Cent. Eur. For. J. 70 (2024) 263–274 DOI: 10.2478/forj-2024-0014

CENTRAL EUROPEAN Forestry Journal

ORIGINAL PAPER

Two unprecedented outbreaks of the European spruce bark beetle, *Ips typographus* L. (Col., Scolytinae) in Austria since 2015: Different causes and different impacts on forests

Till Hallas[1, 2], Gottfried Steyrer[1], Gregor Laaha[3], Gernot Hoch[1]*

[1]BFW – Austrian Research Centre for Forest, Department of Forest Protection, Seckendorff-Gudent-Weg 8, A-1131 Vienna, Austria

[2]BOKU University, Department of Forest- and Soil Sciences, Peter-Jordan-Straße 82, A-1190 Vienna, Austria

[3]BOKU University, Department of Landscape, Spatial and Infrastructure Sciences, Institute of Statistics, Peter-Jordan-Straße 82, A-1190 Vienna, Austria

Abstract

Austria has been facing two outbreaks of the European spruce bark beetle, *Ips typographus* L., in the last ten years. In this study, we compile data of damage caused by *I. typographus* L. as well as storm and snow breakage from 2002 to 2022 in two regions affected by these bark beetle outbreaks based on the Documentation of Forest Damaging Factors in Austria and analyze them in context of climatic factors. The first outbreak started in 2015 and affected Norway spruce forests at low elevation (< 600 m) in the north of Austria. Annual damage peaked in 2018 at 3.3 million m^3 (representing 2.6% of total growing stock in the area). The second outbreak started in 2021 and affected mountainous spruce forests in the south of Austria. In this case extensive damage by storm in 2018 and snow breakage in the two following winters preceded the bark beetle outbreak. Annual damage by *I. typographus* L. reached 1.7 million m^3 (2.4% of growing stock) in 2022. Most forests are located on steep mountain slopes and have important protective function against natural hazards. High temperatures allowed completion of two generations up to 1,400 m elevation. Linear regression models showed that damage by *I. typographus* L. was significantly affected by climatic water balance. This effect was stronger in the north than in the south. We discuss the different patterns of the outbreaks and challenges for bark beetle management in the context of climate change.

Key words: *Ips typographus* L.; bark beetles; forest damage; drought; climate change; forest management

Editor: Jaroslav Holuša

1. Introduction

Outbreaks of the European spruce bark beetle, *Ips typographus* L. (Col., Scolytinae), have received much attention in recent years because of significant impacts on ecosystems and ecosystem services, economy, and society (Hlásny et al. 2021a). In recent years, parts of Central Europe were particularly affected. Massive mortality of Norway spruce (*Picea abies* [L.] Karst.) was reported from Czech Republic, peaking in 2019, when volume of salvaged spruce reached approximately 23 million m^3 (i.e. 3.2% of total growing stock) (Hlásny et al. 2021b). Likewise, enormous damage was reported from German federal states, such as North Rhine-Westphalia (Niesar et al. 2023), Thuringia (Wenzel et al. 2023), or Saxony (Otto et al. 2023). Also, Austria has seen years of unprecedented damage by *I. typographus* L. starting in 2015 and peaking in 2018 at 4.7 million m^3 annual damage (Steyrer et al. 2020). There is wide agreement that disturbances by bark beetles will increase with climate change due to faster development resulting in more generations per year as well as weakened defenses of host trees under increasing drought conditions (e.g., Raffa et al. 2008; Seidl et al. 2008; Jakoby et al. 2019; Hlásny et al. 2021b). These trends are supported by the extensive bark beetle induced damages in Austria with *I. typographus* L. accounting for more than 80% of the damage in the last decade (Hoch & Schopf 2019). The second most damaging species is *Pityogenes chalcographus* L., followed by pine bark beetle species. The year 2018 marked the unprecedented peak (5.2 million m^3), followed by 2019, 2022 and 2023. The top ten years of bark beetle damage do not rank any dates prior to 2004 in a time series since 1960 (Hoch & Steyrer 2020). What seems relatively low

---

**Corresponding author. Gernot Hoch, e-mail: gernot.hoch@bfw.gv.at, phone: +43 1 878 38 11 55*

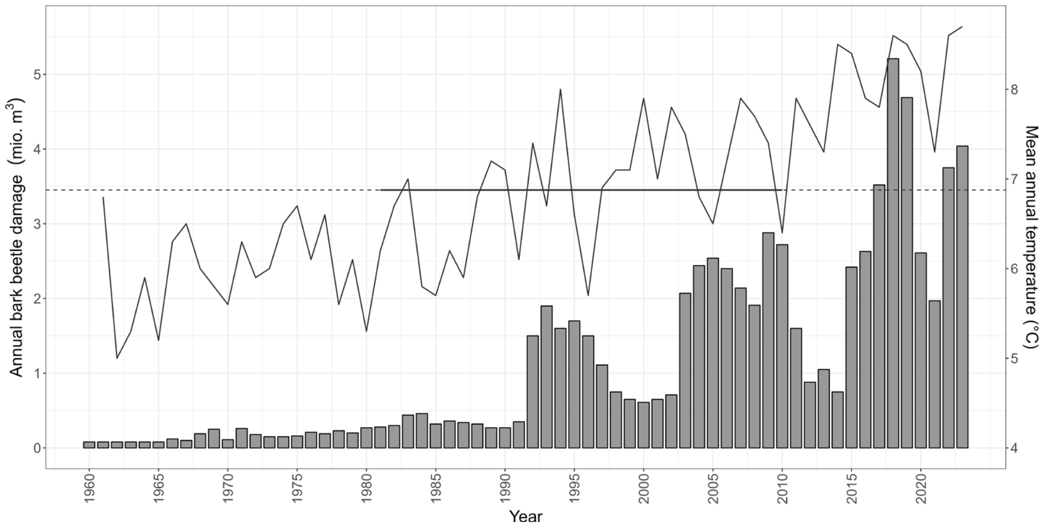

Fig. 1. Annual damage by bark beetles and annual mean temperature in Austria. The horizontal line indicates mean temperature for period 1981–2010. Damage data based on Documentation of Forest Damaging Factors, temperature from GeoSphere Austria (2023); figure modified and updated from Hoch & Steyrer (2020).

damage volumes now, like slightly less than 2 million m^3 in 2021, would have been unthinkably high before the 1990s (Fig. 1). Climate change has induced massive challenges of Norway spruce in lowland areas of Austria (Jandl 2020).

Ips typographus L. has the ability to switch from an endemic phase with low population density and attack of weakened trees only (typically windthrown or otherwise acutely damaged trees) to an epidemic phase with high population density and attack of healthy trees (Hlásny et al. 2019). Its main host is Norway spruce, *Picea abies* [L.] Karst. Older trees (typically 60 years or older) are preferred (Wermelinger 2004; Hlásny et al. 2021a). The transition from endemic to epidemic phase is triggered by abiotic events such as windthrow providing high quantities of easily accessible breeding material or prolonged drought and high temperatures (Marini et al. 2017; Hlásny et al. 2019). In Austria, the epidemic phase is typically preceded by windthrow or massive snow breakage events (Hoch & Schopf 2019). The dependency of *I. typographus* L. development on temperature is well understood and mathematical models calculating development rates or time based on weather data are available (Wermelinger & Seiffert 1998; Baier et al. 2007; Ogris et al. 2019). When accumulated effective temperature sums are sufficiently high, two or three generations can develop (Wermelinger 2004; Baier et al. 2007). There are, however, populations in northern Europe with obligate univoltine life cycle (Schebeck et al. 2022).

In this paper, we describe two recent outbreaks of *I. typographus* L. in Austria (Fig. 2). The first outbreak began in 2015, attacks decreased after 2019. It affected only the north of Austria, mostly spruce forests at lower elevation (typically below 600 m) along and north of the Danube and occurred in synchrony with the devastating outbreak in the adjacent Czech Republic. When this outbreak declined, another strong increase in bark beetle infestation was reported from the south of Austria (Steyrer et al. 2022). This new outbreak occurred in a region separated from the previous outbreak area by the Alpine ridge and by large areas of spruce dominated forest at that time not affected by *I. typographus* L. at epidemic level. The affected spruce forests in the south grow on mountain slopes at elevations from 700 m up to the upper limit of spruce dominated forests at approximately 1,800 m. We analyzed the two outbreaks in connection to climate as well as preceding damage of spruce due to storm and snow breakage. The challenges for forest management responding to the outbreaks as well as socio-economic consequences are discussed.

2. Material and methods

2.1. Damage data

Data on damage by *I. typographus* L., damage by storm and damage by snow breakage are based on the Documentation of Forest Damaging Factors, the comprehensive documentation of damage by pests, diseases and abiotic factors to forest trees in Austria organized by the Austrian Research Centre for Forests (BFW). Briefly, damage by listed factors is estimated by foresters of the forest authorities in their district. Damage by agents such as bark beetles, storm or snow is estimated in damaged volume per forest district, regardless of later salvage harvest or leaving dead wood on the site. Data are reported annually at the end of the year at forest district level to BFW, where they are compiled to the national reports. These comprehensive time series are available from 2002 to 2023.

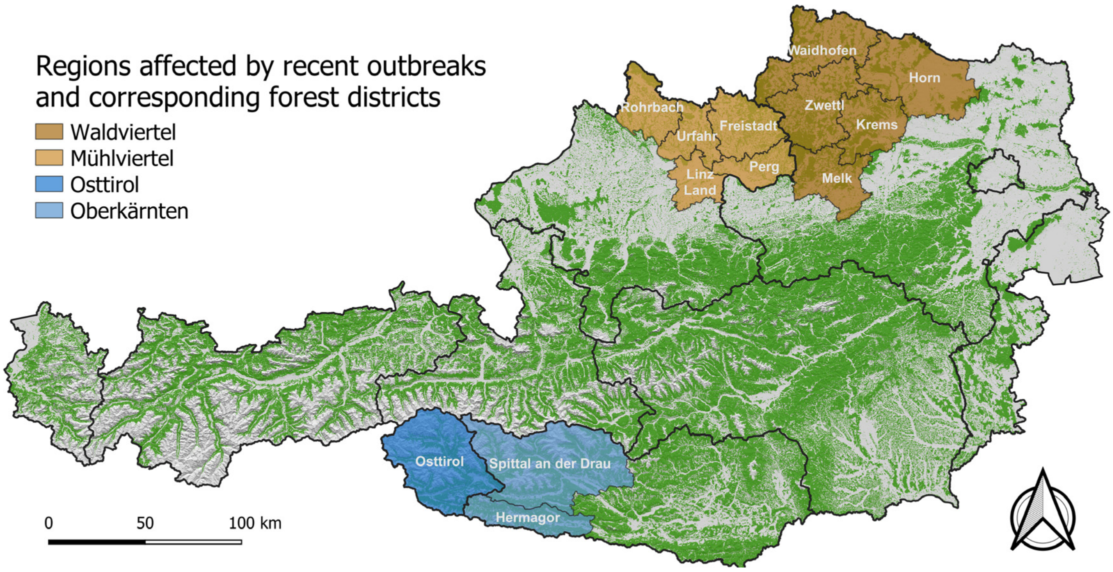

Fig. 2. Regions affected by recent outbreaks of *I. typographus* L. and analyzed in this paper. Waldviertel and Mühlviertel were affected by an outbreak starting in 2015 and peaking in 2018, Osttirol and Oberkärnten by an outbreak starting in 2021. Forest area in Austria is indicated by green color. The map is based on the official forest map provided by Department of Forest Inventory (BFW).

For this paper, we analyzed time series of forest districts from four regions in Austria (note that the included districts do not exactly match the geographic boundaries of the region), representing the areas affected by the recent outbreaks (Fig. 2). The regions (1) Waldviertel (forest districts Horn, Krems, Melk, Waidhofen an der Thaya, and Zwettl) and (2) Mühlviertel (forest districts Freistadt, Linz-Land, Perg, Rohrbach, and Urfahr-Umgebung) are located in the north of Austria (northern cluster) and were most severely affected by the outbreak from 2015–2021. The regions (3) Osttirol (forest district Osttirol) and (4) Oberkärnten (forest districts Spittal an der Drau and Hermagor) are located in the south of Austria (southern cluster) and have been affected by the still ongoing outbreak starting in 2021.

The official forest map of the Department of Forest Inventory of the Austrian Research Centre for Forests with a spatial resolution of 1 m (Bauerhansl 2020) was utilized to calculate the forest areas of the four regions of interest and each included forest district by counting all contained raster cells. We obtained the following forest areas for the regions: Waldviertel 261,061 ha, Mühlviertel 1,234,945 ha, Oberkärnten 183,468 ha, and Osttirol 67,028 ha. Forest area was used to calculate the damaged volume per hectare by bark beetles (DV_{ips}) as well as storm and snow together (DV_s) for each forest district and the regions to make the magnitude of damage comparable.

Data for total growing stock, area of protective forest and age class were retrieved from the Austrian National Forest Inventory online database (Austrian National Forest Inventory 2022).

2.2. Geodata

All climate data used was provided by the Austrian Geosphere Data Hub with a spatial resolution of 1,000 m (GeoSphere Austria 2023a). The potential evapotranspiration sum was obtained from the WINDFORE v2.1 data set in daily resolution, the precipitation sum and daily mean temperature from the SPARTACUS v.2.1 data set in monthly resolution. The monthly climatic water balance was derived from the precipitation and potential evapotranspiration sums. For further data analysis, the mean daily temperature ($tmean_v$) and the sum of the climatic water balance (cwb_v) of the growing season (April to September) were used. Of these, the arithmetic mean of all 1,000 m grid cells included was calculated for each forest district.

2.3. Data analysis

All data handling steps and calculations were conducted in R using the integrated development environment RStudio (R Core Team 2022; Posit Team 2023) with various R packages, only the most important of which are presented below: The packages “terra”, “sf”, and “gdal” were applied for geodata processing tasks. The packages “car” and “stats” were utilized for statistical analysis and visualization was realized with the packages “ggplot2”, “ggpubr”, “ggExtra” and “cowplot”. For the statistical analysis, log-transformed DV_{ips} was used as the response variable, as this allowed a normalization of the originally strongly left-skewed distribution for most forest districts. Cwb_v and $tmean_v$ as well as log-transformed DV_s were used as predictor variables. Lagged DV_{ips} of the previous years was also included as well. Lagged effects were previously investigated for both response and predictor variables using autocorrelation (acf) and cross-correlation function (ccf) from the "stats" package. Correlation analysis (Pearson's r) was applied to investigate the general effect of predictors on DV_{ips} for both clusters. Linear regression models (lm function of the "stats" package) were fitted (i) globally (i.e., for all forest districts together) and (ii) stratified by the northern and southern clusters to examine the combined influence of predictors on DV_{ips}. First, an automatic backward selection (step function of the "stats" package) was performed. Afterwards, non-significant predictors were dropped one by one to fit the final models. All predictors were subsequently checked for collinearity using variance inflation factors (vif function of the "car package), and predictors with vif values > 5 were discarded to fit the final linear regression models.

3. Results

3.1. Outbreak development

The bark beetle outbreak in the two hotspot regions Waldviertel and Mühlviertel in northern Austria developed synchronously and reached unprecedented intensity (Fig. 3). A steep rise in damage by *I. typographus* L. occurred in

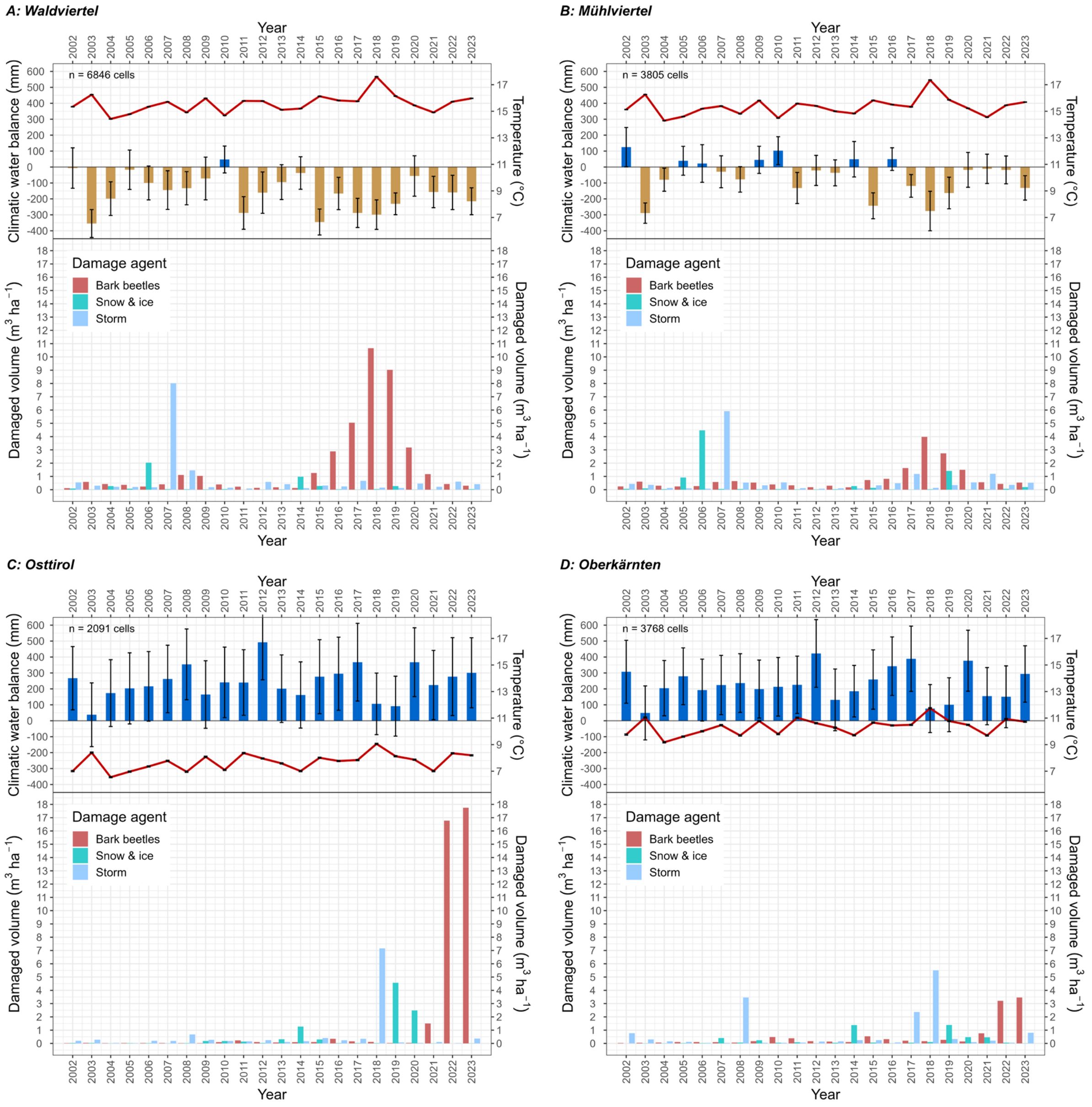

Fig. 3. Times series of damaged volume per ha forest area by *I. typographus* L. as well as storm and snow or ice from 2002 until 2023 and mean temperature (red line) and climatic water balance (blue/beige columns) (months April to September) for: A) Waldviertel and B) Mühlviertel (northern cluster), as well as C) Osttirol and B) Oberkärnten (southern cluster).

2015 leading to the until then highest absolute damage in our time series since 2002. Attacks further increased in the subsequent years. The outbreak peaked in 2018 in both regions, followed by decline of damage, which, however, has not yet reached pre-outbreak level (Fig. 3). Outbreak intensity was much higher in Waldviertel. A total volume of 2.78 million m^3 spruce was damaged in 2018, which represents 3.6% of total growing stock in this area. The damage in Mühlviertel likewise peaked in 2018 at 0.54 million m^3, representing 1.1% of total growing stock. Total damage in the two regions from 2015–2021 was 10.29 million m^3, representing 8.1% of total growing stock. Infestations were not evenly distributed; spruce forests suffered highest damage in the northern and eastern parts of Waldviertel, and in the more southern parts of Mühlviertel. Both regions are characterized by rather dry conditions during the vegetation period. 2015 was characterized by a remarkably negative climatic water balance and high temperature (Fig. 3). First massive bark beetle attacks were reported starting in the summer of 2015. Field visits by the authors showed that these were scattered and widely distributed throughout the regions without apparent connection to preceding storm or snow/ice damage. Although parts of the regions had been affected by ice breakage in winter 2014/15, bark beetle attacks simultaneously occurred in damaged and undamaged areas. Climatic conditions remained very warm and dry in the following years. 2018 had extremely high temperatures in the vegetation period and a highly negative climatic water balance. 2020 and 2021 were less dry and clearly cooler.

A massive eruption of attacks by *I. typographus* L. on standing trees was reported from a mountainous region in the western part of southern Austria in summer 2021 (Fig. 3). Field visits by one of the authors showed that attacks occurred scattered all over the region Osttirol as well as the westernmost part of Oberkärnten. In contrast to the outbreak in the north of Austria, this bark beetle outbreak was preceded by significant abiotic damage events in the forests. The area was struck by the storm Vaia in October 2018 that caused extensive damage in northern Italy and parts of southern Austria. A volume of 0.48 million m^3 was damaged by the storm in Osttirol and 1.03 million m^3 in Oberkärnten. Two winters with very high amounts of snow breakage followed (Fig. 3). These events provided large amounts of easily accessible breeding material for *I. typographus* L. In spring and summer of 2021, the augmented bark beetle population apparently switched to attacking standing trees. Bark beetle attacks further increased and reached unprecedented 1.13 million m^3 and 0.59 million m^3 in 2022. This annual damage represents 5.3% and 1.2%, respectively, of total growing stock in the regions. Damage at similarly high level occurred in 2023.

3.2. Correlation analysis

Temporal autocorrelation of *I. typographus* L. damage ($\log(DV_{ips})$) with $\log(DV_{ips}\ \text{lag1})$ was observed for all forest districts (Table 1). Furthermore, continuous autocorrelation up to $\log(DV_{ips}\ \text{lag2})$ was detected in two and up to $\log(DV_{ips}\ \text{lag3})$ in one forest district. For the further statistical analyses only $\log(DV_{ips}\ \text{lag1})$ and $\log(DV_{ips}\ \text{lag2})$ were considered. The scatterplots in Fig. 4 illustrate this strong autocorrelation of $\log(DV_{ips})$ up to lag2 in both clusters.

Cross-correlation of $\log(DV_{ips})$ with $\log(DV_s)$ and the climatic parameters cwb_v and $tmean_v$ was analyzed via ccf function (Table 1). Regarding $\log(DV_s)$, only in one forest district a continuous cross-correlation up to lag2 could be detected. As storm and snow damage occurs in rare years, the cross-correlations are dominated by non-event years and tend to be small. There were also no significant cross-correlations for the climate variables in the southern cluster. In contrast, in the northern cluster a cross-correlation of $\log(DV_{ips})$ with $tmean_v$ of the current year was consistently detected for all forest districts and with $tmean_v$ lag 1 of the previous year for 8 out of 10 forest districts. Furthermore, $\log(DV_{ips})$ was correlated with cwb_v of the current year in four and with lag1 and with lag1 and lag2, respectively in one northern forest district (Table 1). Cross-correlations were taken into

Table 1. Significant lags in auto- and cross-correlation of logarithmised *I. typographus* L. damage $\log(DV_{ips})$ by forest district (autocorrelation was detected via acf method, cross-correlation via ccf method).

Forest district	Cluster	Autocorrelation sig. lags	Cross-correlation		
			$\log(DV_s)$	cwb_v	$tmean_v$
Horn	North	0, 1, 2	—	—	–1,0
Krems	North	0, 1	—	—	–1,0
Melk	North	0, 1	—	—	–1,0
Waidhofen/Thaya	North	0, 1	—	–2, –1	–2, –1, 0
Zwettl	North	0, 1	—	–1	–1,0
Freistadt	North	0, 1	—	0	0
Linz-Land	North	0, 1, 2, 3	—	0	–1, 0
Perg	North	0, 1, 2	—	0	–1, 0
Rohrbach	North	0, 1	–2, –1	—	0
Urfahr-Umgebung	North	0, 1	—	0	–1, 0
Hermagor	South	0, 1	—	—	—
Spittal an der Drau	South	0, 1	—	—	—
Osttirol	South	0, 1	—	—	—

account in the statistical analyses by including lag1 and lag2 of tmean$_v$ and cwb$_v$, and lag1 to lag3 of log(DV$_s$).

In both, the northern and southern cluster, log(DV$_{ips}$) was strongly positively correlated with log(DV$_{ips}$ lag1) indicating a clear dependence of bark beetle damage from the damage of the previous year (Fig. 4). There was also a positive, though somewhat weaker, correlation between damage two years earlier and our response variable. For this reason, previous bark beetle damages up to lag2 was included in the linear regression. In the northern cluster (Waldviertel and Mühlviertel), bark beetle damaged volume log(DV$_{ips}$) was negatively correlated with cwb$_v$ and cwb$_v$ lag1 and positively correlated with tmean$_v$ and tmean$_v$ lag1 (Fig. 5).

In the southern cluster, log(DV$_{ips}$) was only positively correlated with tmean$_v$ and tmean$_v$ lag1 and no significant correlation could be detected with climatic water balance (Fig. 5).

Regarding the influence of storm and snow damages log(DV$_s$) on bark beetle damage log(DV$_{ips}$), only in the northern cluster slightly positive correlations could be found for lag1 ($r = 0.19$, $p = 0.006$) and lag3 ($r = 0.19$, $p = 0.009$). Interestingly, especially in the southern cluster, where preceding storm and snow damages seemed to be the main drivers, log(DV$_{ips}$) was not correlated with any preceding storm or snow events up to lag3 and also not with damages of the current year. Despite lacking correlation, we nevertheless considered preceding log(DV$_s$) up to lag3 as possible predictors for log(DV$_{ips}$) in the following linear regression model analysis.

3.3 Linear regression models

Based on previous correlation analysis suitable predictors were selected to fit linear regression models globally for all 13 forest districts together and separated by the northern and southern clusters (Table 2).

The results show that all three linear regression models performed very well, achieving adjusted R^2-values from 0.7490 for the northern up to 0.7613 for the southern model (Table 2). Regarding previous bark beetle damage, log(DV$_{ips}$ lag1) is an important predictor in all three models. Furthermore, log(DV$_{ips}$ lag2) is of major importance in the global and northern model. Likewise, preceding storm and snow damages are found to be suitable predictors in all three models. On the one hand, log(DV$_s$ lag3) are included in the global and northern model, on the other hand, log(DV$_s$ lag2) is found in the southern model. Although preceding damages can be considered as most important variables, taking climatic factors into account significantly improved all models. The cwb$_v$ of the recent year is included in all three models, and furthermore cwb$_v$ lag1 in the global model. In addition to the variables described above, year was also included as a trend variable into the model selection, indicating trends in time that are not explained by other predictors. Interestingly, the temporal trend was found to be significant for the global and southern model, but not for the northern model.

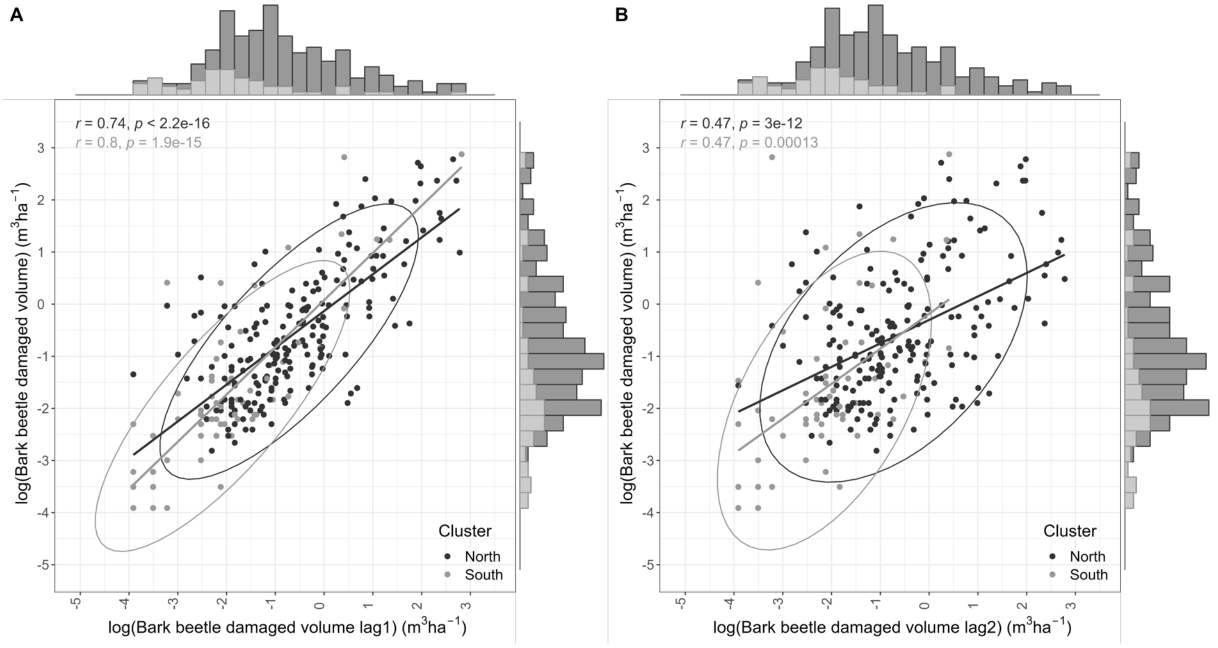

Fig. 4. Scatterplots of *Ips typographus* L. damage: log(DV$_{ips}$) vs. A) log(DV$_{ips}$ lag1) and B) log(DV$_{ips}$ lag2) in the two studied clusters North (Waldviertel and Mühlviertel, $n = 220$) and South (Osttirol and Oberkärnten, $n = 66$) illustrating strong temporal autocorrelation of damage by *I. typographus* L.

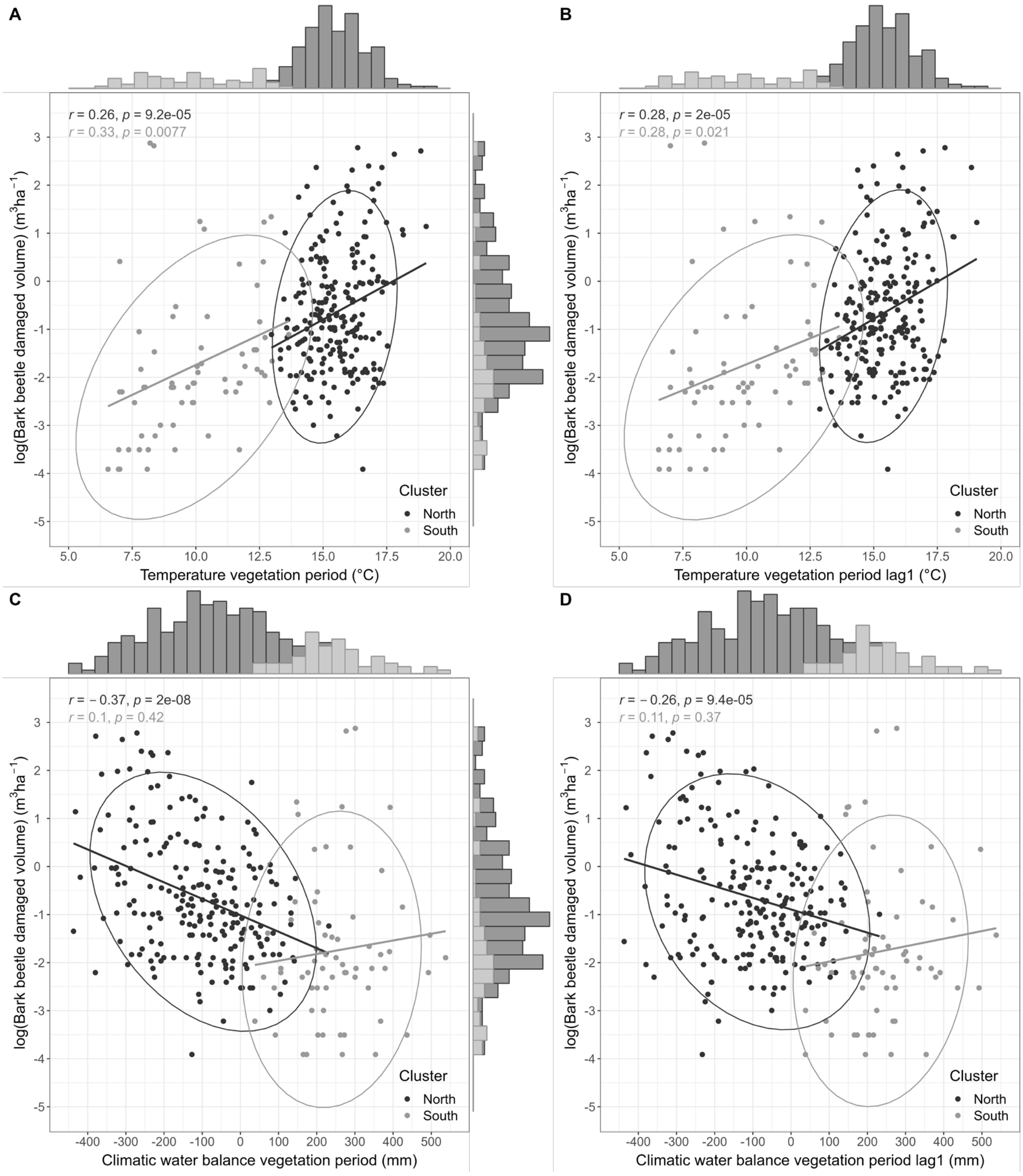

Fig. 5. Scatterplots of *I. typographus* L. damage and temperature as well as climatic water balance: log(DV_{ips}) vs. A) $tmean_v$ and B) $tmean_v$ lag1 as well as C) cwb_v and D) cwb_v, lag1 in the two studied clusters North (Waldviertel and Mühlviertel, n = 220) and South (Osttirol and Oberkärnten, n = 66).

4. Discussion

Since 2015, there have been two major mass outbreaks of *I. typographus* L. with opposed character in Austria. In the north of Austria, *I. typographus* L. attacks affected Norway spruce dominated and often pure Norway spruce forests at elevations mostly below 600 m. These are typically secondary spruce forests, i.e. forests in which the proportion of spruce has been artificially increased and where spruce is at the margin (or outside) of its natural range. Such forests are more prone to bark beetle attack (e.g., Marini et al. 2012; de Groot et al. 2019). Model projections indicated that Norway spruce would show declining growth in these areas with increasing temperature (Schadauer et al. 2019); hence, climate change induced stress for spruce in the region was not unexpected. In the south of Austria, on the other hand, the attacks affected Norway spruce in mountain forests at elevations above 700 m and up to at least 1,800 m. The above-mentioned model projections showed an increasing growth of spruce with increasing temperatures in this area (Schadauer et al. 2019). Analyzing preceding

Table 2. Linear regression models obtained by automatic backward selection and removal of non-significant ($\alpha = 0.05$) predictors or ones violating collinearity requirements (vif > 5): A) Global model for all 13 forest districts, B) Model for the northern cluster Waldviertel and Mühlviertel (10 forest districts), C) Model for the southern cluster Osttirol and Oberkärnten (3 forest districts) (R^2: multiple R-squared; adj. R^2: adjusted R-squared; rmse: root mean square error; df: degrees of freedom; F stat.: F-statistic; se: standard error; Pr: probability; sig.: significance).

A: Global model	R^2	adj. R^2	rmse	df	F stat.	p-value
	0.7593	0.7533	0.6942	240	126.2	< 2.2e–16
Variable	Estimate	se	t value	Pr(>|t|)	sig.	vif
(Intercept)	–6.979e+01	1.908e+01	–3.658	0.000312	***	—
year	3.456e–02	9.463e–03	3.652	0.000319	***	1.377
log(DV_{ips} lag1)	1.043e+00	5.725e–02	18.218	< 2e–16	***	3.223
log(DV_{ips} lag2)	-4.218e–01	5.545e–02	–7.608	6.32e–13	***	2.964
log(DV_s lag3)	1.308e–01	2.962e–02	4.415	1.52e–05	***	1.035
cwb_v	–2.389e–03	3.300e–04	–7.240	6.06e–12	***	2.103
cwb_v lag1	1.169e–03	3.544e–04	3.297	0.001124	**	2.360

B: Northern model	R^2	adj. R^2	rmse	df	F stat.	p-value
	0.7490	0.7436	0.6489	185	138	< 2.2e–16
Variable	Estimate	se	t value	Pr(>|t|)	sig.	vif
(Intercept)	–0.3539127	0.0707245	–5.004	1.30e–06	***	—
log(DV_{ips} lag1)	0.9380357	0.0586886	15.983	< 2e–16	***	2.539
log(DV_{ips} lag2)	–0.2774343	0.0588438	–4.715	4.75e–06	***	2.521
log(DV_s lag3)	0.1486224	0.0317618	4.679	5.55e–06	***	1.052
cwb_v	–0.0030979	0.0003771	–8.215	3.58e–14	***	1.044

C: Southern model	R^2	adj. R^2	rmse	df	F stat.	p-value
	0.7784	0.7613	0.7398	52	45.66	< 2.2e–16
Variable	Estimate	se	t value	Pr(>|t|)	sig.	vif
(Intercept)	–2.244e+02	4.836e+01	–4.641	2.39e–05	***	—
year	1.114e–01	2.394e–02	4.654	2.28e–05	***	1.791
log(DV_{ips} lag1)	6.523e–01	9.776e–02	6.672	1.65e–08	***	1.716
log(DV_s lag2)	–3.546e–01	7.375e–02	–4.807	1.35e–05	***	1.193
cwb_v	–2.065e–03	9.902e–04	–2.086	0.0419	*	1.095

damage by storm, snow- or ice-breakage as well as climatic factors, indicates differences but also similarities in outbreaks in the two regions. Linear regression analysis showed strong effects of preceding damage by *I. typographus* L. and – with lag 2 or 3 – by storm and snow. Climatic water balance had highly significant influence in the global as well as the northern model; the effect was marginally significant in the southern model.

We conclude that the transition from endemic to epidemic phase of *I. typographus* L. was connected to extended drought and high temperatures in the north of Austria. The affected area is the southern extension of the area in Czech Republic affected by the vast *I. typographus* L. outbreak. There, bark beetle damage showed a strong response to the standardized precipitation evapotranspiration index (SPEI) (Hlásny et al. 2021b). SPEI was also shown to have great influence on *I. typographus* L. damage in South Sweden, both in current year as well as with one year time lag (Kärvemo et al. 2023). Also in northern Austria, the years 2015–2019 were characterized by highly negative climatic water balance and high temperatures during the vegetation period. The linear regression analysis indicated a highly significant effect of climatic water balance on damage by *I. typographus* L. Notably, a long-term shift in precipitation patterns had occurred in the area with reduced precipitation in winter when comparing 2000–2019 with the whole available time series 1883–2019 (Jandl 2020), which could lead to reduced water supply when trees are starting into the growing season. Moreover, the annual mean temperature has increased by 1.6 °C in this period (Jandl 2020), leading to increased evapotranspiration rates. In 2015, a long period without precipitation and very high temperatures occurred in July and August (GeoSphere Austria 2023b). As shown by Netherer et al. (2019), particularly acute drought affecting stands on normally well supplied soils can lead to increasing bark beetle attacks. There is experimental evidence that drought stress of spruce can support *I. typographus* L. attacks (Netherer et al. 2015; Netherer et al. 2024). But to better understand the complex interactions between host tree, beetle and symbiotic fungi under drought conditions more research is needed (Netherer & Hammerbacher 2022).

Temperatures in the outbreak area in the north of Austria allow *I. typographus* L. to complete bi- or trivoltine lifecycles. The developmental model PHENIPS (Baier et al. 2007) shows that at least two generations per year could be completed in the whole area of Waldviertel in 2023. On more than 90% of the area, two generations plus sister broods, and on approximately one third of the area, three generations were possible (PHENIPS plus 2023). Temperature conditions for bark beetle development were similar in the adjacent Mühlviertel. Multi-voltinism allows very fast buildup of *I. typographus* L. populations and thus, a fast switch from endemic to epidemic phase (Biedermann et al. 2019). Based on temperature-dependent potential development of *I. typographus* L., predisposition of sites in these lowland regions is typically high. Interestingly, mean temperature did not have a significant effect on *I. typographus* L. damage despite a strong correlation (Fig. 4). Apparently, it was dropped because of an overall more pronounced effect of the climatic water balance, and a strong negative correlation of these two predictors.

The outbreak in the south of Austria, on the other hand, was clearly triggered by preceding storm and snow damage, i.e. representing the pattern typically observed in Austria. Storm and snow damage with time lag of two years had a significant effect on bark beetle damage in the linear regression model for the south. Although significant, the effect of climatic water balance was less pronounced than in the north. This corresponds to an analysis from southern Sweden that showed that mean drought index was also important for bark beetle outbreak triggered by storm but had a much higher impact on infestation size in a drought triggered outbreak (Kärvemo et al. 2023). A time lag was also demonstrated for *I. typographus* L. following storm damage at high elevation in Slovakia (Økland et al. 2016) or after a large ice breakage event in Slovenia (de Groot et al. 2018). The switch from brood development on lying trees to attack of standing trees can be faster at lower elevations (Wichmann & Ravn 2001). The extensive storm and snow damage in Osttirol and Oberkärnten provided vast amounts of easily available breeding material for *I. typographus* L. While the storm damage was somewhat localized and forest managers made great efforts to salvage as much as possible, snow breakage in the following years was scattered all over the region. This massively extended the supply of breeding material for the bark beetles and counteracted previous management efforts. High temperatures likely played an important role for the intensity of the outbreak although we found no significant effect of temperature on *I. typographus* L. damage in the linear regression model. In 2022, temperatures allowed completion of two generations up to 1,400 m elevation and three generations in the valleys (PHENIPS plus 2023).

The meteorological station in Lienz (Osttirol) recorded annual mean air temperature of 8.3 °C for the period 1981–2010. Mean temperature was 9.6 °C from 2019–2022 (maximum 10.3 °C in 2022) (GeoSphere Austria 2023b). A projection based on the model PHENIPS indicated a significant increase of areas with bi- or trivoltine lifecycle of *I. typographus* L. at temperature increase of 1 °C or 2.8 °C compared to 1981–2010 (Hoch et al. 2021). Such upward movement of elevations where two annual generations can be completed was also modelled for Switzerland; temperature increase according to the IPCC scenario A2 elevated the limit for two generations from 400 m to 600 m in 2035 and 1,400 m in 2085 (Jakoby et al. 2019). Likewise, a northward expansion of areas with bivoltine development of *I. typographus* L. has been modelled for European Russia (Romashkin et al. 2020). Another factor that may have contributed to the extent of the attacks in the south of Austria is the age structure of the forests. Approximately half of the forest area in the affected regions is stocked with trees older than 60 years (Austrian National Forest Inventory 2022). Spruce trees older than 60 years, with thicker bark, are favored by *I. typographus* L. (Wermelinger 2004; Hlásny et al. 2021a). After switching to the epidemic phase, *I. typographus* L. likely found a large supply of suitable host trees. It would be tempting to conclude that the significant effect of year in the linear regression model for the south indicates increasing supply of susceptible host trees (i.e. more trees reaching higher age class). However, this effect could also be due to the still ongoing outbreak at the end of the analyzed time series.

Landscape characteristics affected bark beetle management in the north and in the south differently. The terrain in the north is relatively flat or hilly; most affected stands are accessible with machinery and the use of harvesters and forwarders is possible. However, the mere quantity of simultaneously attacked spruce led to problems of availability of human and technical resources and to logistic problems. Consequently, timely removal of infested trees, which is a crucial element of bark beetle management (Hlásny et al. 2019), was not achieved in many cases. Moreover, soon a deficiency in transport and storage capacity for infested wood became evident. The situation was worsened by a steep drop of timber prices, particularly for infested wood, for which prices dropped from 70 €/m^3 to below 30 €/m^3 – just slightly above harvesting costs (Jandl 2020).

The forests in the south are mostly located on very steep terrain. Of the forest area in this region, 39% are protective forests according to Austrian legal definition, i.e. they have site protective function (Austrian National Forest Inventory 2022). For comparison, this percentage is only 1% in the north of Austria. In steep terrain, cable yarding is the standard method for harvesting. Moreover, many areas are hardly or not accessible. Such prerequisites made it impossible to clear the many scattered bark beetle attacks that appeared in summer 2021 on a large area. Timber prices were relatively high and at least partially supported also costly harvesting operations. Due to the landscape situation, many of the affected forests have also protective function to protect people and infrastructure against natural hazards such as avalanches, rockfall, debris flow, etc. Therefore, bark beetle management had to take requirements for these protective functions into consideration right from the beginning. The outbreak is not over yet, and very high damage is expected for 2024. In June 2023, an analysis of Sentinel-2 data by the National Forest Inventory prepared for the forest authorities showed that 33% of forests with protective functions (i.e. 8,600 ha) had been damaged by storm, snow breakage and bark beetles since 2018 (Schadauer, personal communication). The socio-economic impact of the outbreak in this region can be expected to be significant. There is an immediate need for technical measures compensating the loss of protective functions of the forest. The risk for natural hazards will increase inevitably. Tree mortality due to bark beetles as well as salvaging reduce protective functions against avalanches (Teich et al. 2019; Caduff et al. 2022). Dead trees will retain some functions for some years but may pose other risks. There is clearly need for research for optimal management of such disturbed forests to maximize their protective function.

5. Conclusion

Two outbreaks of *I. typographus* L. since 2015 in Austria illustrate how drought and preceeding damage by storm and/or snow can trigger the transition from endemic to epidemic phase, with the effect of drought being more pronounced for the forests at lower elevation in the north. Both patterns are known for *I. typographus* L. and an increased risk of outbreaks due to climate change was expected. However, the enormous extent of the damage and the loss of large areas of mature spruce forests in very short time surprised forest managers. The outbreaks highlight that under climate warming forest management needs to be prepared for outbreaks of *I. typographus* L. in the whole spruce area in Central Europe, also at higher elevation. Together with mid- and long-term silvicultural measures, improved monitoring techniques supported by risk analysis and early warning systems, a good road infrastructure, and contingency planning to quickly respond to outbreaks are highly needed.

Acknowledgements

The effort of many district foresters submitting data to the Documentation of Forest Damaging Factors and the cooperation with forest authorities at district and federal state level is highly appreciated. Funding was provided by Waldfonds – Republic of Austria: Project RAWLog, BMLRT/III-2021-M4/2 (FAI.2).

References

Baier, P., Pennerstorfer, J., Schopf, A., 2007: PHENIPS-A comprehensive phenology model of *Ips typographus* (L.) (Col., Scolytinae) as a tool for hazard rating of bark beetle infestation. Forest Ecology and Management, 249:171–186.

Biedermann, P. H. W., Müller, J., Grégoire, J.-C., Gruppe, A., Hagge, J., Hammerbacher, A. et al., 2019: Bark beetle population dynamics in the anthropocene: challenges and solutions. Trends in Ecology & Evolution, 34:914–924.

Caduff, M. E., Brožová, N., Kupferschmid, A. D., Krumm, F., Bebi, P., 2022: How large-scale bark beetle infestations influence the protective effects of forest stands against avalanches: A case study in the Swiss Alps. Forest Ecology and Management, 514:120201.

de Groot, M., Ogris, N., Kobler, A., 2018: The effects of a large-scale ice storm event on the drivers of bark beetle outbreaks and associated management practices. Forest Ecology and Management, 408:195–201.

de Groot, M., Diaci, J., Ogris, N., 2019: Forest management history is an important factor in bark beetle outbreaks. Lessons for the future. Forest Ecology and Management, 433:467–474.

Hlásny, T., Krokene, P., Liebhold, A., Montagné-Huck, C., Müller, J., Qin, H. et al., 2019: Living with bark beetles: impacts, outlook and management options. From Science to Policy 8. European Forest Institute, 50 p.

Hlásny, T., König, L., Krokene, P., Lindner, M., Montagné-Huck, C., Müller, J. et al., 2021a: Bark beetle outbreaks in Europe: state of knowledge and ways forward for management. Current Forestry Reports, 7:38–165.

Hlásny, T., Zimová, S., Merganičová, K., Štěpánek, P., Modlinger, R., Turčáni, M., 2021b: Devastating outbreak of bark beetles in the Czech Republic: Drivers, impacts, and management implications. Forest Ecology and Management, 490:119075.

Hoch, G., Schopf, A., 2019: 1 Einleitung. In: Hoch, G., Schopf, A., Weizer, G. (eds.): Der Buchdrucker – Biologie, Ökologie, Management. Wien, BFW Bundesforschungszentrum für Wald, p. 1–8. (In German).

Hoch, G., Kirisits, T., Baier, P., Cech, T., 2021: Forstschutz im Schutzwald – biotische Schadfaktoren (Insekten, Pilze, Eipilze). In: Freudenschuß, A., Markart, G., Scheidl, C., Schadauer, K. (eds.): Schutzwald in Österreich – Wissensstand und Forschungsbedarf. Langfassung. Wien, BFW Bundesforschungszentrum für Wald, p. 147–153. (In German).

Jakoby, O., Lischke, H., Wermelinger, B., 2019: Climate change alters elevational phenology patterns of the European spruce bark beetle (*Ips typographus*). Climate Change Biology, 25:4048–4063.

Jandl, R., 2020: Climate-induced challenges of Norway spruce in Northern Austria. Trees, Forests and People, 1:100008.

Kärvemo, S., Huo, L., Öhrn, P., Lindberg, E., Persson, H. J., 2023: Different triggers, different stories: Bark-beetle infestation patterns after storm and drought-induced outbreaks. Forest Ecology and Management, 545:121255.

Marini, L., Ayres, M. P., Battisti, A., Faccoli, M., 2012: Climate affects severity and altitudinal distribution of outbreaks in an eruptive bark beetle. Climatic Change, 115:327–341.

Marini, L., Økland, B., Jönsson, A. M., Bentz, B., Carroll, A., Forster, B. et al., 2017: Climate drivers of bark beetle outbreak dynamics in Norway spruce forests. Ecography, 40:1426–1435.

Netherer, S., Matthews, B., Katzensteiner, K., Blackwell, E., Henschke, P., Hietz, P. et al., 2015: Do water-limiting conditions predispose Norway spruce to bark beetle attack? New Phytologist, 205:1128–1141.

Netherer, S., Panassiti, B., Pennerstorfer, J., Matthews, B., 2019: Acute drought is an important driver of bark beetle infestation in Austrian Norway spruce stands. Frontiers in Forests and Global Change, 2:39.

Netherer, S., Hammerbacher, A., 2022: 4 – The Eurasian spruce bark beetle in a warming climate: Phenology, behavior, and biotic interactions. In: Gandhi, K. J. K., Hofstetter, R. W. (eds.): Bark beetle management, ecology, and climate change. Academic Press, p. 89–131.

Netherer, S., Lehmanski, L., Bachlehner, A., Rosner, S., Savi, T., Schmidt, A. et al., 2024: Drought increases Norway spruce susceptibility to the Eurasian spruce bark beetle and its associated fungi. New Phytologist, 242:1000–1017.

Niesar, M., Geisthoff, N., Bürvenich, J., Theisinger, W., Theisinger, O., Lieffertz, A. et al., 2023: Waldschutzsituation 2022 in Nordrhein. AFZ-DerWald, 9:38–41. (In German).

Ogris, N., Ferlan, M., Hauptman, T., Pavlin, R., Kavčič, A., Jurc, M. et al., 2019: RITY – A phenology model of *Ips typographus* as a tool for optimization of its monitoring. Ecological Modelling, 410:108775.

Økland, B., Nikolov, Ch., Krokene, P., Vakula, J., 2016: Transition from windfall- to patch-driven outbreak dynamics of the spruce bark beetle *Ips typographus*. Forest Ecology and Management, 363:63–73.

Otto, L.-F., Matschulla, F., Sonnemann, S., 2023: Waldschutzsituation 2022/23 in Sachsen. AFZ-DerWald, 9:33–37. (In German).

Raffa, K. F., Aukema, B. H., Bentz, B. J., Carroll, A. L., Hicke, J. A., Turner, M. G. et al., 2008: Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. BioScience, 58:501–517.

Romashkin, I., Neuvonen, S., Tikkanen, O.-P., 2020: Northward shift in temperature sum isoclines may favour *Ips typographus* outbreaks in European Russia. Agricultural and Forest Entomology, 22:238–249.

Schadauer, K., Freudenschuss, A., Ledermann, T., Kindermann, G., 2019: Gefährdete Fichtenstandorte: Modelle, Zahlen, Fakten. BFW Praxisinformation, 49:3–7. (In German).

Schebeck, M., Dobart, N., Ragland, G. J., Schopf, A., Stauffer, C., 2022: Facultative and obligate diapause phenotypes in populations of the European spruce bark beetle Ips typographus. Journal of Pest Science, 95:889–899.

Seidl, R., Rammer, W., Jäger, D., Lexer, M. J., 2008: Impact of bark beetle (*Ips typographus* L.) disturbance on timber production and carbon sequestration in different management strategies under climate change. Forest Ecology and Management, 256:209–220.

Steyrer, G., Cech, T. L., Fürst, A., Hoch, G., Perny, B., 2020: Waldschutzsituation 2018 in Österreich: Borkenkäferkalamität legt im Nordosten weiter zu. Forstschutz Aktuell, 64:23–32. (In German).

Steyrer, G., Cech, T. L., Fürst, A., Perny, B., Schwanda, K., Tatzber, M. et al., 2022: Waldschutzsituation 2021 in Österreich: Neue Borkenkäferkalamität im Süden. Forstschutz Aktuell, 67:15–27. (In German).

Teich, M., Giunta, A. D., Hagenmuller, P., Bebi, P., Schneebeli, M., Jenkins, M. J., 2019: Effects of bark beetle attacks on forest snowpack and avalanche formation – Implications for protection forest management. Forest Ecology and Management, 438:186–203.

Wenzel, A., Thiel, J., Stürtz, M., 2023: Waldschutzsituation 2022 in Thüringen. AFZ-DerWald, 9:29–32. (In German).

Wermelinger, B., Seifert, M., 1998: Analysis of the temperature dependent development of the spruce bark beetle *Ips typographus* (L.) (Col., Scolytidae). Journal of Applied Entomology, 122:185–191.

Wermelinger, B., 2004: Ecology and management of the spruce bark beetle *Ips typographus* – a review of recent research. Forest Ecology and Management, 202:67–82.

Wichmann, L., Ravn, H. P., 2001: The spread of *Ips typographus* (L.) (Coleoptera, Scolytidae) attacks following heavy windthrow in Denmark, analysed using GIS. Forest Ecology and Management, 48:31–39.

Other sources

Austrian National Forest Inventory, 2022: Online database of the Austrian National Forest Inventory. BFW – Bundesforschungszentrum für Wald, Wien. Retreived 4.12.2023, from https://waldinventur.at/#/.

Bauerhansl, C., 2020: Erste hochgenaue Waldkarte der Waldinventur. Retrieved 17.12.2023, from https://www.bfw.gv.at/hochgenaue-waldkarte-waldinventur/.(In German).

GeoSphere Austria, 2023a: Data hub. Retrieved 05.12.2023, from https://data.hub.geosphere.at/. (In German).

GeoSphere Austria, 2023b: Klima aktuell. Retrieved 4.12.2023, from https://www.zamg.ac.at/cms/de/klima/klima-aktuell. (In German).

Hoch, G., Steyrer, G., 2020: Zunehmende Schäden durch Borkenkäfer im Klimawandel. Climate Change Centre Austria, CCCA Fact Sheet #31/2020. 2 p. Available at https://ccca.ac.at/wissenstransfer/fact-sheets. (In German).

PHENIPS plus, 2023: PHENIPS plus – Monitoring and Risk Analysis. BOKU – University of Natural Resources and Life Sciences, Vienna. https://ifff-server.boku.ac.at/wordpress/index.php/language/de/phenips-online-monitoring/phenips-online-osterreich/flachige-darstellung-der-borkenkaferentwicklung-3/kurzanleitung/. (In German).

Posit Team, 2023: RStudio: Integrated Development Environment for R. Posit Software, PBC, Boston, MA. Available at http://www.posit.co/.

R Core Team, 2022: R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available at https://www.R-project.org/.