Forest Ecology and Management 597 (2025) 123136

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Mitigating bark beetle damage in Norway spruce stands: Insights from Belgium's latest outbreak

Arthur Gilles [*], Jonathan Lisein, Nicolas Latte, Hugues Claessens

TERRA Teaching and Research Centre (Forest Is Life), ULiège, Gembloux Agro-Bio Tech, Passage des Déportés 2, Gembloux 5030, Belgium

ARTICLE INFO

Keywords:
Bark beetle
Norway spruce
Hotspot spreading
Multivariate analysis
Environmental conditions
Stands conditions

ABSTRACT

For several years, Europe has witnessed a significant dieback of diverse forest tree species, and the Norway spruce, a common species across the continent, is no exception. The combination of drought events and bark beetle infestations appears to play a significant role in these widespread diebacks, raising concerns about the future viability of this species in some regions.

The Ardenne, located in southern Belgium where spruce is not native, has also experienced significant dieback during the 2017–2022 period. An analysis of the drivers related to spruce bark beetle attacks was performed to better anticipate probable future significant spruce dieback. The available cartographic data describing potential climatic, growth-condition and management drivers influencing these diebacks have been gathered using GIS tools (Geographic Information Systems) and linked with the Norway spruce health map that have been produced using Sentinel-2 satellite imagery from our previous research, helping to identify affected areas. Lidar flights conducted prior to the outbreak provide detailed descriptions of the forest stands. All our analysis were conducted with a huge quantity of cartographic and remote sensing data covering the entire Belgian spruce forest (120,000 ha).

A random forest analysis followed by a profile model assessment, was employed to pinpoint the key drivers contributing to dieback. Statistical analysis showed that stands with greater dominant height and closer distance from bark beetle hotspots in previous years were associated with higher dieback intensity. Stands located in bioclimatic zones characterized by low altitude, or those with climatic conditions marked by a summer water deficit (P-ETP) or a more rapid decrease in summer water deficit during the 2010–2021 period, were associated with increased damage in Norway spruce stands. These results were interpreted to propose management guidelines for limiting the impact of future bark beetle outbreaks in spruce stands, which will be increasingly stressed in this century's climate. High-resolution remote sensing data can identify variations within seemingly uniform forests, providing insights into disease outbreak patterns.

1. Introduction

Over the last decade, European Norway spruce (*Picea abies (L.) H. Karst.*) forests have suffered from bark beetle infestations (Bárta et al., 2021; Dalponte et al., 2022; Gilles et al., 2024; Nardi et al., 2023; Saintonge et al., 2022). This pest has caused the loss of millions of cubic meters of timber across Europe (Patacca et al., 2023). The spruce dieback raises concerns about the future of this widespread and economically important tree species. It is essential to identify the drivers contributing to dieback and assess the viability of timber production for this species. Where possible, silvicultural practices need to be adapted to reduce the impact of future disturbances on spruce stands.

The Norway spruce is endemic to the Alpine, Hercynian-Carpathian and Nordic-Baltic regions (Jansen et al., 2017). In its natural range, this tree species is able to grow on a wide range of sites as long as it has sufficient water supply. Due to its high plasticity and economic versatility, it has been introduced into many regions outside its natural range (Spiecker, 2003), even in plains, and covers an area of 30,000,000 ha in Europe (Klimo, 2000). In this area, the main bark beetle problems are caused by *Ips typographus* (Hlásny et al., 2021; Seidl et al., 2008), which attacks preferentially Norway spruce. A theoretical model, first proposed by Berryman (1978) and later expanded by Christiansen et al. (1987), links the population-level threshold for successful bark beetle attacks to the vigour of individual trees or stands. This model is based on

* Corresponding author.
E-mail address: arthur.gilles@uliege.be (A. Gilles).

https://doi.org/10.1016/j.foreco.2025.123136
Received 13 March 2025; Received in revised form 25 August 2025; Accepted 28 August 2025
Available online 5 September 2025

two hypotheses: i) the occurrence of bark beetle outbreaks is contingent upon population levels exceeding a critical threshold, whereby positive feedback, such as mass attacks and reproduction, becomes predominant over natural controls including predation and host resistance and ii) the more vigorous the tree, the larger the beetle population required to overcome its defences. Indeed, healthy trees have been shown to repel beetle colonization through the production of resin, the release of chemical defences, and the rapid closure of wounds, even in the presence of moderate infestations. Conversely, stressed or weakened trees (e.g., due to drought, ageing, or prior damage) demonstrate reduced defensive capacity, thereby effectively lowering the beetle threshold density. Consequently, a small beetle population can initiate mass attacks of considerable success, thus leading to epidemic dynamics (Hlásny et al., 2021).

When *Ips typographus* populations are at low levels, they only target weakened trees (Hlásny et al., 2021). However, when conditions are favourable for bark beetle development, such as high temperatures (Annila, 1969; Baier et al., 2007), the availability of a large number of weakened trees due to windthrow (Hroššo et al., 2020; Kärvemo et al., 2014; Mezei et al., 2017) or drought events (Seidl et al., 2011), the bark beetle populations can explode and also attack healthy trees, and causing massive dieback.

The study of drivers causing spruce dieback highlights a complex process involving climatic, environmental and silvicultural aspects (Lausch et al., 2011) which have an effect on forest stands, individual trees, insects, and their interaction. Numerous studies have been conducted on this topic in Germany (Kautz et al., 2013; Lausch et al., 2011; Seidl et al., 2009), France (Nardi et al., 2023; Piedallu et al., 2023), Slovakia (Hroššo et al., 2020; Jakuš, 1995; Mezei et al., 2017; Potterf et al., 2019), Italy (Faccoli, 2009), Sweden (Kärvemo et al., 2014) and Russia (Trubin et al., 2022). The main environmental stressors of spruce lack of water supply due to climatic events such as rainfall deficit (Marini et al., 2017; Piedallu et al., 2023), high temperatures increasing water demand (Mezei et al., 2017) or both (Trubin et al., 2022), that are often approximated with altitude (Faccoli, 2009; Nardi et al., 2023; Potterf et al., 2023), as well as windstorms (Hroššo et al., 2020; Kärvemo et al., 2014; Mezei et al., 2017). Furthermore, local site factors can exacerbate water deficit as the environmental drivers influencing spruce dieback include altitude (Faccoli, 2009; Nardi et al., 2023; Potterf et al., 2023), low soil water reserve conditions (Nardi et al., 2023; Piedallu et al., 2023), slopes through their draining effect or the increased radiation and soil dryness (Nardi et al., 2023; Piedallu et al., 2023) and potential radiation (Kautz et al., 2013; Mezei et al., 2014, 2019). In addition, at the stand level, silvicultural drivers influenced by forest management can also weaken spruce stands and predispose them to bark beetle attacks. They include the share of spruce in the stand composition (Faccoli, 2009; Jactel et al., 2021; Jakuš, 1995; Nardi et al., 2023; Piedallu et al., 2023; Potterf et al., 2023), the lack of stand structure (Jactel et al., 2021; Piedallu et al., 2023), or exposed forest edges (Kautz et al., 2013; Piedallu et al., 2023; Stříbrská et al., 2022). Old trees are also more susceptible to bark beetle attacks (Piedallu et al., 2023; Potterf et al., 2023). There are very few ways of limiting bark beetle outbreaks. They consist of salvage logging and sanitary felling to limit the emergence of new infestation spots (Dobor et al., 2020; Stadelmann et al., 2013). Conversely, the use of pheromone traps to minimize infestations has been shown to be ineffective during severe outbreaks (Kuhn et al., 2022). Subsequently, push-and-pull method performed well in post-windthrow conditions (Deganutti et al., 2024) but show ineffectiveness during severe outbreak (Jakuš et al., 2022). Preventive measures would therefore be more useful than curative methods.

In Belgium, Norway spruce stands cover nowadays around 120,000 ha, mostly in the Ardenne ecoregion which contains 80 % of the resource area of Belgium, where climate and soil conditions correspond to the autecology of the species. However, between 2017 and 2022, they were affected by a bark beetle outbreak. This is not the first time that such an event has occurred since the introduction of Norway spruce in the Ardenne. Major dieback has been recorded in several periods, including 1887–1900 (Carle, 1975), as well as 1911 (Barbey, 1923), 1921 (Barbey, 1923), 1976 after the driest year of the century (Lévieux et al., 1985) and 1990–1993 period following the severe windthrows of 1990 (Grégoire and De Proft, 1996).

The Belgian spruce area decreased by 10 % (13,000 ha) during the last bark beetle outbreak from 2017 to 2022 (Gilles et al., 2024). The lowlands, below 300 m in altitude, were severely affected, with mortality rates around 35–40 %, but the damages became less severe as the altitude increased. Indeed, a preliminary study at a regional scale (Wallonia and north-eastern France) has shown that the intensity of the dry and warm events of the 2017–2020 period was the most important explanatory factor for the outbreak at the regional scale. Consequently, in the Ardenne plateau, which lies between 300 m and 700 m in altitude and is the main spruce-growing region of Belgium, the mortality rate was lower than at lower altitudes, ranging from 5 % to 13 % depending on elevation (Gilles et al., 2024).

The last major bark beetle outbreak and spruce dieback provide an opportunity to highlight the environmental and silvicultural stresses that make spruce forests vulnerable to infestation, and to develop strategies to mitigate future damage.

Our hypothesis is that during the stressful climatic event of 2018–2021, the development of the outbreak may have been favoured by various factors linked to the local site, the tree, the stand and its management.

The large number of attacked stands in the Ardenne, combined with the wide availability of cartographic and remote sensing data should make it possible to identify, through statistical analysis at a regional scale, the most significant factors in the development of the outbreak. This study aims then to identify the drivers over which the forester can have an influence through their action to prevent bark beetle damage in the future.

Indeed, in southern Belgium, the democratization of satellite data, such as freely available 10-meter resolution Sentinel-2 imagery, has enabled the production of Norway spruce health maps (Gilles et al., 2024). Combined with the availability of a Digital Terrain Model (DTM), a Canopy Height Model (CHM), and a high-resolution digital soil map at a 1:20,000 scale, these data facilitate a comprehensive regional analysis. These resources support the investigation of spatial drivers contributing to Norway spruce dieback across 120,000 ha in southern Belgium from 2017 to 2020. This is an unprecedented achievement, as it marks the first time worldwide that a bark beetle outbreak has been analysed at a regional scale using only digital soil and topographic data, combined with freely available 10-meter resolution satellite imagery.

2. Material and methods

2.1. Study area

In order to focus this analysis on these local drivers, the study was limited to the ecoregion of the Ardenne (south-eastern of Belgium) which is relatively homogeneous in terms of soil and climate and is quite favourable to spruce in terms of climate (Fig. 1). Indeed, even though the Ardenne is included in the temperate oceanic bioclimatic zone (Lindner et al., 2010), its climate shows a mountain influence with an annual rainfall of around 1114 mm and an average temperature of 8.7°C (data from IRM for the period 1991–2020). This ecoregion is part of the Hercynian Massif, with acidic soils and a poor nutrient status. According to the Walloon forest inventory (Alderweireld et al., 2015), the Ardenne forest covers 290,600 ha (58 % of the region's area) and is dominated by conifers (64 %). The main tree species are Norway spruce (45 %), mostly in even-aged stands (95 %), oak (11 %) and European beech (10 %). Norway spruce was introduced in the region at the end of the 19th century. The Ardenne has since become the main spruce producing region of Belgium. A significant amount of cartographic data information is readily available for this region. Climate data are available from

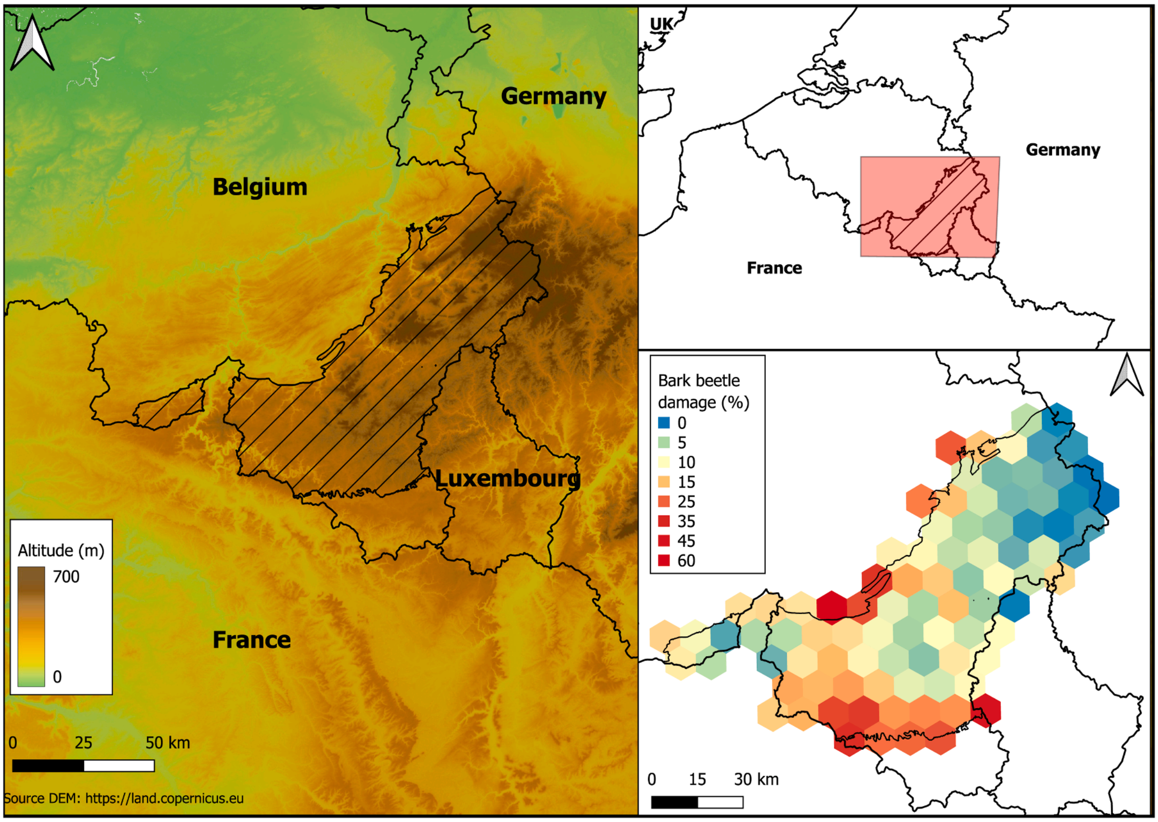

Fig. 1. Location of the study area (black slant lines) and the proportion of damage sustained by Norway spruce stands in the Ardenne between 2018 and 2020. The location of the study area corresponds to the old Hercynian plateau of the Ardenne where the altitude varies between from 200 m in the valleys to 700 m on the high eastern plateau near Germany.

gridded observations (pixels of 5 km of resolution) of the Royal Meteorological Institute of Belgium (RMI). The aerial laser survey (LiDAR) carried out between 2013 and 2014 provides a detailed description of the topography and information on the height and density of forest stands. A Soil map at a scale of 1:20,000 is also available for the entire region (Legrain et al., 2014). All these cartographic data allow for a detailed description of forest areas and the characteristics of forest stands.

To determine the influence of spatio-temporal drivers on spruce dieback in the Ardenne during the period 2018–2020, three Norway spruce health status maps (one per year) (Gilles et al., 2024) were used to distinguish areas of stands affected by bark beetle infestation from those that remained healthy during this period. By linking all the cartographic data with the dieback data, the main drivers contributing to these extensive diebacks can be identified. Consequently, with its relatively homogeneous soil and climate and the wide availability of high-quality environmental data, the Ardenne region offers ideal conditions for identifying the drivers related to Norway spruce bark beetle damage.

2.2. Overall methodology

The analytical process consists of 3 steps (Fig. 2): i. the plots generation focusing on selecting appropriate areas of spruce stands; ii. the production of potential explanatory variable maps derived from other maps (DTM, CHM, soil map, meteorological data); and iii. the selection of the best predictive variables and the analysis of their importance. These three steps are described in detail below.

2.2.1. Plots selection

Dieback intensity was determined for all spruce stands in the Belgian Ardenne using annual health maps from our previous research (Gilles et al., 2024). The health maps were produced by detecting the vegetation anomalies in time series analysis of Sentinel-2 satellite imagery. Five liveliness states were considered: green live spruce, spruce suffering dieback during the current year, older dieback, harvest cutting, and sanitary cutting. Due to the magnitude of the outbreak, all observed cases of Norway spruce dieback are, for the purposes of this study, attributed to bark beetle infestation. The spatial resolution is 10 m. There are three maps, one per year during the period 2018–2020. In this study, spruce stands were considered as a continuous squared area of 0.49 ha (Fig. 3), resulting in a ground square sample of 70 × 70 m. This resolution reflects both forest stand and forest site (environmental conditions) with relatively homogenous characteristics.

The 101,780 ha of spruce forest were thus gridded into square plots and those presenting at minimum 50 % of forested area with at least 33 % of spruce cover in the stand were considered, resulting in 209,644 observations. For each year of the 2018–2020 period, the dieback intensity was then calculated for each square plot using the spruce health maps. The dieback intensity was computed as the proportion of surface of the spruce impacted by dieback during the current year on the total surface of healthy spruce at the beginning of the year (values between 0 and 1).

To ensure balanced class representation and the proper functioning of the random forest algorithm, we divided the data into 12 distinct classes. For each combination of year (2018, 2019, 2020) and damage percentage (0–0.25, 0.25–0.5, 0.5–0.75,0.75–1) (Table 1), we randomly retained either the minimum number of observations per class or a maximum of 1,000 observations per class. This classification process resulted a refined dataset comprising 13,460 observations, which was subsequently used for statistical analysis.

Each plot corresponded only to one year, the year of the maximum

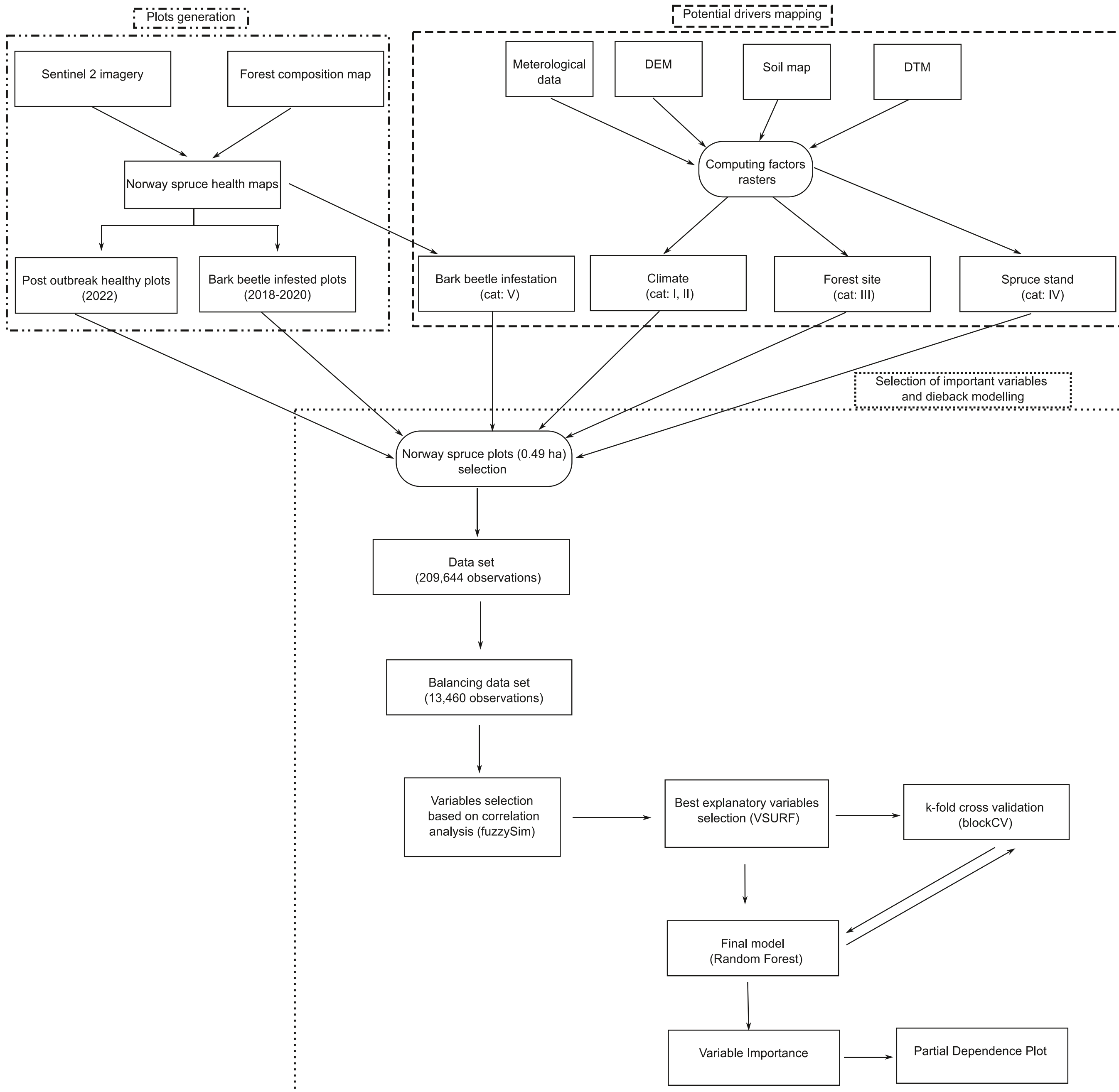

Fig. 2. Workflow illustrating the analyses process. The categories I, II, III, IV and V refer to the categories of Table 2.

dieback. Plots that never affected by bark beetle attacks during the period from 2018 to 2022 are considered as healthy plots and were randomly and evenly distributed between the three years.

2.2.2. Potential drivers of the dieback

An extensive description of the forest stands and forest sites was carried outby extracting various types of information from available cartographic layers covering the whole region of interest (Table 2). For each plot, long-term climatic, and soil and topographic potential drivers were estimated. Spruce stands were also described in terms of maturity and composition. In addition to these potential drivers of the dieback that are relevant during the entire outbreak, inter annual characterisation was performed for climatic conditions and proximity to the nearest infested spot.

3. Climate conditions

Mesoclimate of forest sites is defined by the bioclimatic zones of the Ardenne, which separate low Ardenne, central plateau and high plateau (Van der Perre et al., 2015). The daily time series of climate gridded-observations (5 km resolution) from the RMI (Journée et al., 2019) was used to characterise forest site. The CDO software (Schulzweida and Quast, 2015) was used to process temperature, precipitation, solar radiation, potential evapotranspiration and wind speed variables. Past and long-term period of 1960–2021 and 2010–2021 were considered to assess the evolution of summer climatic water deficit, a comprehensive proxy for water availability. Slope coefficient from linear regression fitted the annual time-series P-ETP was computed for these two periods, according to Piedallu (2023).

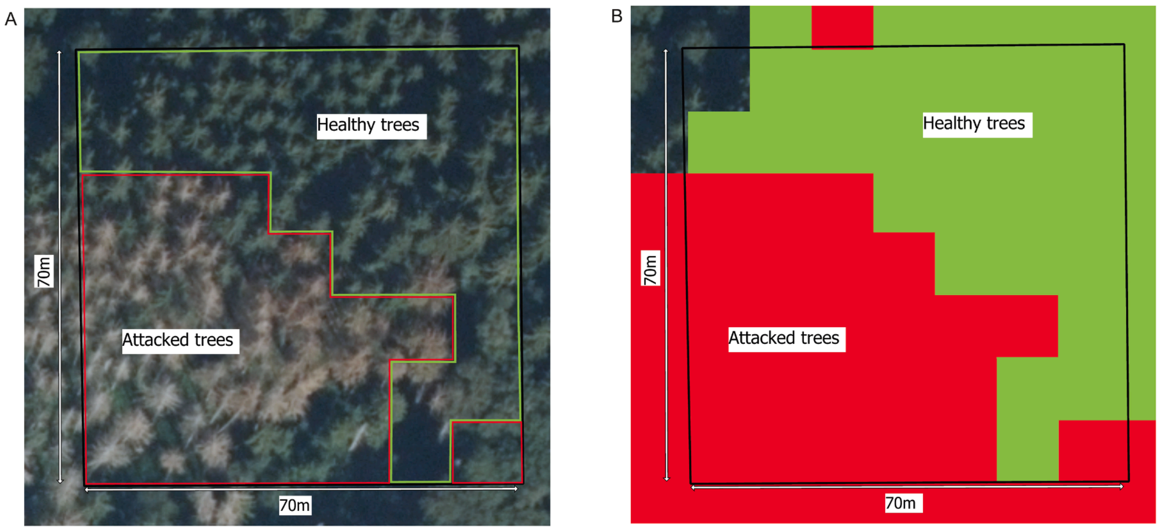

Fig. 3. Illustration of square plots of 70 m by 70 m with an orthophoto plan of 2019 (A) and the Norway spruce health map of 2018 (B) (Gilles et al., 2024).

Table 1
Number of plots by status and by year.

Year	Healthy observations	Dieback intensity class observations					Total
		1 %-25 %	25 %-50 %	50 %-75 %	75 %-100 %	total	
2018	48,654	29,594	5,085	1,677	3,343	39,699	88,353
2019	48,654	4,956	1,049	557	1,993	8,555	57,209
2020	48,656	10,902	1,906	865	1,753	15,426	64,082
Total	145,964	45,452	8,040	3,099	7,089	63,680	209,644

3.1. Inter-annual climatic indices

To account for inter-annual variations of climate during the bark beetle outbreak, diverse indices were computed from the daily time series of climate observation. The same climatic indices were computed for plot considering current and previous climatic conditions. For instance, "y-2" corresponds to the two years before the bark beetle attack, e. g., if the attack occurs in 2020, "y-2" refers to the climatic conditions in 2018. The climate indices were also computed for different time periods: the entire year, spring period (March to June) and summer period (June to September). This approach enables the analysis of how climatic conditions during specific periods affect spruce mortality. Additionally, the summer climatic water deficit (petp_5_9) was also computed. Various other indices derived from rainfall data were generated: total rainfall by season and for the year(rf), rainfall anomalies (rf_ano), consecutive dry days (dry_day), and consecutive wet days (wet_day). Rainfall anomalies were computed following the eq1.

$$rf\_ano = \frac{Summer\_rainfall_{year} - P\_90\_summer\_rainfall_{(1970-1999)}}{P\_90\_summer\_rainfall_{(1970-1999)}} \quad (1)$$

Temperature-related potential drivers were generated using the CDO software (Schulzweida, 2023). These potential drivers include the annual average daily temperature, maximum spring temperature, maximum summer temperature, minimum spring temperature, annual temperature anomalies compared to the 1970–1999 baseline, degree days, and the number of frost days.

Consecutive dry days index (dry_day), consecutive frost days (frost_day), consecutive wet days (wet_day), and frost days (frost_day) were calculated according to the CDO definition.

3.2. Forest site: soil and topography

The Digital Soil Map of Wallonia (Legrain et al., 2014) and the LiDAR CHM were used to describe the forest sites across the study area. For each plot, five topographic variables were derived from DTM: elevation, aspect, slope, radiative exposition and potential radiation.

The soil map of Wallonia comes from a campaign of soil measurements based on an average of two hand augerings per hectare and extensive field observations, subsequently digitized. Forest sites were characterized by the soil properties that express the availability of water, nutrients and oxygen, but also by other properties such as soil depth, texture, stone content, traces of hydromorphy (Lisein et al., 2022). These variables were completed by the forest site types identified in the Ardenne (Tossens et al., 2024).

The old-growth forests map of Wallonia (Kervyn et al., 2014) was used to discern whether a plot of land has been continuously covered by forest since the 18th century or if it was recently utilized as farmland. Farmland has received considerable amount of nutrient input, which is likely to increase the vulnerability of spruce trees to damage from *Heterobasidion annosum* (Delatour, 1972), thereby potentially making spruce more attractive to bark beetles (Wahlman et al., 2025).

3.3. Spruce stand

Maturity and composition of forest spruce stands were also described. The dominant height was used as a proxy for the stand maturity. It was computed as the average height of the 50 tallest trees present in each squared plot (DHM of 2014), composition was grasped through the percentage of spruce and through the broadleaved area. Both were derived from the species proportion map of Wallonia (Bolyn et al., 2022). The proportion of spruce in each plot is number of 10 m × 10 m pixels classified as Norway spruce in the plot divided by number number of pixels classified as forest in the plot. The proportion of broadleaves is calculated with the same process.

The gap area in the plot was calculated using the same DHM as the sum of all gaps surface within the plot. The forest edge corresponds to

Table 2
List of the 79 potential explanatory variables. The y-1 and y-2 correspond to the year respectively 1 or 2 years before the bark beetle attack year (for example: if the year of attack is 2018, the y-2 corresponds to the year 2016). The spring season runs from March to May, and summer from June to September.

	Short names	Time	Variables	Resolution
Category I: climate conditions (long term)				
Mesoclimate	zbio		Bioclimatic zones	100 × 100
Climate trends	trend1_petp		Trend of summer P-ETP during the period 1961 and 2021	5000 × 5000
	trend2_petp		Trend of summer P-ETP during the period 2010 and 2021	5000 × 5000
Category II: climate (inter-annual variation)				
		Time		
Comprehensive indicator	petp_5_9	y,y-1,y-2	Difference of the precipitation and evapotranspiration during the growing period (may-September)	5000 × 5000
Rainfall	rf	y,y-1,y-2	Sum of rainfall for one year	5000 × 5000
	rf_spring	y,y-1,y-2	Sum of spring rainfall	5000 × 5000
	rf_summer	y,y-1,y-2	Sum of summer rainfall for the year	5000 × 5000
	rf_ano	y,y-1,y-2	Summer rainfall anomaly of the summer compared to the 1970–1999 period	5000 × 5000
	dry_day	y,y-1,y-2	Consecutive dry days index	5000 × 5000
	wet_day	y,y-1,y-2	Consecutive wet days index per time	5000 × 5000
Temperature	t_g	y,y-1,y-2	Average of daily mean temperature of the year	5000 × 5000
	t_x_spring	y,y-1,y-2	Maximum of spring temperature of the year	5000 × 5000
	t_x_summer	y,y-1,y-2	Maximum of summer temperature of the year	5000 × 5000
	t_n_spring	y,y-1,y-2	Minimum of spring temperature of the year	5000 × 5000
	temp_ano	y,y-1,y-2	Summer temperature anomaly of the year compared to the 1970–1999 period	5000 × 5000
	dd	y,y-1,y-2	Accumulation of degree-day (basis 8,3°C) with daily mean temperature of the day of the year	5000 × 5000
	frost_day	y,y-1,y-2	Number of frost day	5000 × 5000
Radiation	solar_rad_spring	y,y-1,y-2	Solar radiation of the spring for the year	5000 × 5000
	solar_rad_summer	y,y-1,y-2	Solar radiation of the summer for the year	5000 × 5000
Wind	max_wind	y,y-1,y-2	Maximum of windspeed	5000 × 5000
	wind_speed	y,y-1,y-2	Average windspeed	5000 × 5000
Category III: forest site (soil and topography)				
Soil	soil_depth		Soil depth	10 × 10
	moisture		Soil moisture regime	10 × 10
	water_flow		Water supply	10 × 10
	water_capacity		Soil water capacity	10 × 10
	oxygen_regime		Soil oxygen deficiency	10 × 10
	nutrient_regime		Soil nutrient regime	10 × 10
	farmland_soil		Age of continuous forest cover	10 × 10
Topographic data derived from DTM	alti		Altitude	10 × 10
	topo		Topographic position	10 × 10
	slope		Slope	10 × 10
	thermal_sector		Radiative exposition	10 × 10
	topo_radiation		Potential radiation	10 × 10
Forest site types	forest_site		Forest site types	10 × 10
Category IV: spruce stand				
Maturity	height		Dominant height of the stand (m)	1 × 1
Composition	compo_spruce		Spruce cover in the plot	10 × 10
	compo_bl		Broadleaves cover in the plot	10 × 10
Structure	forest_gap		Gap area in the plot	1 × 1
	forest_edge		Presence of forest edges	10 × 10
Forest Management	asf		African swine fever area	10 × 10
	public_prop		Percentage of public property in the plot	10 × 10
Category V: bark beetle infestation				
	dist_bb_hotspot_minus_1 year		Distance to the previous year's bark beetle hotspot year	10 × 10

the importance of canopy discontinuities in each plot. It has been determined based on the 2016 Digital Surface Model to which we apply a Gaussian smoothing followed by a Sobel filter of the EdgeExtraction application of OTB (Grizonnet et al., 2017). A higher forest edge value indicates a more abundant the canopy discontinuity.

During the 2018–2020 period, the Walloon wild boar population was affected by an outbreak of African swine fever in the southern Ardenne. To prevent the spread of the disease during the summer of 2018 and until 2019, the forest was fenced off and closed to all traffic, including logging activities (Licoppe et al., 2023). These measures have also prevented the sanitary felling that could have controlled the bark beetle's development. The plot is located in an area that is either infected or not infected by African swine fever. Consequently, a binary variable was used.

The percentage of public ownership in the parcel is the percentage of forest area managed by the public service in the forest area of the plot. Indeed, public managers are expected to monitor forest health more closely.

3.4. Bark beetle outbreak

The distance to the previous year's bark beetle hotspot was calculated as the minimum distance between the edge of a plot and the boundary of the nearest pixel identified as a bark beetle hotspot in the previous year. These distances were calculated using Norway spruce health maps from 2017, 2018, and 2019 using a chamfer distance filter.

3.5. Selection of important variables and dieback modelling

After selecting the plots attacked by bark beetles and the plots that remained alive or vital during the disturbance period, potential climatic, site, stand and bark beetle outbreak drivers were extracted for each plot using the terra package in R (Core Team, 2023). For categorial variables (e. g., forest site types), the majority class was retained. The resulting dataset consists of 79 potential drivers for 209,644 observations. The intensity of bark beetle damage serves as the continuous response variable to be explained.

To reduce the number of variables before modelling, a pre-selection was conducted through a correlation analysis (using continuous variables only) with the R package FuzzySim (Barbosa, 2015). The most explanatory were then selected from the remaining continuous variables and the other factorial variables using the R package VSURF (Genuer et al., 2015). VSURF algorithm was used to efficiently select the most relevant variables for prediction, improving model interpretability and performance. VSURF is a variable selection algorithm using multiple random forests designed to identify the most relevant features for prediction. The ranger R package (Wright and Ziegler, 2017) was used as the backend for the VSURF algorithm.

After variable selection, a final random forest model was built with the most predictive remaining variables. To interpret the model, and analyse the variable importance and partial dependencies the DALEX R package (Biecek, 2018) and the hstats R package (Friedman and Popescu, 2008) were used.

3.6. Model validation

The final model was validated through spatial cross-validation using the BlockCV R package (Valavi et al., 2019). Ten folds were considered. The area was split into 94 hexagons, with centres positioned 10,000 m apart (Fig. 4).

4. Results

4.1. Selection of important potential drivers

An analysis of correlations between variables led to the elimination of 24 out of the 79 variables due to high intercorrelation. Following this step, the VSURF algorithm (Genuer et al., 2015) was applied to identify key variables. Two variables from the long-term climate (Category I) and spruce stand (Category IV) categories were retained, while one variable from the inter-annual variation climate (Category II) and bark beetle infestation (Category V) categories was also selected. However, no variable from the forest site category (Category III) was selected. The selected variables, in order of importance included: dominant height (height), the distance to the previous year's bark beetle hotspot (dist_bb_hotspot_minus_1), summer water deficit during the year of attack (petp_5_9_y), the forest edge presence (forest_edge), bioclimatic area (zbio) and the trend of summer P-ETP during the 2010–2021 period (trend2_petp) (Fig. 5).

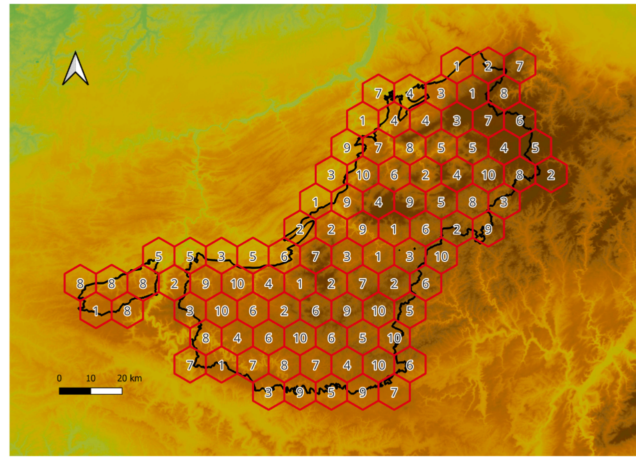

Fig. 4. The study area (Ardenne) is split into 10 folds composed of hexagons in order to test the spatial independence of our Random Forest model predicting intensity of bark beetle damage.

5. Model of damages intensity

The final model achieved an R^2 of 0.37 and the k-fold cross validation confirmed a good performance with R^2 values ranging from 0.233 to 0.438 depending across the 10 folds with an average R^2 of 0.3 ± 0.053 (Table 3).

5.1. Effect of the variables

Spruce damage intensity is strongly influenced by the dominant tree height. Damage remains consistently low and stable for trees with heights up to 15 m. However, as the dominant height approaches 20 m, damage begins to increase noticeably. The intensity of damage seems to reach its highest value for trees exceeding 30 m in height (Fig. 6A).

A second variable influencing spruce mortality in our model is the distance to the previous year's bark beetle hotspot. Damage is most severe in plots located closer to the hotspot, with significant damage observed within 100 m (Fig. 6B).

Climate potential drivers also play a significant role. Lower summer P-ETP values for the year increase damage, with P-ETP below –150 mm. Above –150 mm, the damage level is lower (Fig. 6C). The trend in summer climatic water deficit (P-ETP) during the 2010–2021 period shows that plots with greater decrease are more affected than those with less variation in P-ETP over this period (Fig. 6F). The presence of forest edge increases dieback intensity, and its absence mitigates the damage (Fig. 6D).

Bioclimatic zone of the high plateau of Ardenne has the weakest partial dependence, followed by the central plateau and the low Ardenne (Fig. 6E).

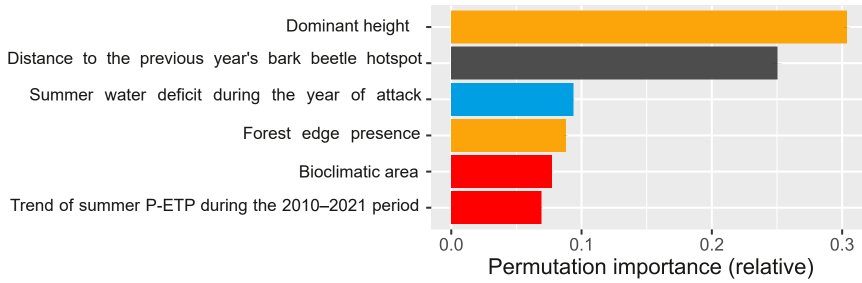

Fig. 5. Relative Permutation importance of the six most important variables selected (importance extracted from the final ranger model). The colours refer to the category of the potential drivers in Table 2 (red: cat I, blue: cat II, orange: cat IV, black: cat V).

Table 3
The R^2 of the model across the different folds.

Folds number	R^2
1	0.288
2	0.303
3	0.337
4	0.312
5	0.233
6	0.285
7	0.438
8	0.273
9	0.284
10	0.302

6. Discussion

The analysis identified several potential drivers from a wide range of potential influencing factors; however, only a limited number were retained in the final model with predictive value for bark beetle attacks in the Ardenne ecoregion. The most relevant variables affecting damage in Norway spruce (*Picea abies*) stands include dominant tree height, proximity to the previous year's bark beetle hotspots, distance to forest edges, summer climatic water deficit (precipitation minus potential evapotranspiration, P–ETP) during the attack year, the trend in climatic water deficit from 2010 to 2021, and the bioclimatic zone. These variables together offer key insights into the spatial and climatic vulnerability of spruce forests to bark beetle infestations.

The Random Forest model predicting area of bark beetle damage achieved a R^2 of 0.37. However, we have confidence in this result. If the use of cartographic variables instead of traditional field measurements may introduce some inaccuracy, this is mitigated by the large number of plots included in the study. The use of remote sensing and GIS tools has resulted in a substantial number of observations, the data balancing and cross-validation process increase the robustness of the model.

However, it is surprising that site potential drivers known to be stressful for spruce, such as soil drought or overexposure to radiation on hot slopes, were not more decisive. The examined variables were not significant predictors of spruce bark beetle attacks in the Ardenne study area. However, drought-related parameters were found to play a notable role in influencing infestation risk. It highlights the limited room for manoeuvre that foresters have to prevent or limit bark beetle outbreaks in established pure spruce stands and the high level of monitoring that such stands require.

6.1. Dominant height

Several studies suggest a positive relationship between Norway spruce dieback and tree height (Kamińska et al., 2021; Kärvemo et al., 2014), a trend that our results also support. In our study, dominant height serves as a proxy for stand age, as taller trees tend to be older. Stand age has been recognized as a critical factor influencing tree mortality in various regions, including the Vosges near the Ardenne (Piedallu et al., 2023), Slovakia (Potterf et al., 2023), the Tatra Mountains (Mezei et al., 2014), and the Białowieża Forest (Kamińska et al., 2021; Stereńczak et al., 2020). Mature Norway spruce trees are particularly vulnerable to bark beetle attacks, as these insects rely on large trees with sufficiently thick phloem to thrive and reproduce successfully (Lausch et al., 2011).

6.2. Distance to the previous year's bark beetle hotspot

Our results confirm that proximity to a previous bark beetle hotspot significantly increases the risk of dieback. While spruce bark beetles are able of flying over several kilometres (Nilsen, 1984;Forsse and Solbreck, 1985; Inward et al., 2024), our results indicate that the highest risk occurs within 100 m of the previous year's outbreak site. This supports the observation that most bark beetles make short flights when potential host trees are abundant nearby, as noted by Kautz et al. (2011) and Wichmann and Ravn (2001). Similar findings were reported by Potterf (2019), who also identified elevated damage within 100 m of active infestations.

This localized damage can also be attributed to adult beetles re-emerging in search of a second host, often flying shorter distances (Zolubas and Byers, 1995) and potentially producing a sister generation nearby. The large number of beetles generated by these sister generations may explain the significant presence of bark beetles near the previous year's hotspots. If infested trees from the prior year are not felled then debarked or removed from the forest, they can serve as a reservoir for an even larger population in the following year.

Additionally, bark beetle attacks near previous hotspots create more favourable microclimatic conditions. If sanitary logging is conducted before swarming, it often results in the creation of new gaps with fresh forest edges within the stand. Norway spruce trees located along these new edges are more vulnerable to fresh bark beetle attacks (Kautz et al., 2013), as the increased temperature and solar radiation create stressful conditions for these trees.

6.3. Forest edge

The impact of forest edges on Norway spruce dieback has been demonstrated in previous research (Mezei et al., 2011; Stříbrská et al., 2022). Edges are areas where trees are more vulnerable to disturbances and stressors, such as wind and solar irradiation (Donis et al., 2018; Jönsson et al., 2007). The microclimatic conditions at forest edges enhance bark beetle dispersal and flight, increase emissions of volatile organic compounds (VOCs) that attract beetles, and weaken tree defence mechanisms (Kautz et al., 2013).

6.4. Summer climatic water deficit (P-ETP) of the attack year

The climatic water deficit during summer is the most impactful climatic variable in the model. During summer, this water deficit is generally associated with heat and drought events that increase evapotranspiration while water availability in the soil is low. These

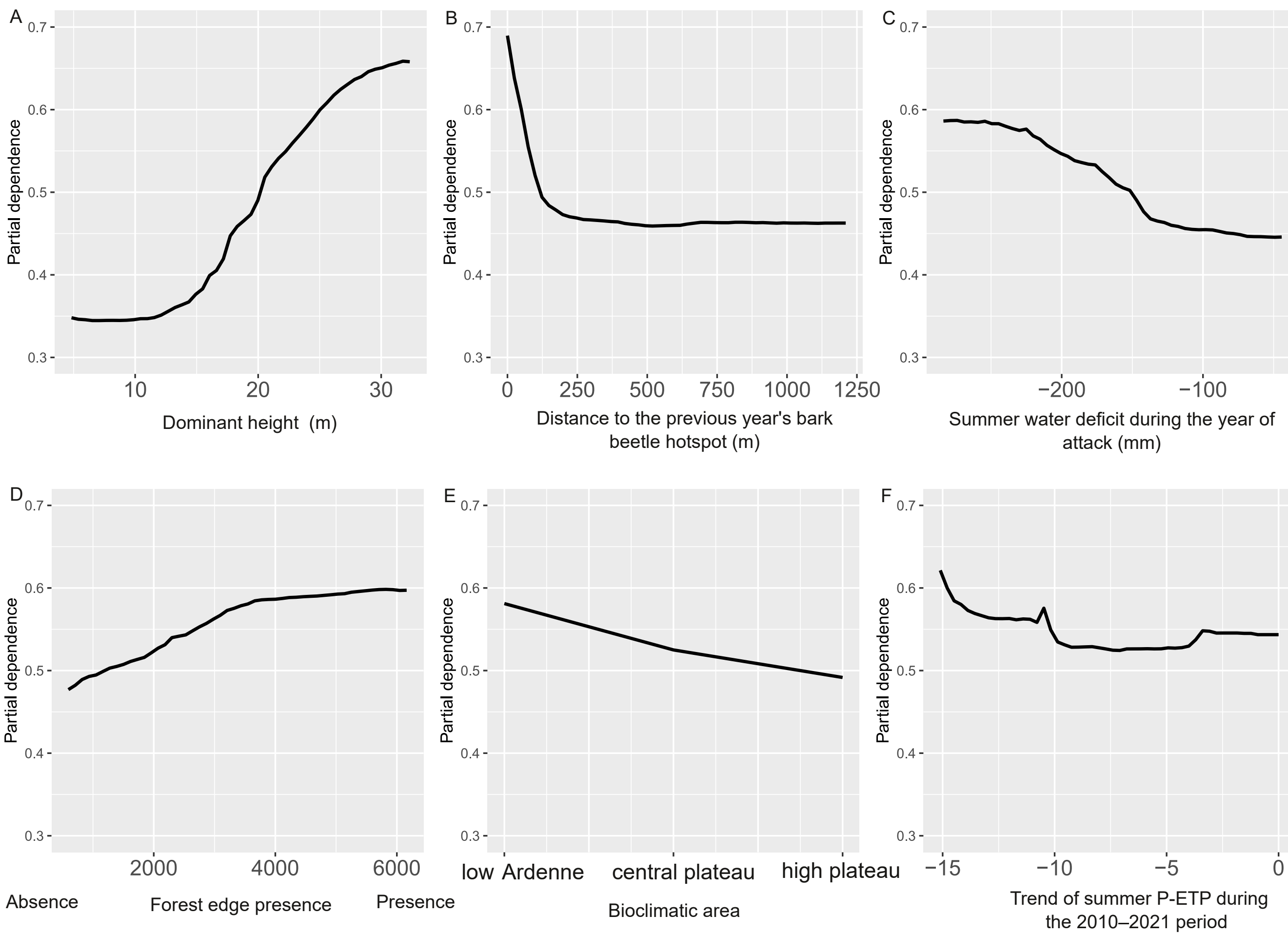

Fig. 6. The following graphs illustrate the partial dependence of bark beetle infestation on the selected variables. Spruce dieback caused by bark beetle attacks increases with greater dominant stand height within the plot (height) and with closer proximity to a bark beetle hotspot from the previous year (bb_hotspot_y_minus1). The presence of forest edge (forest_edge) in the plot increases the dieback intensity. In contrast, dieback intensity tends to decrease with higher current-year (petp_5_9_y) and long-term P-ETP values (trend2_petp), as well as when the plot is located in the High Ardenne region (zbio).

conditions stress the Norway Spruce, increasing emissions of volatile organic compounds (VOCs) that attract beetles, and weaken tree defence mechanisms (Kautz et al., 2013; Netherer et al., 2015, 2019). On the other hand, these warmer conditions favour the development of several generations of bark beetles (Annila, 1969; Baier et al., 2007; Jakoby et al., 2019) and the low precipitation levels allows easy swarming of bark beetle and an increase in flight activity.

6.5. *Trend of the climatic water deficit over the 2010–2021 period*

The trend observed in P-ETP over the 2010–2021 period highlights the accelerating decrease of summer P-ETP over this timeframe. Under conditions of water deficiency, the stands experiencing more intense decrease also exhibit greater damage, indicating that these stands are more severely destabilised. The stress endured by trees under these conditions exacerbates their vulnerability, making them more susceptible and attractive to bark beetles. Piedallu et al. (2023) found similar relationships in the Vosges with other indices that represent the summer soil water deficit.

The variable "Trend2-petp" illustrates the evolution of the climatic water deficit over an eleven-year period. Areas with smaller changes in the climatic water deficit are less affected by bark beetle attack compared to those experiencing significant shifts. Trees in drier forest sites generally exhibit less pronounced climate-related changes than those in wetter forest sites. Norway spruce in drought-prone areas appear to acclimatize to these conditions and suffer less damage (Netherer et al., 2019). Conversely, Norway spruce in wetter, more favourable sites, where the climatic water deficit worsens, tend to experience greater damage (Nardi et al., 2023).

6.6. *Bioclimatic zones*

The Ardenne region is divided into three bioclimatic zones defined by a combination of potential climatic drivers associated with orographic effects (Van der Perre et al., 2015): the high plateau, above 500 m in altitude with a climate showing a significant montane trend, the central plateau, and the low Ardenne with a milder Atlantic climate.

The colder climate of the high plateau is more favourable for Norway spruce and less hospitable for bark beetles. Conversely, heat waves are more severe in the milder climate of the low Ardenne.

However, the majority of the Norway spruce stands of the Ardenne are located above 400 m in altitude (central plateau) and are less affected by extreme heat waves than those in the low Ardenne (Gilles et al., 2024). Moreover, the public forest districts, located at the higher altitudes are experienced in managing large areas of spruce, with a well-established tradition of proactive health management strategies that limit bark beetle development. These strategies include early detection with regular marking of affected trees, followed by their rapid felling and removal. This proactivity in the higher altitude districts may also help explain the lower damage observed at this altitude.

6.7. Management guidelines

Our analysis of bark beetle outbreaks due to the extreme climatic conditions during the 2017–2020 period which were stressful for Norway spruce highlighted some local potential drivers favouring bark beetle attacks. However, their influence on damage is secondary to the severe climatic events, such as high temperatures or high climatic water deficit, which are assumed to have both weakened spruce and favoured bark beetle outbreaks. Forest managers therefore have little room for manoeuvre, but they can control some of the identified predisposing factors.

Old stands in the study area were significantly more susceptible to bark beetle attack, especially trees over 30 m tall. It is advisable to limit the age at which spruce trees must be harvested, especially as it limits the period during which they are exposed to the risk of ever-increasing climatic hazards. Moreover, spruce trees close to bark beetle hotspots are at high risk of being affected, especially within a radius of a hundred metres. This means that affected trees must be identified by monitoring and quickly removed from the forest before the beetle's emergence. This should help to limit the extent of the outbreak and the resulting economic losses. The presence of forest edges also increases the intensity of damage. Stands with canopy discontinuities should be prioritized for monitoring to detect trees attacked by bark beetles and to ensure windthrown trees are removed before spring.

Additionally, climatic conditions are reliable indicators of bark beetle outbreak risks. Our study showed that a summer P-ETP below -150 mm is associated with a high outbreak potential. Furthermore, the P-ETP trend from 2010 to 2021 indicates that stands subjected to an increasing summer water deficit trend experience greater damage compared to those in regions with more stable summer water deficit conditions.

Regarding the effect of mesoclimatic region (bioclimatic area) on the impact of bark beetle attacks, further preservation of spruce monocultures is discouraged in low Ardenne. On the central and high plateaus, spruce stands have held up relatively well against the bark beetle attacks of the 2017–2020 period, although some of this resilience appears to be due to close stand monitoring and prompt felling of attacked trees.

All these high-risk situations call for careful monitoring to promptly detect the presence of bark beetle attacks, especially when weather conditions are favourable for the development of insect populations. Forest monitoring and hygiene then become essential to limit the impact of a bark beetle outbreak.

To increase the resilience of the Ardenne Forest to climate change, a significant change in forest management is needed to transform the spruce monocultures into structurally and species-rich mixed forests (Jactel et al., 2021).

Nevertheless, considering climate change, it is clear that all these risks will increase in the future, and that the suitable altitudinal limit for spruce forestry will move towards the Ardenne high plateau over the next few decades. Gradually, climate and bark beetles will act together to weaken spruce stands and complicate their silviculture in the Ardenne, as several models have already predicted for the end of this century (Falk and Hempelmann, 2013; Hanewinkel et al., 2013).

7. Conclusion

The relationships between potential climatic, environmental and silvicultural drivers and forest dieback are a complex subject of study, which continues to emerge from one bark beetle outbreak to the next. However, advances in remote sensing technologies for forest dieback characterisation and forest environment modelling now make it possible to carry out comprehensive research over entire regions. The Ardenne region is gathering all the necessary conditions to conduct a study aimed at analysing the main potential drivers contributing to spruce dieback between 2018 and 2020. Remote sensing is a powerful tool for understanding the complex causes and patterns of forest dieback.

During the drought event of 2018 and 2020, spruce forests in the Ardenne experienced significant dieback, as revealed by damage mapping using Sentinel-2 imagery. This mapping helped highlight a number of key variables that can help foresters to manage bark beetle attacks expected during the future severe climatic events. Indeed, although climatic events were the main cause of mortality, there are also some stand characteristics that predispose trees to bark beetle attacks. At the same time, it is essential to monitor existing pure stands and remove attacked trees immediately in order to prevent outbreaks from spiralling out of control. A new management approach for spruce stands, favouring mixed and structurally diverse compositions, is needed particularly at lower altitudes.

CRediT authorship contribution statement

Nicolas Latte: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Jonathan Lisein:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Hugues Claessens:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition. **Arthur Gilles:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation.

Funding

The work was financially supported by the Plan quinquennal de recherches forestières of the Service Public de Wallonie (forest administration).

Declarations

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

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.

Acknowledgements

This research has been funded thanks to the five-year forestry research plan of the Public Service of Wallonia (forest administration).

Data availability

Data will be made available on request.

References

Alderweireld, M., Burnay, F., & Pitchugin, M. (avec Blerot, P.). 2015. Inventaire forestier wallon résultats 1994-2012. SPW DGO DNF Direction des Ressources forestières.
Annila, E., 1969. Influence of temperature upon the development and voltinism of ips typographus L.(Coleoptera, Scolytidae). Ann. Zool. Fenn. 161–208.
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. For. Ecol. Manag. 249 (3), 171–186.
Barbey, A., 1923. La Forêt européenne et sa résistance aux attaques des insectes ravageurs. Rev. De. Bot. Appliquée Et. D. 'Agric. Colonia 3 (25), 593–604. https://doi.org/10.3406/jatba.1923.4101.
Barbosa, A.M., 2015. Fuzzysim: applying fuzzy logic to binary similarity indices in ecology. Methods Ecol. Evol. 6 (7), 853–858. https://doi.org/10.1111/2041-210X.12372.

Bárta, V., Lukeš, P., Homolová, L., 2021. Early detection of bark beetle infestation in Norway spruce forests of central Europe using Sentinel-2. Int. J. Appl. Earth Obs. Geoinf. 100, 102335.
Berryman, A.A., 1978. Towards a theory of insect epidemiology. Popul. Ecol. 19 (2), 181–196. https://doi.org/10.1007/BF02518826.
Biecek, P., 2018. DALEX: explainers for complex predictive models in r. J. Mach. Learn. Res. 19 (84), 1–5.
Bolyn, C., Lejeune, P., Michez, A., Latte, N., 2022. Mapping tree species proportions from satellite imagery using spectral–spatial deep learning. Remote Sens. Environ. 280, 113205. https://doi.org/10.1016/j.rse.2022.113205. ISSN 0034-4257.
Carle, P., 1975. Dendroctonus micans kug. (Col. Scolytidae), l'Hylésine géant Ou dendroctone de l'Epicéa (note bibliographique). Rev. For. ère Française (2), 115. https://doi.org/10.4267/2042/20924.
Christiansen, E., Waring, R.H., Berryman, A.A., 1987. Resistance of conifers to bark beetle attack: searching for general relationships. For. Ecol. Manag. 22 (1-2), 89–106. https://doi.org/10.1016/0378-1127(87)90098-3.
Dalponte, M., Solano-Correa, Y.T., Frizzera, L., Gianelle, D., 2022. Mapping a european spruce bark beetle outbreak using Sentinel-2 remote sensing data. Remote Sens. 14 (13), 3135.
Deganutti, L., Biscontin, F., Bernardinelli, I., Faccoli, M., 2024. The semiochemical push-and-pull technique can reduce bark beetle damage in disturbed Norway spruce forests affected by the vaia storm. Agric. For. Entomol. 26 (1), 115–125. https://doi.org/10.1111/afe.12600.
Delatour, C., 1972. Le fomes annosus. Rev. For. ère Française 1, 20. https://doi.org/10.4267/2042/20586.
Dobor, L., Hlásny, T., Rammer, W., Zimová, S., Barka, I., Seidl, R., 2020. Spatial configuration matters when removing windfelled trees to manage bark beetle disturbances in central european forest landscapes. J. Environ. Manag. 254, 109792. https://doi.org/10.1016/j.jenvman.2019.109792.
Donis, J., Kitenberga, M., Snepsts, G., Dubrovskis, E., Jansons, A., 2018. Factors affecting windstorm damage at the stand level in hemiboreal forests in Latvia: case study of 2005 winter storm. Silva Fenn. 52 (4). https://doi.org/10.14214/sf.10009.
Faccoli, M., 2009. Effect of weather on *Ips* typographus (Coleoptera Curculionidae) phenology, voltinism, and associated spruce mortality in the southeastern Alps. Environ. Entomol. 38 (2), 307–316. https://doi.org/10.1603/022.038.0202.
Falk, W., Hempelmann, N., 2013. Species favourability shift in Europe due to climate change: a case study for *Fagus* sylvatica L. And *Picea* abies (L.) karst. Based on an ensemble of climate models. J. Climatol. 2013, 1–18. https://doi.org/10.1155/2013/787250.
Forsse, E., Solbreck, C.H., 1985. Migration in the bark beetle ips typographus L.: duration, timing and height of flight. Z. F. üR. Angew. Èntomol. 100 (1-5), 47–57. https://doi.org/10.1111/j.1439-0418.1985.tb02756.x.
Friedman, J.H., Popescu, B.E., 2008. Predictive learning via rule ensembles. Ann. Appl. Stat. 2 (3), 916–954. https://doi.org/10.1214/07-AOAS148.
Genuer, R., Poggi, J.-M., Tuleau-Malot, C., 2015. VSURF: an r package for variable selection using random forests. R. J. 7 (2), 19. https://doi.org/10.32614/RJ-2015-018.
Gilles, A., Lisein, J., Cansell, J., Latte, N., Piedallu, P., Claessens, H., 2024. Spatial and remote sensing monitoring shows the end of the bark beetle outbreak on Belgian and north-eastern France Norway spruce (Picea abies) stands. Environ. Monit. Assess. 196 (3), 226. https://doi.org/10.1007/s10661-024-12372-0.
Grégoire, J.-C., De Proft, M., 1996. Protection des forêts contre l'Ips typographus. Minist. ère De. la Région Wallon DGRNE 17.
Grizonnet, M., Michel, J., Poughon, V., Inglada, J., Savinaud, M., Cresson, R., 2017. Orfeo ToolBox: open source processing of remote sensing images. Open Geospatial Data Softw. Stand. 2 (1), 15.
Hanewinkel, M., Cullmann, D.A., Schelhaas, M.-J., Nabuurs, G.-J., Zimmermann, N.E., 2013. Climate change May cause severe loss in the economic value of european forest land. Nat. Clim. Change 3 (3), 203–207.
Hlásny, T., König, L., Krokene, P., Lindner, M., Montagné-Huck, C., Müller, J., Qin, H., Raffa, K.F., Schelhaas, M.-J., Svoboda, M., Viiri, H., Seidl, R., 2021. Bark beetle outbreaks in Europe: state of knowledge and ways forward for management. Curr. For. Rep. 7 (3), 138–165. https://doi.org/10.1007/s40725-021-00142-x.
Hroššo, B., Mezei, P., Potterf, M., Majdák, A., Blaženec, M., Korolyova, N., Jakuš, R., 2020. Drivers of spruce bark beetle (Ips typographus) infestations on downed trees after severe windthrow. Forests 11 (12), 1290.
Inward, D.J.G., Caiti, E., Barnard, K., Hasbroucq, S., Reed, K., Grégoire, J.-C., 2024. Evidence of cross-channel dispersal into england of the forest pest ips typographus. J. Pest Sci. https://doi.org/10.1007/s10340-024-01763-4.
Jactel, H., Moreira, X., Castagneyrol, B., 2021. Tree diversity and forest resistance to insect pests: patterns, mechanisms, and prospects. Annu. Rev. Entomol. 66 (1), 277–296.
Jakoby, O., Lischke, H., Wermelinger, B., 2019. Climate change alters elevational phenology patterns of the european spruce bark beetle (Ips typographus). Glob. Change Biol. 25 (12), 4048–4063. https://doi.org/10.1111/gcb.14766.
Jakuš, R., 1995. Bark beetle (Col., Scolytidae) communities and host and site factors on tree level in Norway spruce primeval natural forest. J. Appl. Entomol. 119 (1-5), 643–651.
Jakuš, R., Modlinger, R., Kašpar, J., Majdák, A., Blaženec, M., Korolyova, N., Jirošová, A., Schlyter, F., 2022. Testing the efficiency of the Push-and-Pull strategy during severe ips typographus outbreak and extreme drought in Norway spruce stands. Forests 13 (12), 2175. https://doi.org/10.3390/f13122175.
Jansen, S., Konrad, H., Geburek, T., 2017. The extent of historic translocation of Norway spruce forest reproductive material in Europe. Ann. For. Sci. 74 (3), 56. https://doi.org/10.1007/s13595-017-0644-z.
Jönsson, M.T., Fraver, S., Jonsson, B.G., Dynesius, M., Rydgård, M., Esseen, P.-A., 2007. Eighteen years of tree mortality and structural change in an experimentally fragmented Norway spruce forest. For. Ecol. Manag. 242 (2-3), 306–313. https://doi.org/10.1016/j.foreco.2007.01.048.
Journée, M., Ingels, R., & Bertrand, C. 2019. Observational gridded data products in Belgium.
Kamińska, A., Lisiewicz, M., Kraszewski, B., Stereńczak, K., 2021. Mass outbreaks and factors related to the spatial dynamics of spruce bark beetle (Ips typographus) dieback considering diverse management regimes in the Białowieża forest. For. Ecol. Manag. 498, 119530. https://doi.org/10.1016/j.foreco.2021.119530.
Kärvemo, S., Rogell, B., Schroeder, M., 2014. Dynamics of spruce bark beetle infestation spots: importance of local population size and landscape characteristics after a storm disturbance. For. Ecol. Manag. 334, 232–240. https://doi.org/10.1016/j.foreco.2014.09.011.
Kautz, M., Dworschak, K., Gruppe, A., Schopf, R., 2011. Quantifying spatio-temporal dispersion of bark beetle infestations in epidemic and non-epidemic conditions. For. Ecol. Manag. 262 (4), 598–608. https://doi.org/10.1016/j.foreco.2011.04.023.
Kautz, M., Schopf, R., Ohser, J., 2013. The "sun-effect": microclimatic alterations predispose forest edges to bark beetle infestations. Eur. J. For. Res. 132 (3), 453–465. https://doi.org/10.1007/s10342-013-0685-2.
Kervyn, T., Jacquemin, F., Branquart, É., Delahaye, L., Dufrêne, M., & Claessens, H. 2014. Les forêts anciennes en wallonie 2ème partie: cartographie.
Klimo, E., 2000. Spruce Monocultures in Central Europe: Problems and Prospects. European Forest Institute.
Kuhn, A., Hautier, L., San Martin, G., 2022. Do pheromone traps help to reduce new attacks of *Ips* typographus at the local scale after a sanitary cut? PeerJ 10, e14093.
Lausch, A., Fahse, L., Heurich, M., 2011. Factors affecting the spatio-temporal dispersion of ips typographus (L.) in bavarian forest national park: a long-term quantitative landscape-level analysis. For. Ecol. Manag. 261 (2), 233–245. https://doi.org/10.1016/j.foreco.2010.10.012.
Legrain, X., Bock, L., Colinet, G., 2014. Suitability of the soil map and legacy data in wallonia (BE) to support the GSM initiative. Glob. Basis Glob. Spat. Soil Inf. Syst. Proc. 1st Glob. Conf. 99–102. https://doi.org/10.1201/b16500-21.
Lévieux, J., Lieutier, F., Delplanque, A., 1985. Les scolytes ravageurs de l'Epicéa. Rev. For. ère Française 5, 347. https://doi.org/10.4267/2042/21822.
Licoppe, A., De Waele, V., Malengreaux, C., Paternostre, J., Van Goethem, A., Desmecht, D., Herman, M., Linden, A., 2023. Management of a focal introduction of ASF virus in wild boar: the Belgian experience. Pathogens 12 (2), 152. https://doi.org/10.3390/pathogens12020152.
Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., Lexer, M.J., Marchetti, M., 2010. Climate change impacts, adaptive capacity, and vulnerability of european forest ecosystems. For. Ecol. Manag. 259 (4), 698–709.
Lisein, J., Fayolle, A., Legrain, A., Prévot, C., Claessens, C., 2022. Prediction of forest nutrient and moisture regimes from understory vegetation with random forest classification models. Ecol. Indic. 144, 109446. https://doi.org/10.1016/j.ecolind.2022.109446.
Marini, L., Økland, B., Jönsson, A.M., Bentz, B., Carroll, A., Forster, B., Grégoire, J.-C., Hurling, R., Nageleisen, L.M., Netherer, S., Ravn, H.P., Weed, A., Schroeder, M., 2017. Climate drivers of bark beetle outbreak dynamics in Norway spruce forests. Ecography 40 (12), 1426–1435. https://doi.org/10.1111/ecog.02769.
Mezei, P., Grodzki, W., Blaženec, M., Škvarenina, J., Brandýsová, V., Jakuš, R., 2014. Host and site factors affecting tree mortality caused by the spruce bark beetle (Ips typographus) in mountainous conditions. For. Ecol. Manag. 331, 196–207.
Mezei, P., Jakuš, R., Blaženec, M., Belánová, S., Šmídt, J., 2011. Population dynamics of spruce bark beetle in a nature reserve in relation to stand edges conditions. Folia Oecologica 38, 73–79.
Mezei, P., Jakuš, R., Pennerstorfer, J., Havašová, M., Škvarenina, J., Ferenčík, J., Slivinský, J., Bičárová, S., Bilčík, D., Blaženec, M., Netherer, S., 2017. Storms, temperature maxima and the eurasian spruce bark beetle ips typographus—An infernal trio in Norway spruce forests of the central european high tatra mountains. Agric. For. Meteorol. 242, 85–95. https://doi.org/10.1016/j.agrformet.2017.04.004.
Nardi, D., Jactel, H., Pagot, E., Samalens, J., Marini, L., 2023. Drought and stand susceptibility to attacks by the european spruce bark beetle: a remote sensing approach. Agric. For. Entomol. 25 (1), 119–129. https://doi.org/10.1111/afe.12536.
Netherer, S., Matthews, B., Katzensteiner, K., Blackwell, E., Henschke, P., Hietz, P., Pennerstorfer, J., Rosner, S., Kikuta, S., Schume, H., Schopf, A., 2015. Do water-limiting conditions predispose Norway spruce to bark beetle attack? New Phytol. 205 (3), 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. Front. For. Glob. Change 2, 39. https://doi.org/10.3389/ffgc.2019.00039.
Nilsen, A. 1984. Long-range aerial dispersal of bark beetles and bark weevils (Coleoptera, Scolytidae and Curculionidae) in northern Finland. 50, 37-42.
Patacca, M., Lindner, M., Lucas-Borja, M.E., Cordonnier, T., Fidej, G., Gardiner, B., Hauf, Y., Jasinevičius, G., Labonne, S., Linkevičius, E., Mahnken, M., Milanovic, S., Nabuurs, G., Nagel, T.A., Nikinmaa, L., Panyatov, M., Bercak, R., Seidl, R., Ostrogović Sever, M.Z., Schelhaas, M., 2023. Significant increase in natural disturbance impacts on european forests since 1950. Glob. Change Biol. 29 (5), 1359–1376. https://doi.org/10.1111/gcb.16531.
Piedallu, C., Dallery, D., Bresson, C., Legay, M., Gégout, J.-C., Pierrat, R., 2023. Spatial vulnerability assessment of silver fir and Norway spruce dieback driven by climate warming. Landsc. Ecol. 38 (2), 341–361. https://doi.org/10.1007/s10980-022-01570-1.

Potterf, M., Nikolov, C., Kočická, E., Ferenčík, J., Mezei, P., Jakuš, R., 2019. Landscape-level spread of beetle infestations from windthrown- and beetle-killed trees in the non-intervention zone of the tatra national park, Slovakia (Central Europe). For. Ecol. Manag. 432, 489–500. https://doi.org/10.1016/j.foreco.2018.09.050.

Potterf, M., Svitok, M., Mezei, P., Jarčuška, B., Jakuš, R., Blaženec, M., Hlásny, T., 2023. Contrasting Norway spruce disturbance dynamics in managed forests and strict forest reserves in Slovakia. Forestry 96 (3), 387–398. https://doi.org/10.1093/forestry/cpac045.

R Core Team. 2023. R: A Language and Environment for Statistical Computing [Logiciel]. R Foundation for Statistical Computing.

Saintonge, F.-X., Gillette, M., Blaser, S., Queloz, V., Leroy, Q., 2022. Situation et gestion de la crise liée aux scolytes de l'Épicéa commun fin 2021 dans l'est de la France, en suisse et en wallonie. Rev. For. ère française 73 (6), 619–641. https://doi.org/10.20870/revforfr.2021.7201.

Schulzweida, U., 2023, octobre). CDO User Guide (Version 2.3.0). Zenodo. https://doi.org/10.5281/zenodo.10020800.

Schulzweida, U., Quast, R., 2015. Clim. Indices CDO, ⟨https://earth.bsc.es/gitlab/ces/cdo/raw/b4f0edf2d5c87630ed4c5ddee5a4992e3e08b06a/doc/cdo_eca.pdf⟩.

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. For. Ecol. Manag. 256 (3), 209–220. https://doi.org/10.1016/j.foreco.2008.04.002.

Seidl, R., Schelhaas, M., Lexer, M.J., 2011. Unraveling the drivers of intensifying forest disturbance regimes in Europe. Glob. Change Biol. 17 (9), 2842–2852. https://doi.org/10.1111/j.1365-2486.2011.02452.x.

Seidl, R., Schelhaas, M.-J., Lindner, M., Lexer, M.J., 2009. Modelling bark beetle disturbances in a large scale forest scenario model to assess climate change impacts and evaluate adaptive management strategies. Reg. Environ. Change 9 (2), 101–119. https://doi.org/10.1007/s10113-008-0068-2.

Spiecker, H., 2003. Silvicultural management in maintaining biodiversity and resistance of forests in Europe—Temperate zone. J. Environ. Manag. 67 (1), 55–65. https://doi.org/10.1016/S0301-4797(02)00188-3.

Stadelmann, G., Bugmann, H., Meier, F., Wermelinger, B., Bigler, C., 2013. Effects of salvage logging and sanitation felling on bark beetle (Ips typographus L.) infestations. For. Ecol. Manag. 305, 273–281.

Stereńczak, K., Mielcarek, M., Kamińska, A., Kraszewski, B., Piasecka, Ż., Miścicki, S., Heurich, M., 2020. Influence of selected habitat and stand factors on bark beetle ips typographus (L.) outbreak in the Bia\textbackslashtextbackslashlowieża forest. For. Ecol. Manag. 459, 117826.

Stříbrská, B., Hradecký, J., Čepl, J., Tomášková, I., Jakuš, R., Modlinger, R., Netherer, S., Jirošová, A., 2022. Forest margins provide favourable microclimatic niches to swarming bark beetles, but Norway spruce trees were not attacked by ips typographus shortly after edge creation in a field experiment. For. Ecol. Manag. 506, 119950. https://doi.org/10.1016/j.foreco.2021.119950.

Tossens, S., Lisein, J., Cordier, S., Claessens, H., 2024. Guide Des. Stations For. èRes D. 'Ardenne.

Trubin, A., Mezei, P., Zabihi, K., Surový, P., Jakuš, R., 2022. Northernmost european spruce bark beetle ips typographus outbreak: modelling tree mortality using remote sensing and climate data. For. Ecol. Manag. 505, 119829.

Valavi, R., Elith, J., Lahoz-Monfort, J.J., Guillera-Arroita, G., 2019. Methods Ecol. Evol.10222523210.1111/2041-210X.13107.

Van der Perre, R., Bythell, S., Bogaert, P., Claessens, H., Ridremont, F., Tricot, C., Vincke, C., Ponette, Q., 2015. La carte bioclimatique de wallonie: un nouveau découpage écologique du territoire pour le choix des essences forestières. *forêt.* Nature 135, 47–58.

Wahlman, W., Kasanen, R., Lappalainen, L., Honkaniemi, J., 2025. Root rot increases the vulnerability of Norway spruce trees to ips typographus infestation. For. Ecol. Manag. 577, 122409. https://doi.org/10.1016/j.foreco.2024.122409.

Wichmann, L., Ravn, H.P., 2001. The spread of ips typographus (L.) (Coleoptera, Scolytidae) attacks following heavy windthrow in Denmark, analysed using GIS. For. Ecol. Manag. 148 (1-3), 31–39. https://doi.org/10.1016/S0378-1127(00)00477-1.

Wright, M.N., Ziegler, A., 2017. *r*anger: a fast implementation of *r*andom forests for high dimensional data in C++ and *r*. J. Stat. Softw. 77 (1). https://doi.org/10.18637/jss.v077.i01.

Zolubas, P., Byers, J.A., 1995. Recapture of dispersing bark beetle ips typographus L. (Col., Scolytidae) In pheromone-baited traps: regression models. J. Appl. Entomol. 119 (1-5), 285–289.