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RESEARCH

Spatial and remote sensing monitoring shows the end of the bark beetle outbreak on Belgian and north-eastern France Norway spruce (*Picea abies*) stands

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Abstract In 2022, Europe emerged from eight of the hottest years on record, leading to significant spruce mortality across Europe. The particularly dry weather conditions of 2018 triggered an outbreak of bark beetles (*Ips typographus*), causing the loss of thousands of hectares of Norway spruce stands, including in Wallonia and North-eastern France. A methodology for detecting the health status of spruce was developed based on a dense time series of satellite imagery (Sentinel-2). The time series of satellite images allowed the modelling of the spectral response of healthy spruce forests over the seasons: a decrease in photosynthetic activity of the forest canopy causes deviations from this normal seasonal vegetation index trajectory. These anomalies are caused by a bark beetle attack and are detected automatically. The method leads in the production of an annual spruce health map of Wallonia and Grand-Est. The goal of this paper is to assess the damage caused by bark beetle using the resulting spruce health maps. A second objective was to compare the influence of basic variables on the mortality of spruce trees in these two regions. Lasted 6 years (2017–2022), bark beetle has destroyed 12.2% (23,674 ha) of the spruce area in Wallonia and Grand-Est of France. This study area is composed of three bioclimatic areas: Plains, Ardennes and Vosges, which have not been equally affected by bark beetle attacks. The plains were the most affected, with 50% of spruce forests destroyed, followed by the Ardennes, which lost 11.3% of its spruce stands. The Vosges was the least affected bioclimatic area, with 5.6% of spruce stands lost. For the most problematic sites, Norway spruce forestry should no longer be considered.

Keywords Norway spruce · Species vulnerability · Bark beetle · Forest management · Forest site · Topographic condition · Time series · Sentinel-2

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Introduction

Global changes are increasing the risk of disturbances in the forest environment: frequency and intensity of abiotic events (fire, storm, drought) and health problems (diseases and pest invasion) will be more recurrent (Lindner et al., 2010). In Western Europe, we expect a decrease in precipitation and an increase in drought events during the vegetation period, which will impact the actual geographic distribution of tree species (Hanewinkel et al., 2013). In this context,

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Norway spruce (*Picea abies L. Karst*) which is one of the most important economic forest species in Europe (Nystedt et al., 2013) is also one of the most triggered species. Indeed, this species is very sensitive to water shortage (Modrzyński, 2007) and lack of water induces stress that affects the growth and health of the tree. Moreover, its major pest, the bark beetle, causes important outbreaks after storm, which provide breeding material, e.g. windfalls, or after severe droughts that weaken trees. A recent bark beetle outbreak, triggered by the exceptionally hot and dry weather of 2018, occurred in Western Europe. It has highlighted the need of improving our understanding of both Norway spruce and bark beetle autecology and synecology for minimizing the impact of bark beetle on spruce stands with adapted management methods. It should concern the monitoring of the bark beetle population and early detection of attacks on trees as well as adapted silvicultural methods and adequate species composition of future forest, especially for the thousand hectares of clear-cut stands decimated by bark beetle attacks.

The Norway spruce is a native species of the boreal or mountainous climates of Europe. It is naturally present at the highest altitude in the Vosges mountains, but it has also been successfully planted out of its native range on warmer sites of low altitude in the Grand-Est (France) and Wallonia (Belgium) during the nineteenth and twentieth centuries (Guinier, 1959; Noirfalise & Thill, 1975). The massive reforestations occurring at this period have led to the formation of large pure even-aged stands. It usually develops a taproot system with fine roots in a shallow depth, although the rooting system can adapt its configuration in constrained soil conditions (Köstler et al., 1968; Puhe, 2003). Stressed Norway spruce produces volatile compounds which attract bark beetles, making itself more susceptible to pest attack (Netherer et al., 2015, 2021). Bark beetles, in particular the species *Ips typographus*, are ubiquitous in the forest, and their populations are generally low (endemic phase) without producing damage to healthy trees. However, the large number of stressed trees causes a shift to an epidemic phasis with an explosion of bark beetle populations during which even healthy trees are massively attacked (Kautz et al., 2014).

The life cycle of bark beetle depends on temperature and photoperiod (Annila, 1969; Baier et al., 2007). In Northern Europe, the bark beetle is univoltine (one single generation), but it is multivoltine (breed two or even three generations) in Western and Central Europe (Annila, 1969). After spring swarming, the adult enters the bark and burrow wood to make a brood gallery where they mate and lay the eggs that mature into larvae in the phloem (Hlásny et al., 2021). The bark beetle adult can re-emerge and swarm a second time to give birth to one sister brood (Zolubas & Byers, 1995). After the larvae maturation that lasts about 7 weeks (Baier et al., 2007), the new generation of beetles emerges and attacks the direct surrounding trees (Zolubas & Byers, 1995). Attacked trees defend themselves by pulsing resin to kill the bark beetle, but these defences failed to resist again numerous simultaneous attacks that induce their decline and rapid death.

The Norway spruce dieback goes through three physiological stages which are denominated green, red and grey stage. During the green stage, the bark beetle has succeeded in penetrating the phloem, and the spruce retains its green needles. The tree is still alive but begins to suffer from water shortage caused by sap conduction problem. After several weeks, the red stage is reached when the needles turn brown–red. After death, the dry needles start to fall. When all the needles have fallen off and the trunk bark has turned grey, the grey stage is reached (Abdullah et al., 2018). To control the infestation of bark beetle, the practical solutions are limited. Pheromone trap systems are commercialized to fight bark beetle, but they failed to limit the economic loss in case of large outbreak (Kuhn et al., 2022). The only solution to limit the bark beetle population and its associated damages is to fall and remove each attacked tree at the green stage, before the swarming. These cuts remove the ideal breeding material for bark beetles and beetles inside trees from the forest.

The European Union's earth observation programme, with its satellite twin constellation Sentinel-2A and Sentinel-2B, provides free earth imagery with a high revisit time, which has been intensively used for forestry purposes. Time series of Sentinel-2 (S2) images enable to model the phenology courses of vegetation indices in order to detect forest disturbances (Löw & Koukal, 2020), like the one caused by bark beetle outbreaks. Infestation maps of the last sanitary outbreak have been generated for Germany (Ali et al., 2021; König et al., 2023; Thonfeld et al., 2022), the Czech Republic (Bárta et al., 2021), Italy (Dalponte et al., 2022), and France (Nardi et al., 2023). This paper aims to assess the spatial and temporal evolution of the bark beetle outbreak during the 2017–2022 period in the 195,000 ha of the Walloon and Grand-Est spruce forests. To this end, we map Norway spruce dieback using S2 time series. Then, we analyse the relationship between the damage intensity and environmental parameters, such as altitude and topography, to determine the most sensitive forest sites where forest managers should prioritize their attention.

Material and methods

Study area

The study area includes Wallonia (south of Belgium) and the Grand-Est region (north-east of France). The Walloon Forest covers 554,600 ha, and Norway spruce stands occupy a quarter of the area (Lejeune et al., 2022). The Norway spruce covers 7% of the 1,939,000 ha of the Grand-Est forest (IGN-Inventaire forestier national français, 2022). Both neighbour countries share some similar environmental conditions. They are included in the temperate oceanic bioclimatic zone (Lindner et al., 2010). However, at a finest scale, 24 ecoregions have been defined, mainly by climate and soil parameters, influencing tree species distributions (Walthert & Meier, 2017). To better analyse the dieback of Norway spruce, the French and Walloon ecoregions have been grouped into three main regions (Fig. 1) according to averages of temperature and precipitation during the growing season (May to September) of the 1991–2020 period and to expert knowledge. The climate variables were provided by the Royal Meteorological Institute of Belgium for Wallonia and from the climate maps Digitalis for the Grand-Est (Piedallu et al., 2014). We summarized the recent climate for these three bioclimatic areas by means of the annual precipitation and the longest drought events by determining the largest number of consecutive dry days according to Schulzweida and Quast (2015) with climate data from the ECA-D (Cornes et al., 2018). The data collection methods in Belgium differ from those employed in France, making their use complicated. Fortunately, the European Climate Assessment & Dataset (ECAD) provides harmonized data for the entire Europe. However, the quality of these data is debatable. Temperature data is consistent, but precipitation data is less precise. Indeed, the number of weather stations used in Belgium for ECAD precipitation modelling is limited, and precipitation interpolation provides inadequate results because the precipitation pattern shows strong spatial variations on a fine scale.

The majority of Ardenne and Vosges spruce forests are located above 400 m in altitude, while in the plains, they are predominantly found below 300 m (Fig. 2A). The Ardenne spruce forest is less mixed compared to the Vosges and plain spruce forests (Fig. 2B).

The regional climate is locally influenced by topography (De Frenne et al., 2021). South-facing slopes are warmer and drier and their temperature difference between day and night are higher than the North-facing ones. Three topographic exposures have been determined using the Delvaux and Galoux (1962) definition. Flat areas have a gentle slope of less than 20% and a valley floor that does not create a particular local climate. Comparatively to flat areas, north-facing orientations are slopes higher than 20% facing north (285 to 125°) with colder and more shade conditions. South-facing orientations are slopes higher than 20% facing south (125 to 285°) with a warmer local climate. The digital elevation model (DEM) data from the Copernicus Land Monitoring Service (Copernicus DEM, 2016) at a resolution of 25 m have been used for altitude and topographic exposures maps.

Sentinel 2 imagery

S2 satellites carry multispectral sensor with a ground resolution of up to 10 m. Bottom of atmosphere reflectance images (L2A product) were downloaded from the Theia data cluster (Theia, 2022) for all the 14 tiles of 100 km × 100 km covering our study area (Fig. 3), from 1st January 2016 to 28 February 2023, provided that the cloud cover does not exceed 35%.

Focus on spruce stands

The first prerequisite to assess spruce dieback was to map the species distribution at a fine scale. For the south of Belgium (Wallonia), we used reliable composition maps from Bolyn et al., (2022), in order to restrict our analysis to Norway spruce stands. These

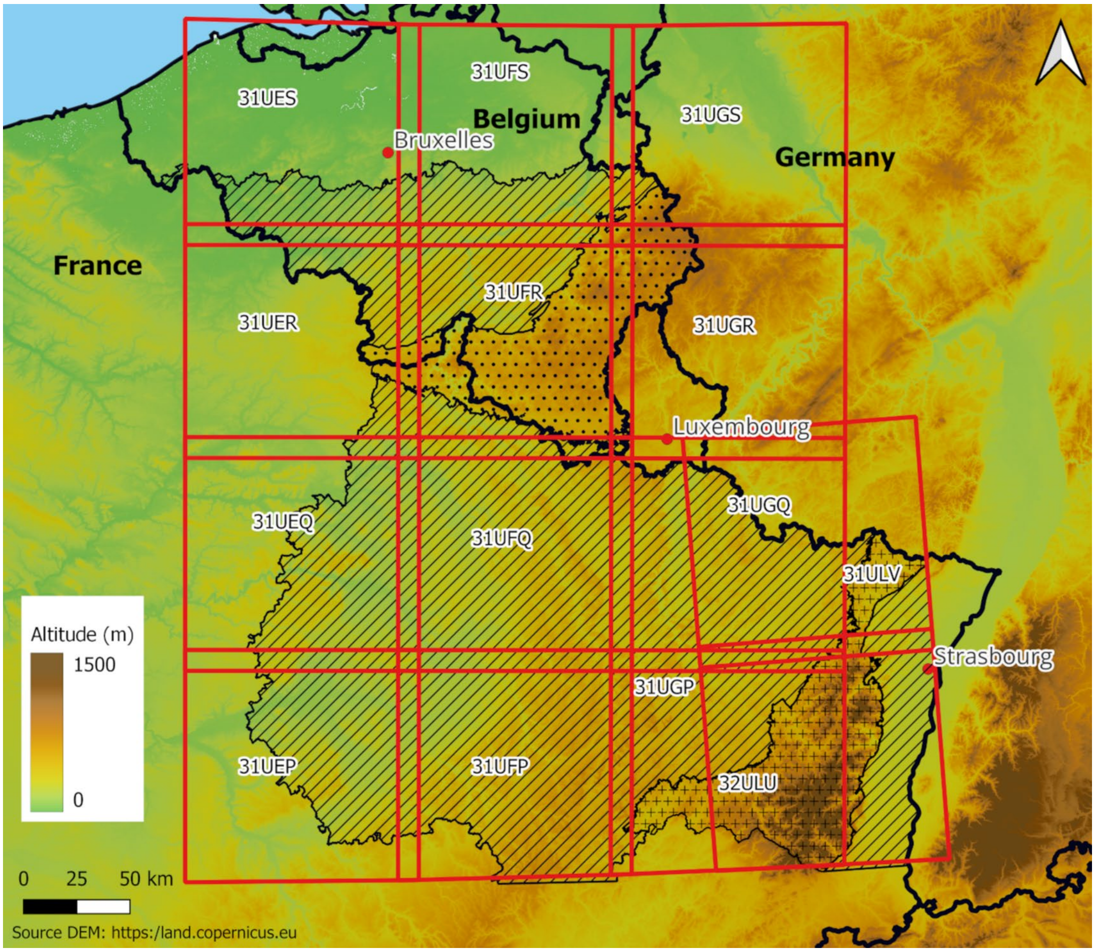

Fig. 1 Study area: Plains (black slant lines, altitude between 100 and 500 m above sea level), Ardenne (black dots, altitude between 200 and 700 m), and Vosges (black crosses, altitude between 300 and 1500 m). Red squares illustrate the extent of Sentinel-2 tiles which are used for the detection of bark beetle attack

composition maps consist in presence probabilities for eight major species, from which we discriminated Norway spruce stands by selecting areas with equal or greater than 80% probability of presence.

In the Grand-Est, the determination of species was first determined by photointerpretation as spruce or fir or as mixed conifers (performed by the National Institute of Geographic and Forest Information) and then refined using Sentinel-2 (S2) spectral time series. Phenology courses are highly suitable for forest tree species discrimination (Grabska et al., 2019; Lisein et al., 2015; Ma et al., 2021). In order to identify and remove every non-spruce pixel, all S2 spectral bands of 10 and 20 m were first summarized for each of the four quarters of the year, by averaging all cloud-free observations occurring during the quarter. We used the satellite observations from 2 years prior to the bark beetle outbreak for computing these multi-year quarterly averages, i.e. 2016 and 2017. A random forest algorithm was then trained on this synthetic time series to discriminate spruce from non-spruce pixels, based on a training set of observations from Wallonia consisting in 1000 sampled pixels (20 m × 20 m) for each of the eight major species (Bolyn et al., 2018). This forest species classifier was applied to the *spruce* or *fir* or *mixed conifers* area of Grand-Est. The proportion of pixels detected as spruce in the Vosges was 43% and corresponds to the level of mixture expected for this bioclimatic area (52%) according to photo-interpreted plots from Piedallu et al. (2023) and the

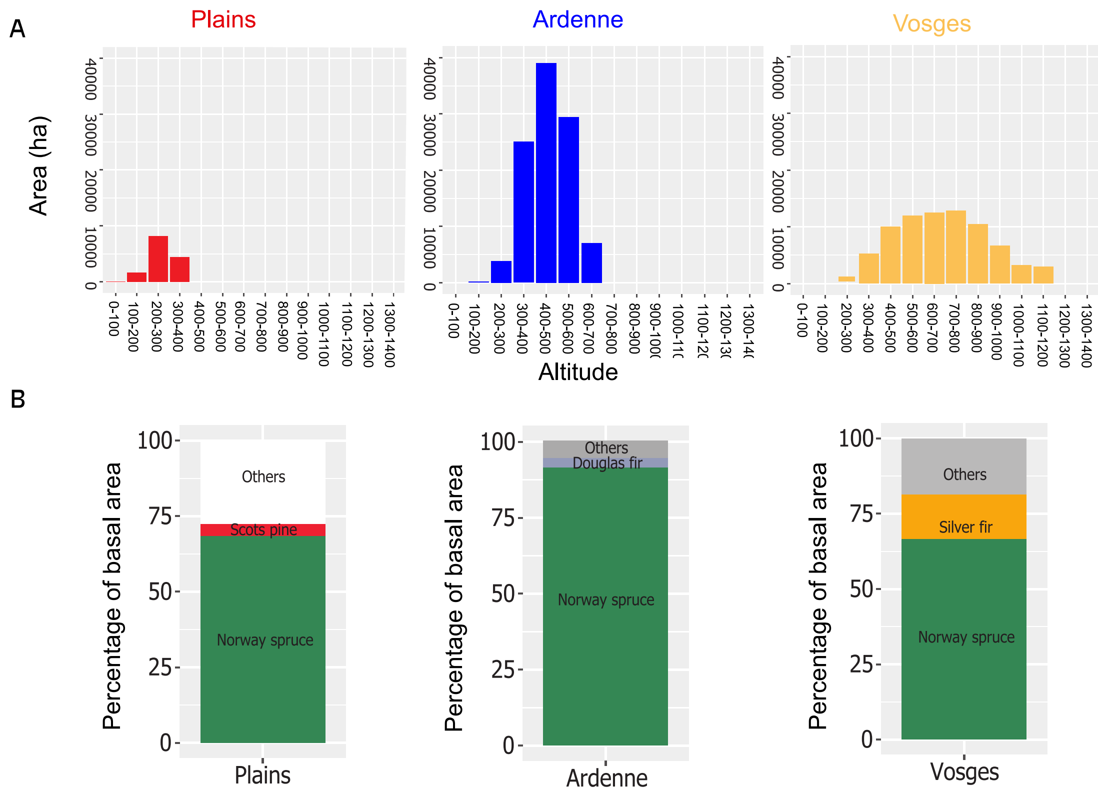

Fig. 2 Altitudinal distribution of spruce (**A**) and composition (**B**) of stands with relative basal area of Norway spruce higher than 25% (Inventaire forestier national français, 2022; Perin, (2023) for the three bioclimatic areas

total spruce surface reached 75,068 ha which is in accordance with French National Forest Inventory data (68,000 + −12,000 ha). Following bark beetle detection was carried on only for 10 × 10 m pixels detected as spruce.

Vegetation index and health status

The detection of Norway spruce dieback was realized using the S2 time series according to the methodology developed by Dutrieux et al. (2021). Vegetation changes were tracked by means of a phenology metric, the *SWIR Continuum Removal* vegetation index ($SWIR_{CR}$). The $SWIR_{CR}$ is based on three spectral bands, the near-infrared, the shortwave infrared 1 band, and the shortwave infrared 2 and is sensitive to the foliage water content: it is theoretically appropriated to detect spruce dieback during the green stage of bark beetle attack (Fig. 3). Seasonal variation of $SWIR_{CR}$ for healthy stands was modelled by fitting a harmonic function on 300 spruce pixels interpreted as healthy on orthophotoplan. The harmonic function is presented in Eq. 1 where t expresses the time as being the day of the year.

$$SWIR_{CR}(t) = a_1 + b_1\sin\left(\frac{2\pi}{365.25}t\right) + b_2\cos\left(\frac{2\pi}{365.25}t\right) + b_3\sin\left(\frac{2\pi}{365.25}2t\right) + b_4\cos\left(\frac{2\pi}{365.25}2t\right) \tag{1}$$

For fitting this equation, we used all cloud-free S2 observations from the 2 years preceding the onset of the bark beetle outbreak, i.e. 2016 and 2017. Then, a bark beetle attack was detected if the $SWIR_{CR}$ observations deviate from the healthy phenology trajectory. Preliminary investigations have led us to consider a multiplying factor of 1.7 applied to the $SWIR_{CR}$ for determining the threshold separating healthy from

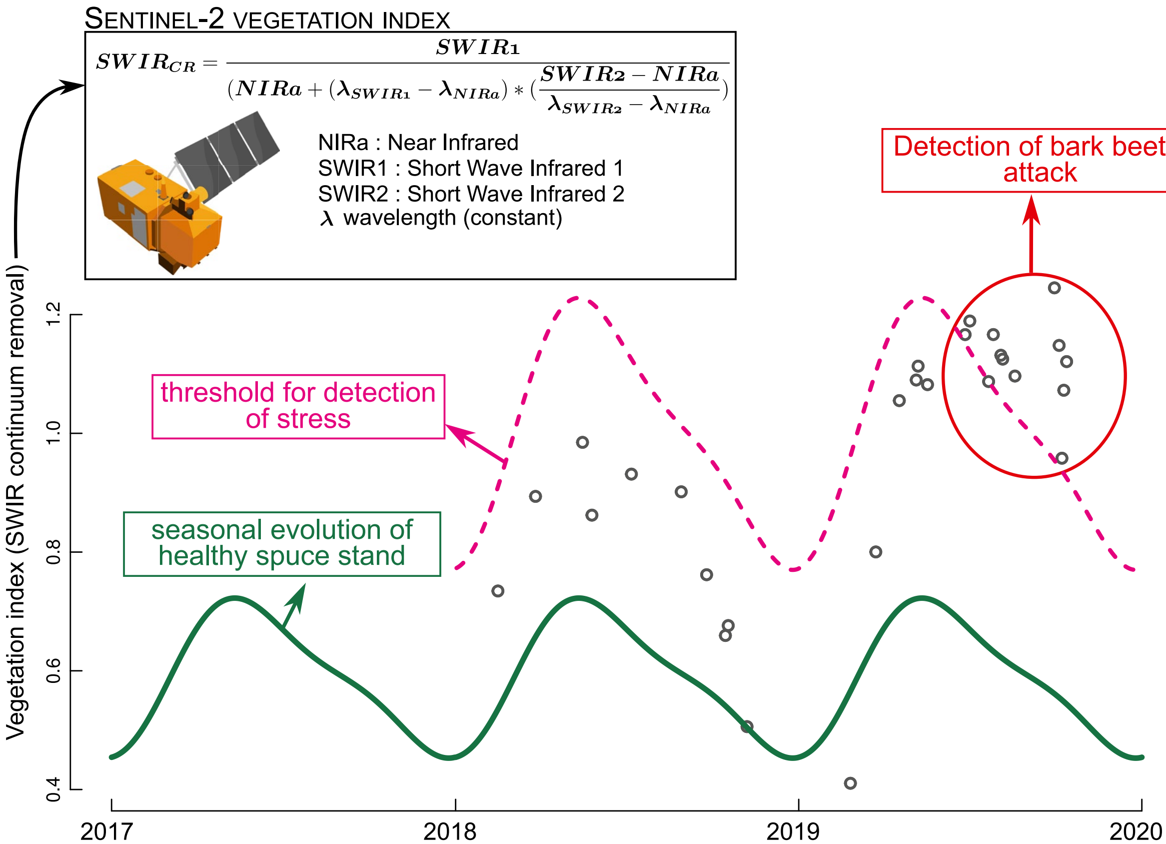

Fig. 3 Bark beetle health maps were computed by detecting changes in the $SWIR_{CR}$ phenology metric. The SWIR continuum removal was computed using three bands from Sentinel-2 imagery for every single acquisition date, and its value was compared to a threshold (purple dashed line, which corresponds to the healthy situation in green multiplied by 1.7) in order to detect vegetation stress. If a stress was detected two consecutive times with a minimum of 20 days between the observations, we assumed that the dieback occurred

stressed situation. Figure 3 illustrates a time series of $SWIR_{CR}$ observations (grey dots) for one single pixel. When the observations exceed the threshold represented by the purple-dashed line (in 2019 in Fig. 3), the spruce stand is probably under severe stress. As soon as $SWIR_{CR}$ vegetation index showed a stress for two consecutive times separated by at least 20 days, we assumed that the stress is permanent (leading to death).

Simultaneously to the detection of bark beetle stress, stand cutting and thinning were subject of particular attention: bare soil was detected by using a combination of thresholds for red, green, blue and shortwave infrared reflectance values (Band 8A $\geq$ 12% reflectance and Band 2 $\leq$ 6% reflectance and Band 3+Band 4 $\geq$ 8% reflectance). Cuttings were classified either as normal or sanitary thinning based on the health status determined by the $SWIR_{CR}$ vegetation index prior to cutting.

Although Dutrieux et al. (2021) have published their methodology as an open-source Python package, named *FORDEAD*, we have adapted the pipeline in C++in order to comply with our specific requirements (input and output in raster instead of vector format and result in the form of annual health maps). Our code is online on the github repository (https://github.com/JoLeBelge/s2-spruce-dieback/).

Annual spruce health maps

The temporal evolution of the bark beetle outbreak was analysed from the S2 time series between first May 2017 and 28 February 2023. This almost 6-year period time series counted at the pixel level a minimum of 134 and a maximum 275 acquisition dates according to the location. The total volume of data was 5.0 Tbit including intermediate results. For every vegetation year, we enumerated a minimum of 10 and a maximum of 65 acquisition dates (median = 30), always with a cloud cover smaller than 35%.

The health status of every single pixel (10-m resolution) located in a spruce stand was classified in one of the four following health classes for each year: healthy, bark beetle attack, normal or sanitary thinning.

On the first hand, a health status is first determined for every acquisition date of the entire time-series of Sentinel-2. On the second hand, the last health status of every vegetation year is selected in order to generate the annual health maps. The annual health maps cover the period starting from May to April of the next calendar year, because we assumed that Norway spruce dieback detected in April is related to bark beetle attack from the previous calendar year (Müller et al., 2022).

A post-processing of the spruce health maps was finally carried out in order to consider certain neighbourhood relationships. Areas of cut spruce directly surrounded by areas classified as sanitary cutting were detected and considered part of the sanitary thinning if the number of neighbouring dieback pixels (8-neighbour relationship) exceeds 50% of the number of pixels composing the cut spruce area.

Validation

The spruce health maps were validated by two different methods.

On the one hand, a stratified random sampling based on the size of the bark beetle attack area on the spruce health map was used for the 2018 vegetation season during which Wallonia suffered a lot of damage. The dieback area is a combination of a bark beetle–attacked area and a sanitary cutting area. Adjacent pixels of dieback were first gathered, polygonised and categorized into six surface categories: ≤ 200 m^2, 200 and ≤ 400 m^2, 400 and ≤ 600 m^2, 600 and ≤ 1000 m^2, 1000 and ≤ 2000 m^2 and ≥ 2000 m^2. Forty-eight dieback polygons were selected for each surface category, a total of 288 located exclusively in Belgian Ardenne. A photointerpretation was then performed using the annual orthophotoplans of the Wallonia. The health status from the health map was compared with the health status deduced from the orthophotoplan, and false detection was expressed as the proportion of surface wrongly detected as bark beetle attack area.

On the other hand, a field validation in the Vosges massif was carried out on 95 stands between February and April 2021. The selection of the circular field plots (diameter of 30 m) was made by photointerpretation of the annual orthophotoplan in order to balance the number of healthy and dieback plots. Each stand was inspected on site for the presence of bark beetles or dead trees and this health status was compared with the spruce health map.

Relation between bark beetle attack and environmental conditions

The forest practitioners of the two countries drew our attention to the variables that seemed to influence spruce dieback. According to them, the south-facing slopes and low altitude favour the spruce dieback. This hypothesis matches with the autecology of spruce, which is known to suffer from heatwaves and low water availability. Indeed, in the study area, precipitation increases with altitude, and temperatures decrease the higher the altitude at least within the tree's main ecoregions. In addition, the warmer climate of south-facing slopes favours the development of the bark beetle population (Annila, 1969; Baier et al., 2007; Jönsson et al., 2009; Marini et al., 2012) and increases the susceptibility of Norway spruce to the attack of bark beetle (Netherer et al., 2015; Wermelinger, 2004). Following this theory, there should be more attacked Norway spruce in low altitude and in south-facing slope in the three climatic areas.

The resulting spruce health map has been used to study the relation between the dieback and these two factors. The altitude has been broken down into 100 m classes and kept the three topographic exposure classes (flat, north-facing slope and south-facing slope). To determine which class of the two factors was most affected, we estimated the dieback areas for each class of each factor based on the health status maps for each year of the period 2017–2021. The total area of spruce at the beginning of the years is composed of the area of healthy spruce area at the beginning of the year. The annual dieback rate is the dieback area during one year divided by the total area of Norway spruce at the beginning of the same year.

Results

Bioclimatic areas

The study area was divided into three bioclimatic zones based on averages of temperature and precipitation during the growing season (Fig. 4). Plains are characterized by the lowest precipitation during the growing season (400 mm) and among the highest mean temperatures during the growing season (15 °C). Ecoregions with rainfall between 400 and 450 mm and temperature lower than 15.5 °C correspond to the bioclimatic area of the Ardenne. The Vosges includes ecoregions with the highest rainfall (400 mm) and temperature between 15.5 and 17 °C.

Across the study area and for the 2017–2022 period, 2022 was the least rainy year of the study period but the longest drought events occurred in 2018 and 2020. In the Plains, annual rainfall has always been below 750 mm except for 2021 which was very rainy (Fig. 5).

The three homogeneous bioclimatic areas, Plains, Ardenne and Vosges, differ in their altitude which can be considered an imperfect proxy for climate. The altitude varies between 100 and 500 m for the Plains, between 200 and 700 m for the Ardenne and between 300 and 1500 m for the Vosges (Table 1). The majority of spruce stands in the Plains is located in low altitude under 300 m in contrast with the Ardenne and the Vosges where the stands are located above 400 m. The studied spruce area covers 104,723 ha in Ardenne, 75,068 ha in the Vosges and 15,028 ha in the Plains.

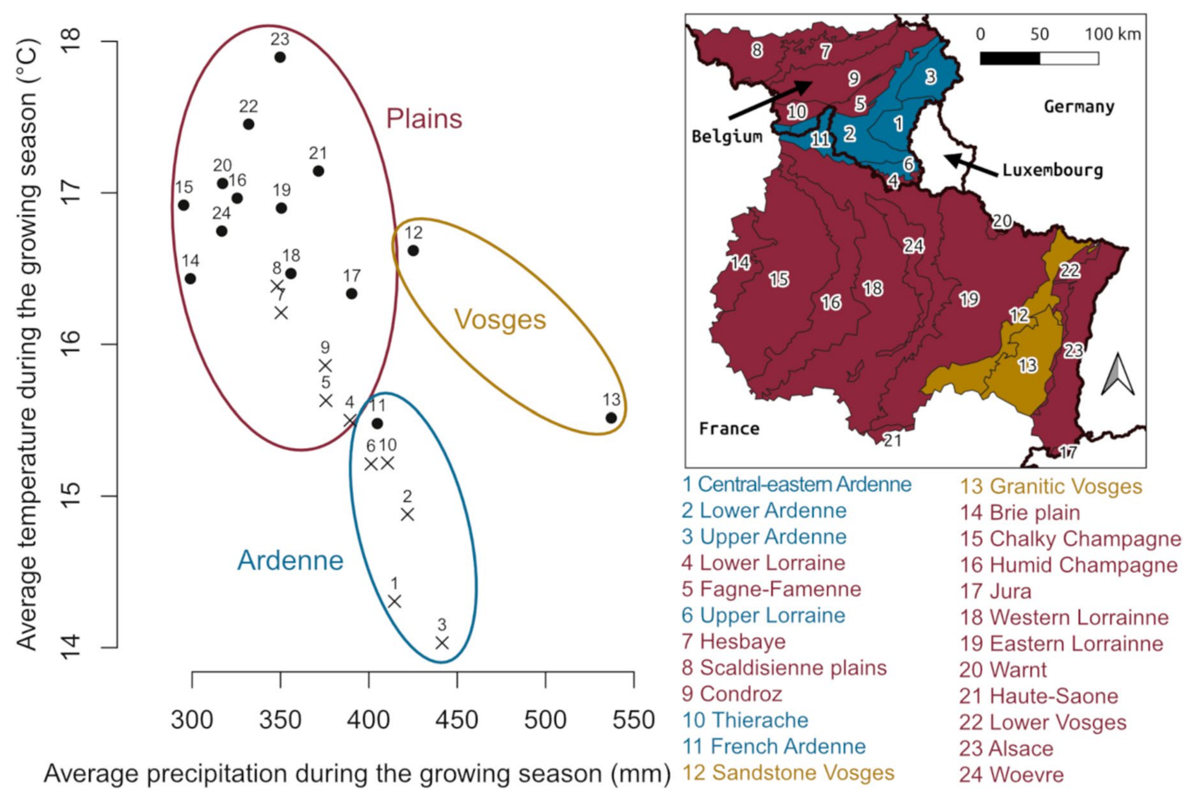

Fig. 4 Localisation (right) and groups of ecoregions (right) according to the temperature and precipitation of the growing season (May–September) during the 1991–2020 period: Ardenne (blue), Plains (red) and Vosges (orange). Walloon ecoregions are depicted with a cross, and Grand-Est regions are illustrated by rounded points

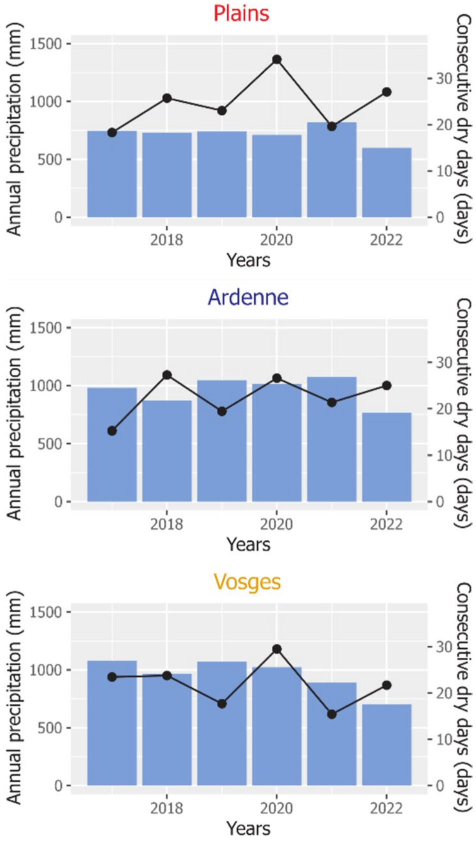

Fig. 5 The climate summary for the three bioclimatic areas showed different trends during the bark beetle outbreak: annual precipitation (blue areas) and longest drought events (black lines)

Spruce health map generation and validation

Sentinel 2 satellite images between 1st January 2017 to 28 February 2023 were used to generate the annual Norway spruce health maps. Figure 6 illustrates the spruce health map. The four health statuses are represented and illustrated on the orthophotoplan.

Validation of the spruce health map for the 2018 vegetation season by photointerpretation showed that 86.1% of the dieback area was confirmed on the orthophotoplan (Table 2). In the remaining area totalling 13.9%, the photointerpretation work concluded that there was no visible dieback (false positive).

The field validation in the Vosges confirms the result of the photointerpretation method. Dead stands are identified correctly in 84.7%. The healthy stands on the spruce health map are validated in 100% of the stands in the field.

Importance of the evolution of the outbreak

After a low spruce mortality rate in 2017, the sanitary outbreak of spruce really began in 2018 especially in the Plains and in Ardenne (Fig. 7). A high level of annual mortality rate has been observed each year for 4 years with a maximum of 2.5% of the spruces in the Vosges, 5% in Ardenne and 22% in the Plains after three critical years (2018–2020). Spruce mortality rates decreased in 2022 and returned to a similar situation as in 2017 with respectively 0, 1 and 3% of new attacked stands for Vosges, Ardenne and Plains. During the period 2017–2022, 23,674 ha of spruce have been destroyed in the study area, then representing 12% of the total spruce area of 2017 (Table 3). The three bioclimatic areas were not equally impacted by spruce mortality: Plains were the most affected with 50.1% of the stands, nearly 10 times more than the Vosges (5.6%) and four times more than the Ardenne (11.3%). The evolution of the outbreak also differed by bioclimatic areas (Fig. 7). Bark beetle attacks began hardly in 2018 in the Plains and in the Ardenne but were more progressive in the Vosges, where the maximum impact was later observed, in 2020.

Influence of altitude on the Norway spruce mortality

Because spruce was planted outside its distribution range in low altitude, and according to studies

Table 1 Description of the three bioclimatics areas

Area	Precipitation (growing season)	Average temperature (growing season)	Altitude	Area	Country
Plains	< 400 mm	> 15 °C	100–500 m	6,099,800 ha	Belgium-France
Ardenne	400–450 mm	< 15.5 °C	200–700 m	724,970 ha	Belgium-France
Vosges	> 400 m	15.5–17 °C	300–1500 m	640,930 ha	France

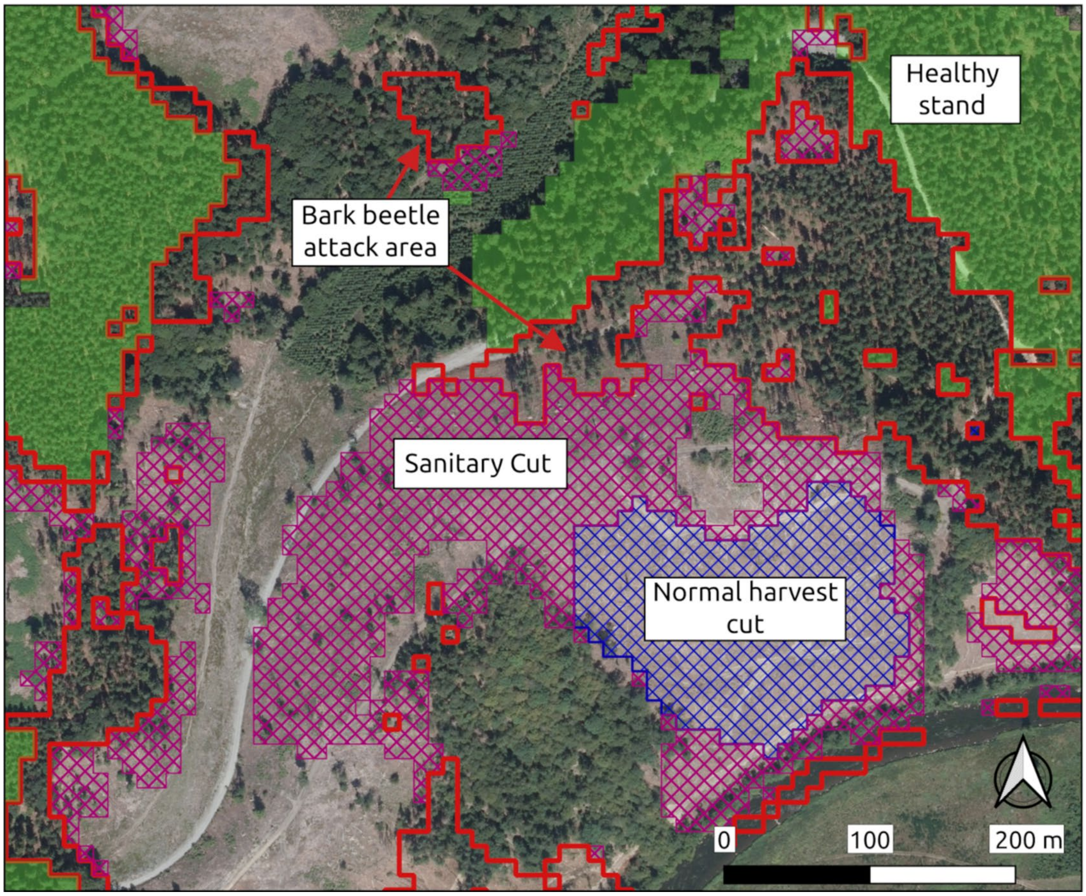

Fig. 6 Norway spruce health map of 2018 and Belgian orthophotoplan of 2019 for an Ardenne forest

Table 2 Validation of the spruce health map using field surveys for 95 spruce stands in the Vosges and orthophotoplan for 288 spruce stands in the Belgian Ardennes

Region		Belgian Ardenne		Vosges	
Validation type		Photointerpretation ($n=288$)		Field survey ($n=95$)	
	Health status	Attacked stands	Healthy stands	Attacked stands	Healthy stands
Spruce health map	Attacked stands	86.1%	13.9%	84.7%	15.3%
	Healthy stands	/	/	0%	100%

showing a shift of species distribution along the altitudinal gradient (Lenoir et al., 2008), more mortality was expected at lower altitude. The variation of the dieback rate during 2017–2022 for the three bioclimatic areas shows an important effect of altitude but with some differences according to the region (Fig. 8). More dieback was observed at low altitude: at the peak of the outbreak, the annual mortality rate exceeded 20% each year in the altitude class under 300 m. In Ardenne, since the beginning of the outbreak, the dieback rate is gradually decreasing when altitude is increasing. Except during 2018, at the peak of the outbreak, spruce forest above 500 m were not severely affected. In the Vosges, the dieback rate was globally low during the outbreak compared to the other bioclimatic areas, except for

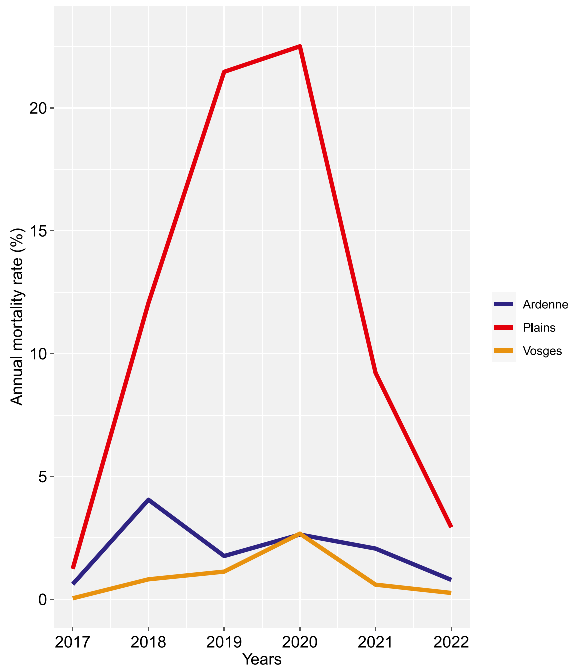

Fig. 7 Evolution of the annual mortality rate during the outbreak (2017–2022)

2020. No clear trend seems to emerge according to the altitude except at the beginning of the outbreak in 2018 in the lower stands below 400 m altitude. However, Vosgian spruces are rare below 400 m (less than 6500 ha).

Influence of exposures on the Norway spruce mortality

The proportion of the cumulative area attacked by bark beetles during the 6 years studied in the spruce area before the outbreak according to exposure (Table 4) shows contrasting results depending on the region. For plains, the north-facing slopes are significantly but slightly more affected than the flat areas or the south-facing slopes. In Ardenne, the flat areas are significantly less impacted than the north and south-facing slopes. In this region, the south-facing slopes are significantly more affected. As opposed to the Ardenne, in the Vosges, the flat areas are significantly more impacted than the north and south-facing slopes.

Discussion

Dynamic of the dieback

In forests, sanitary outbreak lasts on average between 3 and 10 years (Brunier et al., 2020). In our study, the spruce dieback has begun in 2018 and decreased in 2022 in all regions. The annual dieback rate has recovered in 2022 to the same level as in 2017. We found that the Vosges lost 5.4% of their spruce area. According to Piedallu et al. (2023), 33% of Vosgian spruce stands are in areas at high risk of dieback. It is therefore likely that new stands will dieback in the years to come. Even if all results show a decrease in mortality, the forestry community should remain vigilant for a new explosion of mortality. The experience gained in remote sensing in previous years should help to detect new bark beetle outbreaks and to contain a potential new outbreak.

The outbreak peaks seem to be linked to the maximum number of consecutive dry days and to the total rainfall of the year. Indeed, for three areas, the outbreak peak is reached in the year with the maximum of consecutive dry day. These annual mortality results can be linked to the climate data of ECAD (Cornes et al., 2018), in particular, the consecutive dry days

Table 3 Spruce area affected by bark beetle outbreak during the outbreak (2017–2022). Data including bark beetle attacks and sanitary felling

Bioclimatic areas	Total spruce dieback area during the outbreak (ha)	Total spruce area before the outbreak (ha)	Rate of area with dieback (%)	Rate of sanitary cut/normal cut
Plains	7634	15,028	50.1	1.24
Ardenne	11,822	104,723	11.3	0.57
Vosges	4218	75,068	5.6	0.92
Total	23,674	194,819	12.2	0.77

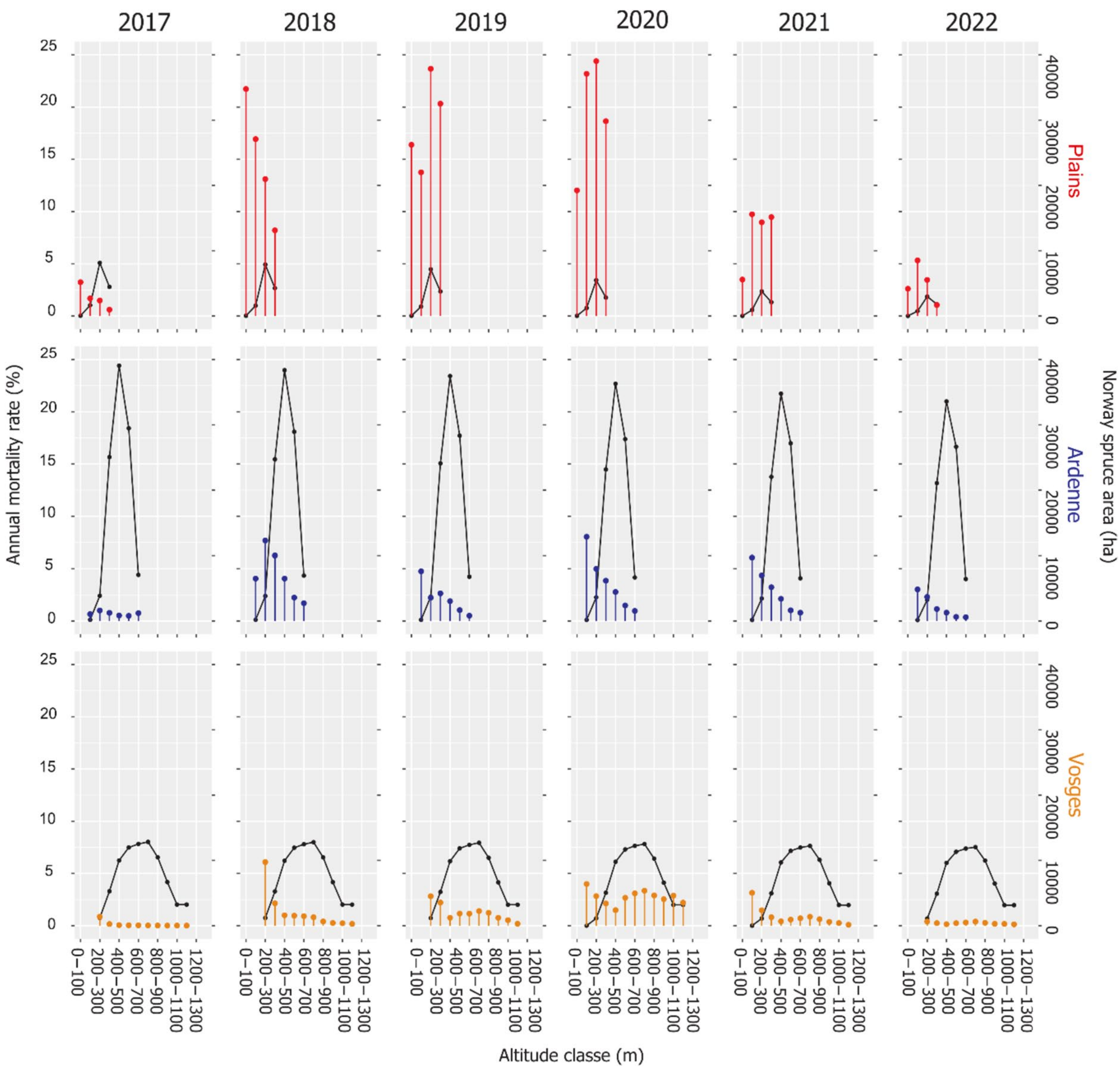

Fig. 8 Variation of the dieback rate from 2017 to 2022 according to the altitude divided into 14 classes of 100 m amplitude for the three bioclimatic area: Plains (red), Ardenne (blue) and Vosges (orange). The spruce area per altitude class is represented in black

Table 4 Proportion of the cumulative bark beetle attacked area by bioclimatic area according to the exposures during the 2017–2022 period. The same letters (a, b, c) identify homogeneous groups with no significant differences for each exposure (based on Pearson's chi-squared test statistic, *p*-value 0.05). Values in bold indicate the most impacted exposure by bioclimatic area

Plains		Ardenne		Vosges	
Exposure	Rate (%)	Exposure	Rate (%)	Exposure	Rate (%)
Flat areas	50.2[a]	Flat areas	10.7[a]	Flat areas	**6.8[a]**
South-facing slopes	52.8[b]	South-facing slopes	**13.8[b]**	South-facing slopes	5.1[b]
North-facing slopes	**54[c]**	North-facing slopes	13.1[c]	North-facing slopes	5.0[c]

(NCDD), which correspond to the largest number of consecutive days with less than 1 mm of precipitation. During the 6 years of monitoring, the mortality peaks occurred in the same years as NCDD peaks, regardless of bioclimatic areas (Fig. 5).

A long period without rain causes intense stress to the trees, weakening them. These conditions allow bark beetles to swarm and penetrate the bark of weakened trees more easily. The severe damage caused in 2018 in the Ardennes, and in 2020 in the plains and Vosges seems to be explained by this drought. However, for the year 2020, in Ardenne, the damage is less important than in 2018 while the NCDD are very close. This difference in damage could be explained by higher rainfall in 2020 compared to 2018 in this bioclimatic area.

Our results of the total dieback area can be compared to the estimates of annual bark beetle damage made at the scale of administrative regions. According to Nardi et al. (2023), the damage during 2018 was assessed at 1185 ha for the Grand-Est based on remote sensing methodology. From our health map for the vegetation season of 2018, we found a total of 1360 ha attacked in this administrative region. In Wallonia, Saintonge et al. (2022) estimate from sale catalogues that the area of spruce attacked by bark beetle between 2018 and 2021 in Wallonia is around 5000 ha. For this very same area and period, we determined that 13,000 ha of spruce were killed by bark beetle. We suppose Saintonge et al. (2022) underestimated the impact of the bark beetle outbreak, because their estimate does not consider unharvested dead spruce. Our method enables us to provide reliable damage area information to politicians and information on the location of bark beetle infestations to foresters and scientists.

Regional impact of the bark beetle attacks

The impact of the bark beetle attacks is different between the three main bioclimatic areas. It could be explained through three parameters: climate, stand structure and composition and forest management. Warm and dry climate, as in the Plains, does not meet the autecological requirements of the spruce species, especially during extreme dry or warm events as in the period 2018–2020 (Rousi et al., 2022). Moreover, during warm seasons, the bark beetle produces multiple generations in a year (Annila, 1969; Baier et al., 2007) that can easily attack these stressed trees. Furthermore, the relations between bark beetle attacks, spruce trees and environmental conditions are very complex (König et al., 2023; Lausch et al., 2011). According to the literature, three parameters could explain the dieback: climate (Baier et al., 2007; Trubin et al., 2022; Wermelinger & Seifert, 1998), stand structure and composition (Kamińska et al., 2021) and forest management (Faccoli & Bernardinelli, 2014; Jactel et al., 2021).

Rapid harvesting of trees attacked by bark beetles protects stands from severe outbreaks (Stadelmann et al., 2013) but this operation is not systematic in regions such as the Plains where the softwood industry is not as developed as in the Ardennes and in the Vosges. Faced with these three parameters, the three main bioclimatic areas are not equal. In the Vosges, the conditions are more favourable, which could explain the limited outbreak during the outbreak (5.6% of the initial area). Indeed, on the opposite, in the Plains, all parameters are unfavourable: the warm and dry climate stressed the trees and favoured the beetles which produced large outbreaks in even-aged pure stands, probably less concerned by sanitary thinning. These conditions explain that the outbreak was not controlled and reached 50.1% of the spruce area. The Ardenne spruce forest is an intermediate situation. The climate is the coldest of the three bioclimatic areas, but less humid than the Vosges. The forest manager generally makes the necessary sanitary felling which is part of the silvicultural tradition. However, spruce grows in pure even-aged stands. These conditions could explain an intermediate situation with damages on 11.3% of the spruce initial area.

Influence of the exposures on the mortality of Norway spruce

The exposure influences received radiation and water balance. South-facing slopes are warmer than north-facing ones. As the life cycle of the bark beetle is influenced by temperature (Baier et al., 2007), this insect should produce more generations in south-facing slopes and thus cause more damage in this exposure (Jakuš, 1995). Moreover, the south-facing slopes store up to 50% less water than in north-facing slopes in early spring (Rouse & Wilson, 1969). Thus, Norway spruces that growth in this orientation should be more often in a situation of water stress and should be more attacked than the north-facing slopes. However, our results do not clearly fit with this hypothesis. In the Plains, the south-facing slopes and the flat areas are less attacked than the north-facing slopes. In Europe and in North America, Gazol et al. (2017) observed that species that grow in drier conditions areas are more resilient to drought. Piedallu et al. (2023) confirmed this observation in the Vosges during the last outbreak. Moreover, in France, a recent study by Nardi et al. (2023) showed that Norway spruce stands on the steep slopes and soils with low water availability are less attacked. In the Vosges, spruce trees growing on the southern slopes and plains have suffered from drier conditions throughout their life and therefore have been less stressed than spruce trees growing on the north-facing slopes. In Ardenne, the south-facing slopes are more affected by bark beetle than other position. Norway spruce that growth in south-facing slopes should be more often in a situation of water stress and should be more attacked than the north facing-slopes. However, the north-facing slopes are not the less attacked. The shallow soil depth on the slopes of Ardenne could explain the dieback rate difference between de slope and the flat areas. In the Ardenne and in the Vosges, the result is opposed for the flat areas. The damage caused in the Vosgian flat areas could be explained by the more important presence of pure even-aged stand in this topographical orientation than in the slope. This stand structure is more sensible to bark beetles.

The trend of bark beetle attacks following the topographical exposures needs further investigations. In view of these results, it seems difficult to give global advice to forest managers.

Potential methodological limitations

The evolution of remote sensing methods allows foresters to have a lot of reliable information quickly, unlike the often time-consuming field surveys. The detection of dieback is based on a dense time series of Sentinel 2 satellite imagery. This approach has been commonly used for several years to detect dieback. However, it is increasingly used because satellite data are more readily available.

Calculating the spruce health map requires a species composition map, in order to limit the analysis to the spruce area. In pure even-aged Norway spruce stand, the spectral response is stable in the absence of mortality, but at the edge of this stand and in mixed stand, this response can vary with season due to the deciduous tree or herbaceous species. In mixed forest and in the border of the stands, the species composition map is less accurate than in pure even-aged stand. In Ardenne and in the Plains, Norway spruce occurs principally in pure even-aged stands. In the Vosges, spruce forests are intimately mixed with silver fir (*abies alba*), and we suppose thus that the species composition map is less accurate than in the other bioclimatic areas. The annual dieback rate is influenced by the Norway spruce area of the composition map. In Ardenne and in the Plains, the area is correctly estimated because spruce stands are purely even aged. On the other hand, in the mixed stands of the Vosges, the surface area is more difficult to evaluate because of the strong variation of tree species that influence the composition of the canopy. An underestimation of the dieback rate is not excluded in this type of stand.

The methodology used allows the detection of the spruce mortality by tracking the water stress of the foliage. This symptom very often reflects a bark beetle attack on a weakened tree, especially during a period of beetle outbreak. This method does not allow to separate individuals killed by the insect from individuals killed by another phenomenon (drought or other parasites). However, in view of the bark beetle outbreaks observed, we can consider that most spruce trees detected as bark beetle attack are due to the bark beetle. Another limitation of the methodology is linked to the felled trees. To limit the damage of bark beetles, it is recommended to quickly remove the attacked trees from the forest. However, if the trees are felled before two images are taken by the satellite, the area will be considered cut for normal harvesting rather than for a sanitary thinning. On the contrary, some felled trees of sanitary thinning can be healthy but considered to be attacked.

Conclusion and perspectives

Our study aimed to assess the evolution of the bark beetle outbreak in the spruce forest by analysing a time series of sentinel-2 satellite images. To our knowledge, only König et al. (2023) dealt with such a comprehensive time series: in their study, they used multi-sensor satellite data with all available acquisitions from January 2015 to 30 April 2021, totalling 662 Sentinel-2 images. We focused on cloudless acquisition, which ended up with a total of 275 acquisition dates in 6 years. The methodology used to identify the damaged stands is robust and effective as far as reliable species composition maps are available. Indeed, to improve the result in the Vosges, a new Norway spruce map is necessary to better distinguish spruce from fir. Taking this limitation into account, remote sensing could be the basis for monitoring bark beetle attacks in spruce forest. This outbreak triggered by the dry and warm events from 2018 to 2020 lasted 5 years and destroyed 12.2% (23,674 ha) of the spruce area in Wallonia and Grand-Est of France. After a rainy year in 2021, new bark beetle attacks in 2022 return to their 2017 level. The outbreak seems to be over. However, foresters must remain vigilant in the face of a resurgence of attacks in the years to come. The damages were not equally distributed on the territory: the Plains are the most impacted bioclimatic area with more than 50% of the spruce area impacted by bark beetles. The devastated area by this pest is estimated around 7634 ha. The Ardenne is the second region that has lost the most spruce areas with 11.3% of its spruce area attacked or around 13,400 ha. The Vosges is the less attacked region with 5.6% of its spruce area killed. The total area impacted in this mountain region is around 4200 ha. This situation could be linked to the climate, the structure and the composition of the stands and the current forest management which differ between the three bioclimatic areas. Taking into account the climate change, which will favour warm and dry events in the near future, our results do not support new plantations of Norway spruce in the Plains. In Ardenne, we advise not to plant any more Norway spruce at lower altitude than 400 m except in specific micro-climate. In the Vosges, the trend differs between the two other regions. More investigation specially dedicated to this region is necessary to draw conclusions. A study considering the effects of environment, climate and silvicultural factors would be interesting to better understand the determining factors of these bark beetle attacks of this important species for the wood industry.

Author contribution Jonathan Lisein and Arthur Gilles developed the annual Norway spruce health maps, Arthur Gilles, Jonathan Lisein and Hugues Claessens analysed the data. Juliette Cansell carried out fieldwork in the Vosges. Arthur Gilles wrote the paper. All authors reviewed the manuscript and have given their final approval for publication.

JL and AG developed the annual Norway spruce health maps, and AG, JL and HC analyzed the data. JC carried out fieldwork in the Vosges. AG wrote the paper. All authors reviewed the manuscript and have given their final approval for publication.

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Data availability Source codes are available at https://github.com/JoLeBelge/s2-spruce-dieback/.

Declarations

Ethics approval 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.

Conflict of interest The authors declare no competing interests.

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