelling show that the mortality of spruce, beech and pine rise with increasing drought duration and longer SPEI aggregation periods. Regarding to second hypothesis, the results indicate that the SPEI₆₀ provides the best model performance for three of the four tree species. It can be suggested that cumulative drought periods of up to five years play a more important role in mortality processes of spruce, beech, and pine than short-term drought events.

The results indicate that long-term SPEI aggregations effectively capture delayed drought effects on tree mortality. Češljarić et al. (2025) also reported that prolonged droughts, often combined with high temperatures, have significantly increased tree mortality over the past decade, which supports our results. These results are consistent with previous studies reporting stronger correlations between prolonged drought events and reductions in radial growth and forest productivity (Bhuyan et al., 2017; Bose et al., 2020; Pohl et al., 2023). Furthermore, the comparable study by Knapp et al. (2024) come to a similar conclusion with rolling means of CWB over periods up to five years. Better performances of longer SPEI aggregation periods are usually explained by persisting and accumulating drought effects over consecutive years or by delayed biotic agent damage. However, most of the mortality events in our dataset occurred after the extreme drought years of 2018–2022, likely favouring the performance of SPEI₆₀, as it covers the whole extent of this period. In other words, the good performance of longer aggregation periods is mainly driven by a single drought event of five years. Additionally, the performance of shorter aggregation periods such as 3 and 12 months is stronger limited by the methodological observation delay of up to 12 months in an annual survey. Nevertheless, our results indicate that short-term drought conditions, represented by SPEI₃, have an effect on tree mortality in spruce and pine (Tab. A 2). This suggests that coniferous species may already be highly sensitive to short-term drought events occurring during the summer months. Similar findings were reported for *Abies cilicica*, where tree mortality events were strongly associated with seasonal water deficits and drought stress during the summer period (Vatandaşlar et al., 2023). Iterative droughts, such as in the years 2018–2020, can cause both acute and long-lasting damage that only becomes apparent in subsequent years. Often, drought-opportunistic biotic agents such as bark beetles in spruce (Netherer et al., 2015) and fungi in beech (Langer and Bußkamp, 2023) are mostly the reason of death, their impact further influenced by delayed reproduction and spread. Additional delayed consequences of drought are hydraulic failure (McDowell et al., 2008), carbon starvation due to reduced photosynthesis (Anderegg et al., 2015; Kannenberg et al., 2020), and decreased resistance to biotic stressors such as the bark beetles events (Netherer et al., 2015) or fungal infections (Langer and Bußkamp, 2023). These effects are particularly increased during consecutive drought years and lead to long-term declines in tree vitality. In recent years, legacy effects following droughts have been increasingly observed (Haberstroh et al., 2025; Pohl et al., 2023). Therefore, lag years after a drought event were also tested to account for these effects, but their influence was generally weaker than the regular SPEI aggregations (Fig. A 4). That supports our findings that aggregation periods are conceptually better suited to capture legacy effects, whereas lag years primarily reflect the natural delay of each response.

According to the second hypothesis, it can be concluded that the influence of iterative drought periods on mortality is captured more

effectively when using longer SPEI aggregation periods. The significance of SPEI₆₀ indicates that multi-year droughts play a particularly important role in tree mortality. Current climate scenarios suggest that the probability of such prolonged drought events will increase substantially in north-western Europe (van der Wiel et al., 2023). Consequently, foresters must expect a significant increase in the risk of mortality.

4.3. Species-specific differences

The loss of vitality leading to tree death is both species-specific and site-specific (Frei et al., 2022; Sterck et al., 2024; Zhang et al., 2017), which is also seen in our results. Regarding the third hypothesis, there are clear differences in the frequency of mortality events among species, as well in the predictive performance of SPEI-derived mortality probabilities.

4.3.1. Spruce

Norway spruce shows both the highest mortality rates during the study period and the strongest sensitivity to negative SPEI values. This suggests that reduced climatic water availability and droughts of extended duration are strongly linked to increased mortality rates, which is consistent with current research findings (Anders et al., 2025; Netherer et al., 2015; Obladen et al., 2021). The higher susceptibility of spruce can be explained by its physiological and ecological characteristics, as it typically prefers deep soils with sufficient water availability (Puhe, 2003). Due to its shallow root system (Czajkowski et al., 2009), spruce depends strongly on near-surface water and is likely unable to access deeper groundwater during long-lasting drought. Consequently, spruce occurs mainly in cooler and more humid regions of Germany with enough precipitation like higher elevations. In extreme regions, such as shallow mountains sites, water supply is often limited. As an isohydric species (Hesse et al., 2023), spruce responds to long-lasting drought conditions with increased physiological stress, as evapotranspiration rises while water uptake remains restricted due to shallow rooting (Wang et al., 2025). This combination of hydraulic failure and carbon deficits increases its susceptibility to secondary disturbance agents, particularly bark beetle infestations (Jakoby et al., 2015; Wermelinger, 2004). Furthermore, tree age has a significant effect on spruce mortality. Large areas of spruce in Germany are characterized by even-aged monocultures established on site with reparation clearing after the second world war, for example in regions such as Harz, Sauerland, and southern Thuringia. All of these stands are particularly prone to mortality due to rapid bark beetle spread in large-scale, evenly structured monocultures. Since they are all roughly 70–80 years old, tree age performs artificially well as a predictor for mortality. Nevertheless, tree age is a natural driver of mortality risks because tree vitality generally declines with age, while vulnerability to drought-induced hydraulic failure and pest infestation tends to increase (Overbeck and Schmidt, 2012; Thiele et al., 2017). As a result of these mechanisms, the extreme drought years of 2018–2020 and 2022 led to high mortality rates, which were further amplified by bark beetle events. McDowell et al. (2008) already determined that long-lasting droughts of moderate intensity can lead to significantly increased mortality in Norway spruce. Due to four extreme drought years between 2018 and 2022, the 5-year SPEI is best suited to capture these high mortality events, showing the strongest influence on mortality and achieve the highest model performance.

4.3.2. Beech

In contrast to spruce, European beech shows the lowest mortality rate and a lower effect of SPEI on mortality. As already described by Hülsmann et al. (2016), beech mortality is characterized by high variability, which can be explained in parts by site and climatic parameters. Nevertheless, long lasting drought periods with reduced water availability and high temperatures led to an increase in beech mortality (Frei et al., 2022; Leuschner, 2020; Rukh et al., 2023). Our results also show increased mortality rates of beech in the extreme drought years

2018–2020, which is consistent with the findings of Knapp et al. (2024). Reduced water availability and drought conditions during these years led to initial vitality losses in European beech in 2018. This was manifested in increased crown defoliation, while branch dieback and mortality of individual trees were frequently associated with sunscald, bark necrosis, and bleeding lesions caused by sap flow. The structural stability and mechanical resistance of affected trees were markedly reduced (Langer and Bußkamp, 2023). Drought-induced physiological stress weakened tree vitality and likely increased susceptibility to fungal infections, which are considered a major contributing factor to beech mortality and to the increased mortality observed during 2018–2022. Nevertheless, Meyer et al. (2022) assess at the same time that this increase in beech mortality in Germany during the drought years 2018–2020 is not significant. Although beech clearly shows vitality losses in terms of defoliation (BMELH, 2025; Frei et al., 2022), comparatively few mortality events are documented. Deciduous tree species generally die successively from the crown to the bottom, but can recover through regrowth from stem or coppice and thus still be considered alive despite the loss of vitality. Furthermore, Hülsmann et al. (2018a) determined that mortality models for beech based on diameter at breast high and annual relative basal area perform well without additional environmental parameters. This suggests that environmental stressors such as drought affect mortality indirectly through their influence on growth variables (Hülsmann et al., 2018a, 2018b). In combination with the generally low mortality, this may explain why the SPEI can only partially account for beech mortality and primarily captures general trends. At the same time, the model performance increases with longer SPEI aggregation periods, suggesting that long-lasting drought can lead to increased mortality rates despite temporary regenerative capacity.

4.3.3. Pine

Pine mortality showed an increasing trend during the drought years 2018–2022, which is consistent with previous findings reported by (Knapp et al., 2024). Both abiotic and biotic factors contributed to this development. The main abiotic driver is the increasing drought intensity and the associated drought stress, which has contributed to the decline in pine vitality in Germany since 2019, as reflected by rising crown defoliation levels (BMELH, 2025). Among the biotic stressors, mistletoe (*Viscum album* L.) represents an important factor contributing to the decline in pine vitality (Dobbertin and Rigling, 2006; Sangüesa-Barreda et al., 2012). According to the WZE survey, mistletoe infestation in pines has increased in recent years. Mistletoe infection can be regarded as a predisposing factor for tree mortality, as it promotes needle loss following drought events and further exacerbates drought-induced water stress (Dobbertin and Rigling, 2006). Persistent drought conditions have likely reduced photosynthetic activity in pines, thereby weakening their physiological resistance and increasing susceptibility to parasite infestation. The combination of drought stress and mistletoe infestation may contribute to pine mortality in the years 2018–2022. The model results for Scots Pine exhibited the lowest AUC values, and no substantial differences were observed between the indices and parameters. Nevertheless, the SPEI, particularly at longer aggregation periods showed the strongest influence on mortality for this species. Recent studies also demonstrate that the effects of drought on tree vitality can be quantified using the SPEI (Bose et al., 2020; Haberstroh et al., 2022). For example, a significant relationship between the SPEI and annual ring or diameter increment is shown for pines in Europe (Bose et al., 2020). Similar to our study, the results indicate that with increasing SPEI aggregation, the resilience of pine to drought and water scarcity decreases (Bose et al., 2020). Although this doesn't refer directly mortality events but to growth, which demonstrate that vitality losses due to water deficits can be captured using the SPEI. Therefore, Pine also responds more to relative deviations from the long-term mean than to absolute aridity conditions. Similar to Knapp et al. (2024), long-term aggregations are the most important predictor of pine mortality, which is comparable to

the results obtained for the SPEI in our study. A possible reason for the stronger effect of SPEI₆₀ is its ability to capture legacy effects through longer aggregation periods. Such legacy effects occur particularly in Scots pine and have been lately reported in recent studies (Haberstroh et al., 2025, 2022). Related to spruce, other parameters, such as mistletoe (*Viscum album* L.) infestation in pine (Dobbertin and Rigling, 2006; Sangüesa-Barreda et al., 2012), influence the mortality. These factors are not captured by SPEI, meaning that climatic indices alone cannot represent the driving mechanisms behind mortality.

4.3.4. Oak

Oak shows the lowest model performances and effects of SPEI on mortality, which is likely attributable to the high variability and generally low mortality rates. Overall, *Quercus* species are considered comparatively resistant to drought stress (Bonfils et al., 2016) and exhibit higher resilience in radial growth following drought events (Anderegg et al., 2015). Thus, oak shows only minor or almost no vitality losses as a consequence of drought (García-Barreda et al., 2023; Gazol et al., 2020; Wang et al., 2025). In Germany, however, increasingly vitality losses and defoliation have recently been documented (BMELH, 2025), which are not represented in the mortality rates. Also Gentilesca et al. (2017) have observed growth reductions in oak in Mediterranean regions of Europe as a result of increasing droughts, suggesting that rising temperatures may lead to an increased vulnerability in Germany in the future. In general, oak mortality often occurs in combination with additional stress factors, such as pathogens or insect infestations, which are benefited by drought conditions (Langer et al., 2025), and this may partly explain the slight increase in mortality observed during 2018–2022, indicating that oak mortality response to climatic stress is complex. The SPEI alone can only insufficiently explain oak mortality, whereas the SWB shows a considerably stronger effect. In a similar study demonstrated by Knapp et al. (2024), site parameters such as volumetric fraction of coarse fragments or clay content are important predictors of oak mortality. This may explain why the SWB, which includes site characteristics through AWC, exhibits a higher correlation with mortality. For instance, Skiadaresis et al. (2019) showed that *Quercus* species growing on sites with access to groundwater can buffer the negative effects of summer drought on growth. Such site-dependent buffering mechanisms could offer a possible explanation for why the SWB, as a combined climate-soil index, captures oak mortality most effectively. However, it should be noted that the correlation between the SWB and oak mortality remains very low, and overinterpretation should be avoided. At the same time, the results indicate that the use of SPEI is limited for modelling oak mortality. Our results did not reveal a clear mortality pattern compared to the other species. This does not necessarily imply that oak forests are more resilient to climate change in Germany. More comprehensive research is required to better understand the drivers of oak mortality under drought conditions. Due to species-specific reactions to drought and the resulting number of mortality events, the selection of tree-species-specific drought or aridity indices is particularly important for future studies.

4.4. Limitations

A general limitation of mortality analyses is the definition of mortality itself. In this study, a tree was classified as a mortality event if the defoliation reached 100% or additional evident of mortality was documented. However, in case of European beech, it is often observed that trees have a distinct crown defoliation (NBV > 80%) over several years in association with drought, without dying completely. Beech frequently recovers in the following years after an apparent complete leaf loss. This complicates the delineation and assessment of mortality in relation to drought, as vitality losses are recorded, but are not considered as mortality. Therefore, future studies should more consider severe crown damage and defoliation as a pre-stage of mortality.

The model predictions are subject to various uncertainties. Firstly,

the resolution of the 16 × 16 km grid of the WZE may be too low to adequately capture the effects of drought-prone site, such as south-facing slopes. Secondly, despite the large WZE dataset, tree mortality is a relatively rare event, resulting in low mortality rates. When interpreting the results, it must be considered that the sample size differs highly among the tree species. For example, the sample size of pine is almost four times larger than for oak. This can affect the comparability of results between species, as larger sample size led to more stable estimates, whereas smaller samples are stronger influenced by random variation. Moreover, with larger sample size, the likelihood of observed mortality also rises. It should be noted that the low absolute mortality rates mean that individual outliers can have a disproportionately influence on the results. This may explain the higher model performance observed for spruce, which is likely attributable to the large number of recorded mortality events.

Since tree mortality is a complex interplay of several biotic and abiotic factors, future modelling approaches should extend beyond the use of SPEI. While the SPEI adequately captures mortality probabilities for Norway spruce, it tends to underestimate the mortality rate of the other species in the drought years 2018–2020 and 2022. Therefore incorporating additional variables such as soil properties (Knapp et al., 2024), rooting depth (Czajkowski et al., 2009), and tree characteristics like size and age (Anders et al., 2025) could improve the mortality predictions for the other species. In addition to climatic variables, forest management practices may also influence tree mortality dynamics. For example, Brandl et al. (2020) showed that management-related factors can affect tree survival probability, and mixed-species stands are generally considered more resistant to disturbances and drought stress. However, detailed information on forest management strategies at the plot level was not available in this study. Therefore, it was not possible to quantitatively assess the effects of management on tree mortality. Future studies are encouraged to incorporate management-related variables to better understand their potential influence on tree mortality patterns. Especially for beech, pine, and oak, it is important to include additional variables or indices, as the SPEI alone captures the mortality of these species only to a limited extent.

5. Conclusion

Our study shows that mortality in three of the four most common tree species in Germany is primarily driven by relative deviations from long-term averages. Standardized drought indices, such as SPEI, capture the observed mortality events in temperate zone better than aridity indices like CWB and SWB. The SPEI exhibits strong potential for modelling mortality rates and serves as a robust indicator for predicting drought-related mortality across dominant tree species in Germany. The effect is particularly evident in spruce, which has the highest mortality rates over the last 30 years. In contrast, for oak, which show substantially lower mortality rates, the SPEI-based models fail to adequately explain mortality, indicating the need for additional predictors and further research. Nevertheless, the goodness of fit increases with longer aggregation periods up to five years across all species, underlining the importance of cumulative and persistent drought stress. Longer aggregation periods also better capture multi-year droughts, such as those from 2018 to 2020 and 2022, which led to increased vitality losses and even mortality events across all observed tree species. The significance of SPEI₆₀ further emphasizes that multi-year droughts play a particularly important role in tree mortality. Given the projected increase in multi-year drought events in Europe, foresters should anticipate a substantial rise in mortality risk. Moreover, decision support systems for forest management often rely on absolute drought indices. Our results indicate that these systems would benefit from incorporating standardized, species-specific drought indices to more accurately predict drought-related tree mortality under future climate scenarios. Accordingly, other standardized indices, especially soil indices, should also be evaluated to determine whether they can explain tree mortality in a manner

comparable to SPEI. Overall, species-specific responses to drought and the resulting variation in mortality events highlight the importance of selecting tree-species-specific drought or aridity indices in future studies. This approach is essential for improving mortality predictions and facilitating climate-adapted tree species selection, which offers practical guidance for forest management.

CRediT authorship contribution statement

Sebastian Fuchs: Writing – review & editing, Conceptualization. **Angelika Olesch:** Writing – review & editing, Visualization, Data curation, Conceptualization. **Bernd Ahrends:** Writing – review & editing, Funding acquisition, Conceptualization. **Luca Smekal:** Writing – review & editing, Visualization, Methodology, Formal analysis. **Laura-Marie Schotte:** Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

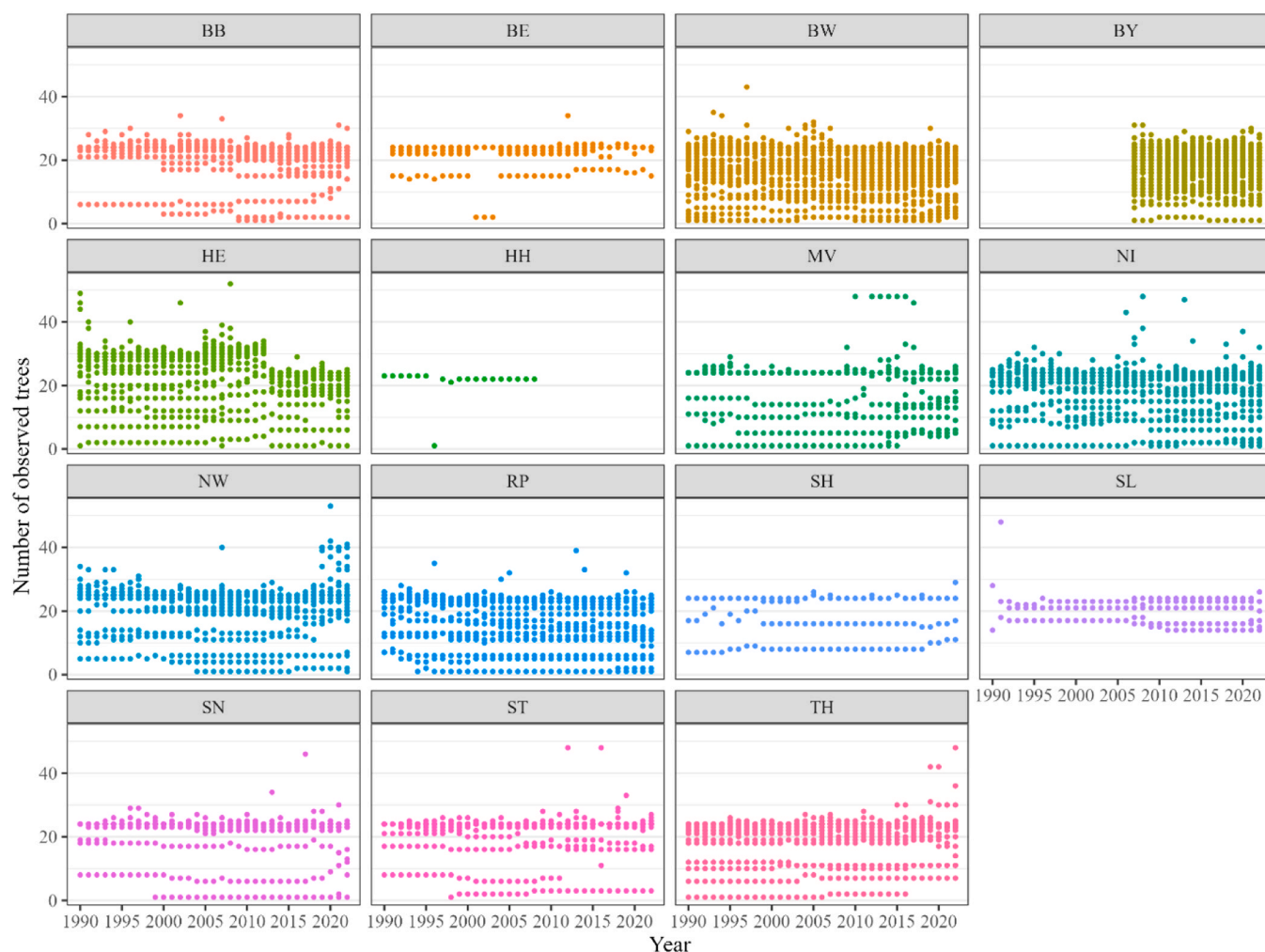


Fig. A 1. Number of observed trees per WZE-Plot, year and federal state in Germany. The reference number of trees per plot is 24. Some plots deviate from this value, with both lower and higher numbers of observed trees

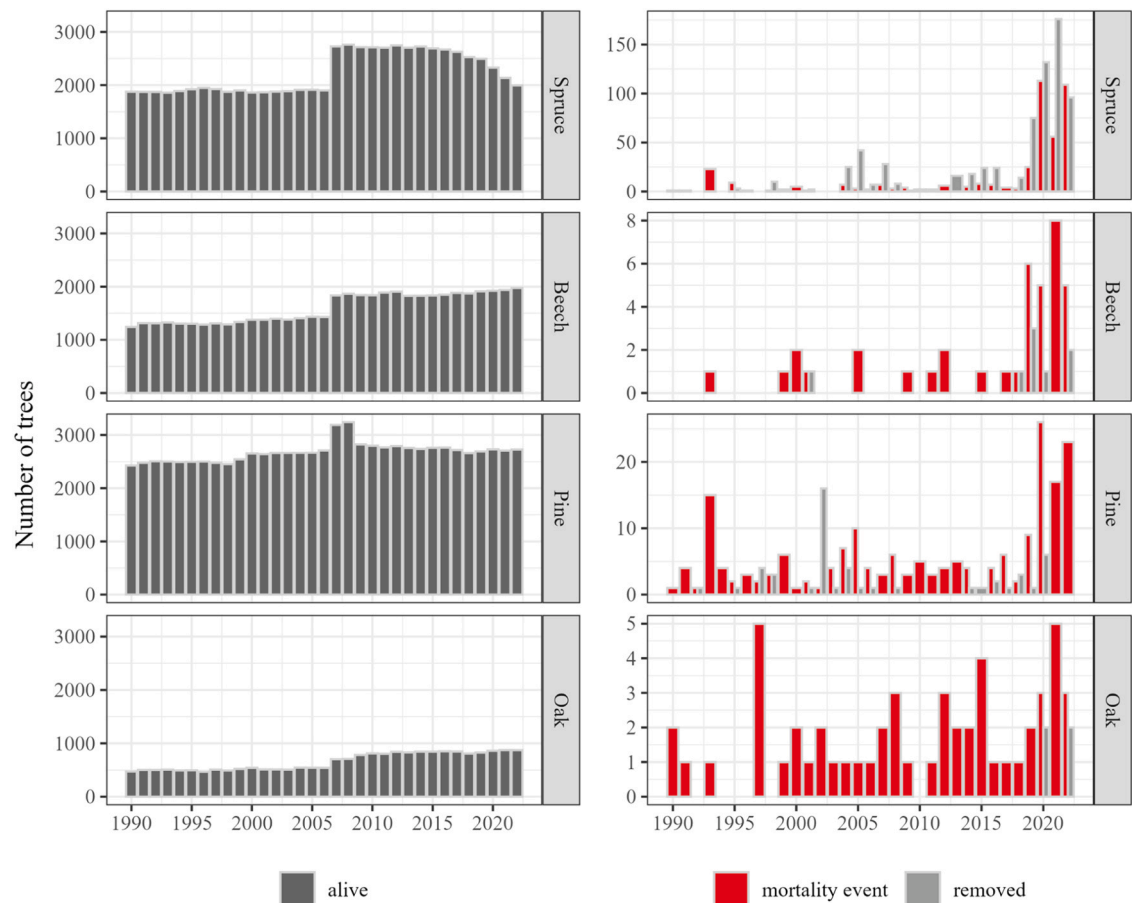


Fig. A 2. Left: Number of living trees per species across all 481 plots from 1990 to 2022. Right: Number of mortality events and removed trees (trees removed for economic reasons or due to windthrow) per species across all plots during the same period

Tab. A 1
Requirements for classifying a tree as “mortality event” at the plot and tree level according to status codes in the WZE

Code	Plot status
12	Removal due to biotic influence
Code	Tree status
12	Use/removal due to biotic influence
32	Dead, standing without fine brushwood due to biotic influence
33	Dead, standing without fine brushwood due to abiotic influence
34	Dead, standing without fine brushwood due to unknown cause
35	Dead, standing, reason not determined
42	Dead, lying without fine brushwood due to biotic influence
43	Dead, lying without fine brushwood due to abiotic influence
44	Dead, lying without fine brushwood due to unknown cause

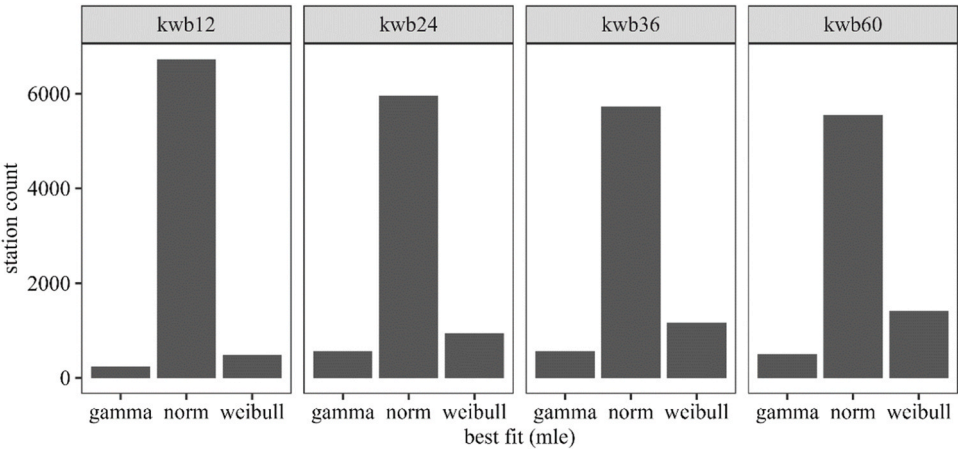


Fig. A 3. Representation of the best-fitting theoretical probability distribution (based on the maximum log-likelihood value) for modeling the aggregated climatic water balance (CWB) per month, plot, and aggregation period (12, 24, 36, 60 months). Shown is the frequency (number of plots) for each of the best-fitting distributions: normal, gamma, and weibull

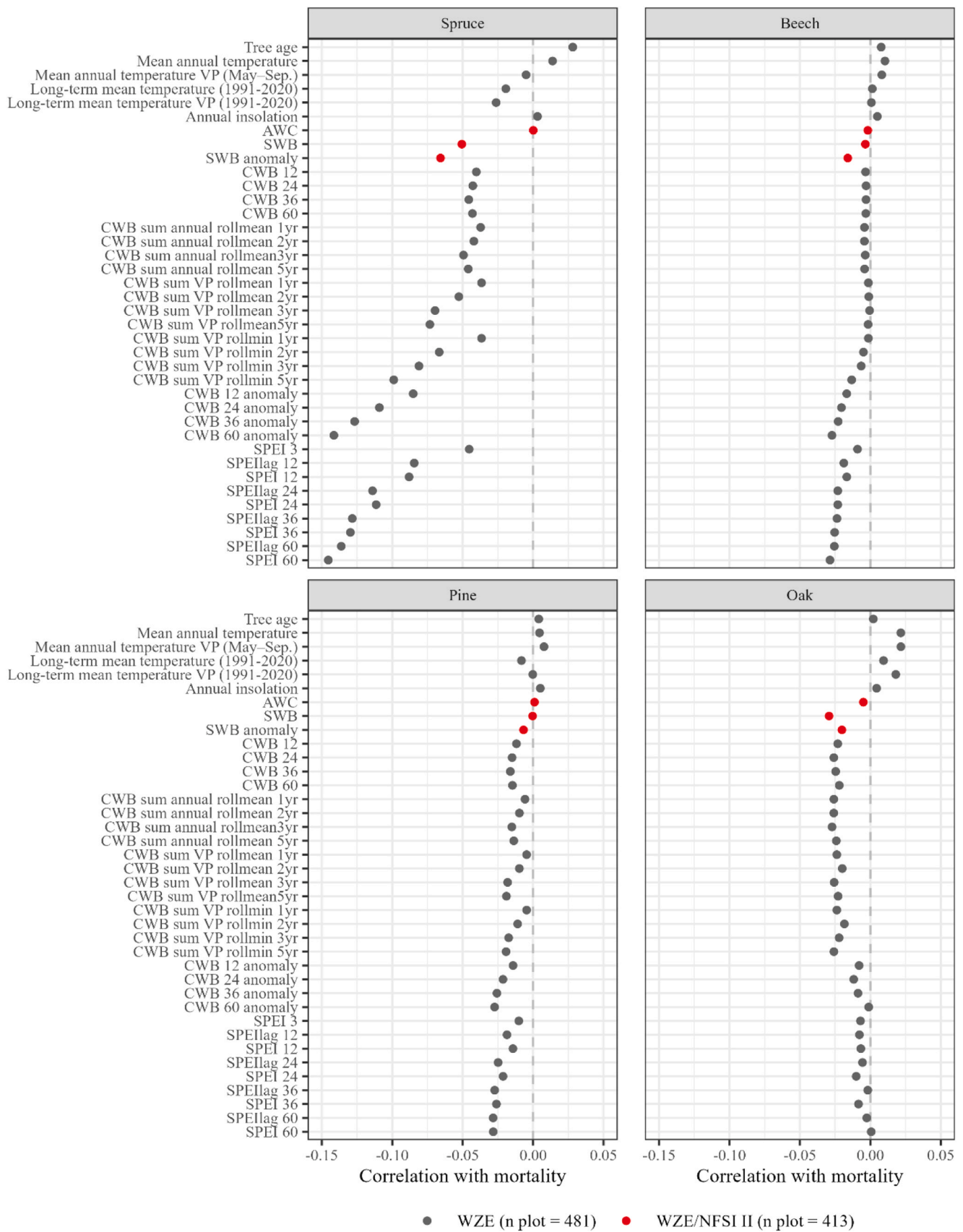


Fig. A 4. Descriptive representation of the effect sizes of all tested climate variables and indices on binary-coded mortality (0 = alive, 1 = mortality event) based on point-biserial correlations, separated by tree species. Climate variables are based on the full WZE dataset (grey points), while the SWB, SWB anomaly and AWC is based on a subset of the combined WZE and NFSI II data (red points)

Tab. A 2
P-values and significance levels of predictor variables influencing tree mortality for each species, based on generalized additive models (GAMs). Predictor variables include drought and aridity indices (SPEI₆₀, SPEI₃, CWB), tree characteristics (tree age, site index), and site/topographic factors (AWC, mean annual insolation, topographic position index TPI300, all derived from a DEM with 50 m resolution), and forest site water regime class (waterlogged and non-waterlogged)). Significance is indicated as ns ($p \geq 0.05$), * ($p < 0.05$), ** ($p < 0.01$), and *** ($p < 0.001$)

Variable	Spruce		Beech		Pine		Oak	
	p	Sig.	p	Sig.	p	Sig.	p	Sig.
SPEI ₆₀	0.000	***	0.000	***	0.000	***	0.115	ns
SPEI ₃	0.000	***	0.763	ns	0.000	***	0.350	ns
CWB	0.919	ns	0.008	**	0.086	ns	0.504	ns
Tree age	0.000	***	0.235	ns	0.443	ns	0.092	ns
AWC	0.831	ns	0.660	ns	0.639	ns	0.669	ns
Mean annual insolation	0.464	ns	0.354	ns	0.403	ns	0.840	ns
TPI300	0.113	ns	0.954	ns	0.638	ns	0.206	ns
Site index	0.204	ns	0.615	ns	0.020	*	0.574	ns
Site water regime class	0.073	ns	0.901	ns	0.652	ns	0.982	ns

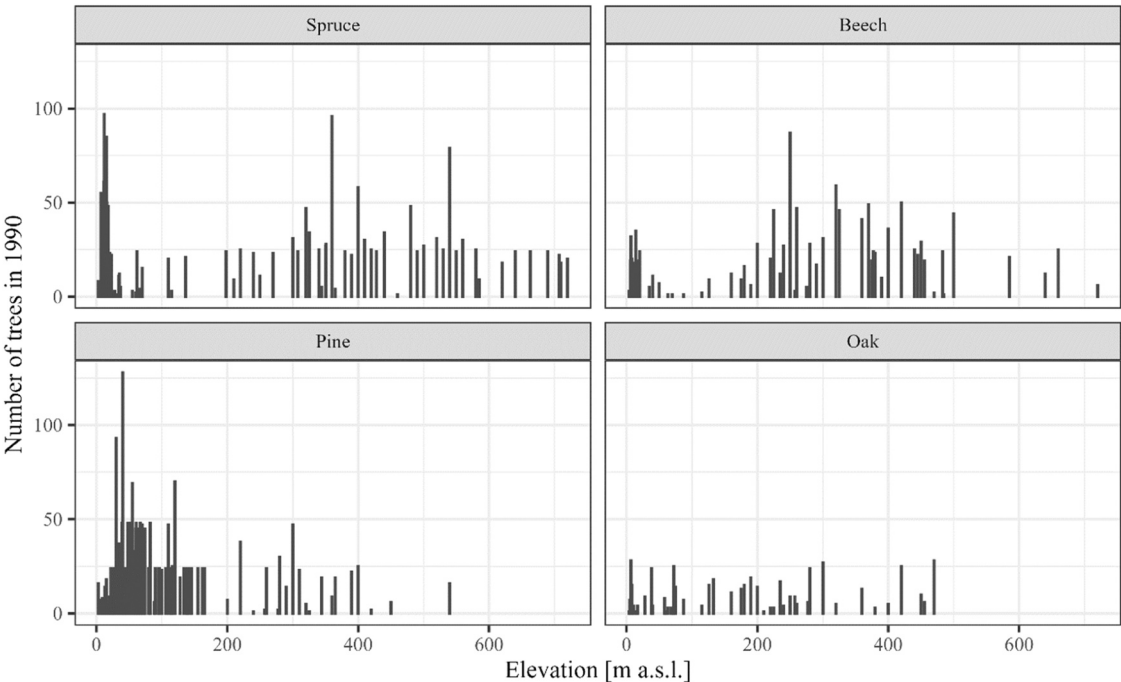


Fig. A 5. Number of trees at different terrain heights (m a.s.l.) in the WZE data set at the reference year of 1990 for all four species, illustrating the predominance of spruce stands in higher elevation regions of Germany compared to the other species

Data availability

Data will be made available on request.

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