Original research papers

Assessment of the evolution of the bark beetle crisis in the spruce forest: a remote sensing multi-temporal analysis in Belgium and North east France.

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Abstract

Keywords: Norway spuce, Species vulnerability, Bark beetle, forest management, forest site, topographic condition, time series, Sentinel-2

1. Introduction

Global changes are increasing the risk of disturbances in forest environment: frequency and intensity of abiotic events (fire, storm, drough) and health problems (diseases and pest invasion) will be more recurrent (Lindner et al., 2010). In Western Europe, we expect a decrease of precipitation and an increase of drought events during the vegetation period, which will impact the actual geographic distribution of tree species (Hanewinkel et al., 2013). In this context, 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, the precipitation are its primary water source (Modrzyński, 2007) and lack of water induces stress that affect 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 drought that weaken trees. A recent bark beetle crisis, triggered by the exceptionally hot and dry weather of 2018, occurred in Western Europe and lasted until 2021. It has higlighted the need of improving our understanding of both Norway spruce and bark beetle autecology and synecology for minimising the impact of bark beetle on spruce stands with adapted management methods. It should concern the monitoring of bark beetle population and early detection of attacks on trees as well as adapted silvicultural methods and adequate species composition of future forest, especially in the thousands of clear-cutted hectares decimated by bark beetle attacks. The Norway spruce is a native species

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of the boreal or mountainous climates of Europe including the Vosges mountains but it has been also successfully planted out of its native range on warmer sites of low altitude in the Grand-Est (France) and Wallonia (Belgium) during the 19^{th} and 20^{th} centuries (Noirfalise and Thill, 1975; Guinier, 1959). The massive reforestations occurring at this time have led to the formation of large pure even-aged stands. It usually develops a taproot system with fine roots in shallow depth, although the roating can adapt its configuration constrained (Puhe, 2003; Köstler et al., 1968). The most important pest for Norway spruce are bark beetles species, especially *Ips typographus* that causes the most damages on spruce stands. Thus in this paper, bark beetle refers to this species. Stressed Norway spruce produce volatile compounds which attract bark beetles, making himself more susceptible to pest attack (Netherer et al., 2015, 2021). Bark beetle is ubiquitous in the forest and their populations are usually low (endemic phasis) without producing damage on healthy trees. However a large amount of stressed trees causes a shift to an epidemic phasis with a 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 enter in the bark and burrow wood to make brood gallery where they mate and lay the eggs that mature to larvae into 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 and Byers, 1995). After the larvae maturation that last about seven weeks (Baier et al., 2007), the new generation of beetles emerges and attacks the direct surrounding trees (Zolubas and Byers, 1995). Attacked trees defend themselves by pulsing resin to kill the bark beetle but these defence 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 to penetrate the phloem and the spruce retains its green needles. The tree is still alive but begins to suffer of water shortage caused by sap conduction problem. After several weeks, the red stage is reached when the needles turn brown-red. The tree is recently dead and the dry needles start to fall. When all the needles of the spruce have fallen off and the grey bark of the trunk is visible, the grey stage is reached (Abdullah et al., 2018). To control the infestation of bark beetle, the practical solutions are limited. The use of phytosanitary product is forbidden in Belgian and French forest. 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 fell and remove each attacked tree at the green stage, before the swarming. It takes this ideal breeding material out of 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 have been intensively used for forestry purpose. Time series of Sentinel-2 (S2) images enable to model the phenology courses of vegetation indices in order to detect forest disturbances (Löw and Koukal, 2020), like the one caused by bark beetle outbreaks. Infestation maps of the last sanitary crisis have been generated for Germany (Ali et al., 2021; Thonfeld et al., 2022), Czech Republic (Bárta et al., 2021), Italy (Dalponte et al., 2022) and France (Nardi et al., 2022). This paper aims to assess the evolution of the bark beetle crisis during the 2017-2022 period in the Walloon and Grand-Est spruce forest using remote sensing. To this end, we map Norway spruce dieback using S2 time series. Then, we roughly analyse the relationship between the level of bark beetle damages and some main environmental parameters such as altitude and topography in order to determine the most sensitive forest sites where Norway spruce sylviculture should no longer be considered..

2. Material and methods

2.1. Study area

The study area covers in Wallonia (south of Belgium) and in the Grand-Est (north-east of France). The Walloon forest covers 554,600 ha and Norway spruce stands occupy quarter of this forest (Lejeune et al., 2022). The Norway spruce covers seven percent of the 1,939,000 ha of the Grand-Est forest (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 in Wallonia and Grand-Est, mainly by climate parameters and therefore influence the tree species distribution (Walthert and Meier, 2017). To better understand the dieback of Norway spruce, the French and Walloon ecoregions have been grouped in three main regions according to average temperature and precipitation during the growing season of the 1990-2020 period in three homogeneous bioclimatic areas: Plains, Ardenne and Vosges (Figure 1). Plains are characterized by the lowest rainfall during the growing season(< 400 mm) and the highest mean temperature during the growing season (> 15 °C); ecoregions with rainfall between 400 mm and 450 mm and temperature (15,5°C) correspond to bioclimatic area of the lower Ardenne. Vosges are ecoregions with the highest rainfall ($>$ 400 mm) and temperature between 15.5 °C and 17°C. The climate variables for Wallonia have been provided by the Institut Royal Météorologique and come from the climate map Digitalis (Piedallu et al., 2014) for the Grand-Est. These three regions also differ in their altitude wich can be considered as an imperfect proxy for climate The Figure 2 shows localisation of the three bioclimatic areas. The majority of spruce in the Plains is located in low altitude under 300 m in contrast with the Ardenne and the Vosges where the majority of Norway spruce stand grow above 400 m. The studied spruce area covers 107,926 ha in Ardenne, 24,462 ha in the Vosges and 75.067 ha in the Plains in the Grand-Est region.

Forest microclimate contrast with the climate. The micro-climate is influenced by topography (De Frenne et al., 2021). South-facing slopes are warmer and drier and their temperature difference between day and night are greater than the north-facing ones. Three topographic exposures have been determined using the Delvaux and Galoux (1962) definition. Plateaus are neutral topographic conditions that does not create a particular micro-climate. North-facing orientations are slopes greater than 20% facing north (285° to 125°) with cold and shady conditions. South-facing orientations are slopes greater than 20% facing south (125° to 285°) with a hot micro-climate. The digital elevation model (DEM) data from the Copernicus Land Monitoring Service (European Union, 2022) at a resolution of 25 m have been used for altitude and topographic exposures maps.

2.2. Mapping the spruce trees and stands.

The first prerequisite to assess spruce dieback is to map the species distribution at a fine scale, especially in mixed stands where management maps consider mixed stands as undifferentiated entities. For the south of Belgium, we used existing reliable composition maps from Bolyn et al. (2022), computed from remote sensing data, in order to restrict our analysis to Norway spruces. In the Grand-Est, the composition map came from the French mapping agency (Institut National de l'Information Géographique et Forestière, 2018). Composition of forest stand was determined by photointerpretation and forest stands identifyed as "spruce or fir" served as starting point to restrict the dieback analysis. Time series are a convenient means to track phenology changes. More broadly than the dectection of bark beetle infestion, phenology courses are highly suitable for forest tree species discrimination (Lisein et al., 2015; Grabska et al., 2019; Ma et al., 2021). We have used S2 spectral bands courses along the vegetation season to refine the determination of species present in the area interpreted as "spruce or fir" in Vosges. The objective was to identify and remove every area that did not correspond to spruce stand, as pixels located on others species than spruce were likely to be wrongly detected as a bark beetle attack. All S2 spectral bands were first summarized for each of the four trimesters of the year, by simply averaging all observations occuring during

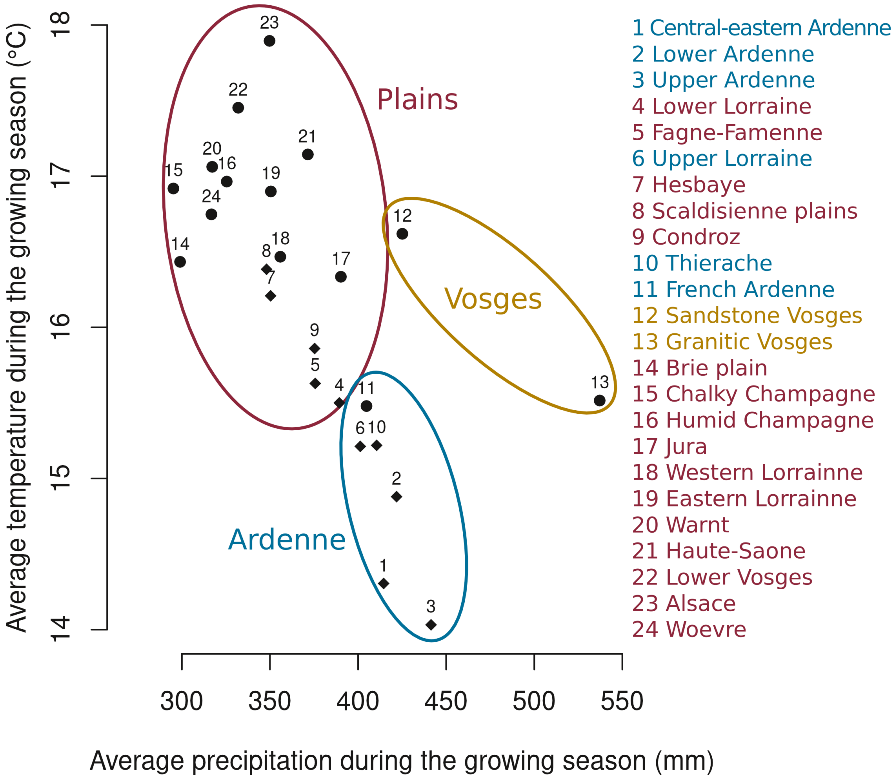

Fig. 1: Grouping of ecoregions according to the temperature and precipitation of the growing season during the 1990-2020 period to form three groups: Ardenne (blue), Plains (red) and Vosges (orange). Walloon ecoregions are depicted with diamond-shaped points, and Grand-Est regions are illustrated by rounded points.

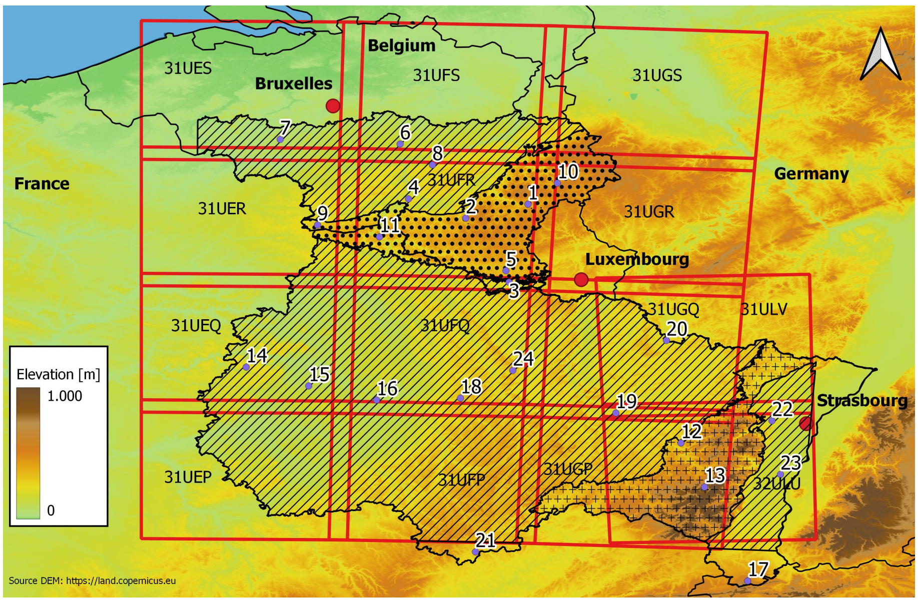

Fig. 2: Study area: Plains (hashed, altitude varying between 100 and 500 meters above see level), Ardenne (black dot, altitude between 200 and 700 m) and Vosges (cross, altitude ranging from 300 to 1300 m). Red squares illustrates the extend of Sentinel satellite 2 tiles which are used for the detection of bark beetle attack.

the trimester. Then, a Random Forest algorithm was trained on these synthetic intra-annual time serie to discriminate spruce from non-spruce pixels, based on a training set of observation from Belgium (Bolyn et al., 2018). Eventually, this Random Forest classifier was applied on "spruce and fir" area of Vosges and bark beetle detection was carried on only for pixels detected as spruce. The detection of Norway spruce dieback was realized by using dense time series of S2 imagery following the methodology developed by Dutrieux et al. (2021). Sentinel-2 (S2) satellites carry multispectral sensor with a ground resolution up to 10 m. The study is covered by 14 Sentinel-2 tiles of 100km x 100km (Figure 2). Vegetation changes were tracked by means of a phenology metric, the *SWIR Continuum Removal* vegetation indice ($SWIR_{CR}$). All S2 acquisitions were used in the analyses, provided that the cloud cover does not exceed 35 percent. Bottom of Atmosphere reflectance images (L2A product) were downloaded from the Theia data cluster (Theia Team, 2022) for all the 14 tiles. 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 appropriated to detect spruce dieback during the green stage of bark beetle attack (Figure 3). Seasonal variation of $SWIR_{CR}$ for healthy stand was modelled and a bark beetle attack was detected if the observations deviates from the healthy phenology trajectory. Figure 3 illustrates a time-serie of $SWIR_{CR}$ observations (grey dots) for one pixel. In 2018, the observations went beyond the threshold represented by the purple-dashed line, which shows that the spruce stand is most likely suffering from a serious stress. As soon as $SWIR_{CR}$ vegetation indice shows a stress for at least three consecutive times Dutrieux et al. (2021). We assume that the stress i caused by a bark beetle attack, in parallel 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). Cutting are thus taken into account and were classified either as normal harvest cutting or as sanitary thinning based on the health status prior to the cutting. The analysis of image time-serie was thus quite straightforward and has been performed individually pixel per pixel starting from the 2016 year, which is the beginning of S2 acquisitions and corresponds to the first reported increase of significant of bark beetles attacks in Belgium. Although Dutrieux et al. (2021) have published their methodology as a open-source python package, named *FORDEAD*, we have adapted the pipeline in C++ in order to comply with our specific requirements (our code is online on github repository `https://github.com/JoLeBelge/s2-spruce-dieback/`). We made use of OTB toolbox (Grizonnet et al., 2017) for image processing and the health status was summarized by seasonnal annual health maps (in raster format). The annual health maps cover the period starting from may and finishing in april of the next calendar year, because we made the assumption that Norway spruce dieback detected in april are related to bark beetle attack from the previous calendar year (Müller et al., 2022). For every years between 2018 and 2022, the health status of every single pixel located in a spruce stand is summarized in one of the four following classes ; healthy, bark beetle attacked, cutted or sanitary thinning. In view of the rapid death of spruce trees, it is assumed that all trees detected as dead are due to bark beetle attack. The dense time-serie covers the 2017-2022 period and count a minimum of 126 and maximum 260 acquisition dates. The annual time-serie enumerate a minimum of 10 and maximum of 51 acquisition dates.

The maps of spruce health status were validated by three different methods. The first method is global validation with annual orthophotoplan on random spruce stand on the 2018-2021 period. The sanitary level of the spruce stand in the sanitary map was compared with observed health status on the orthophotoplan. For the second method, a stratified random sampling base on the size of the dieback area on the sanitary map was used for 2018. The dieback area is a combination of bark beetle attacked area and sanitary cutting area. The selected stands were photo-interpreted with the annual orthophotoplan of the Wallonia. A field validation on the Vosges massif have been realized on 95 stands in winter 2020-2021. Each stand have been inspected for the presence of bark beetles or dead trees. The result of this field inspection have been compared with the sanitary map.

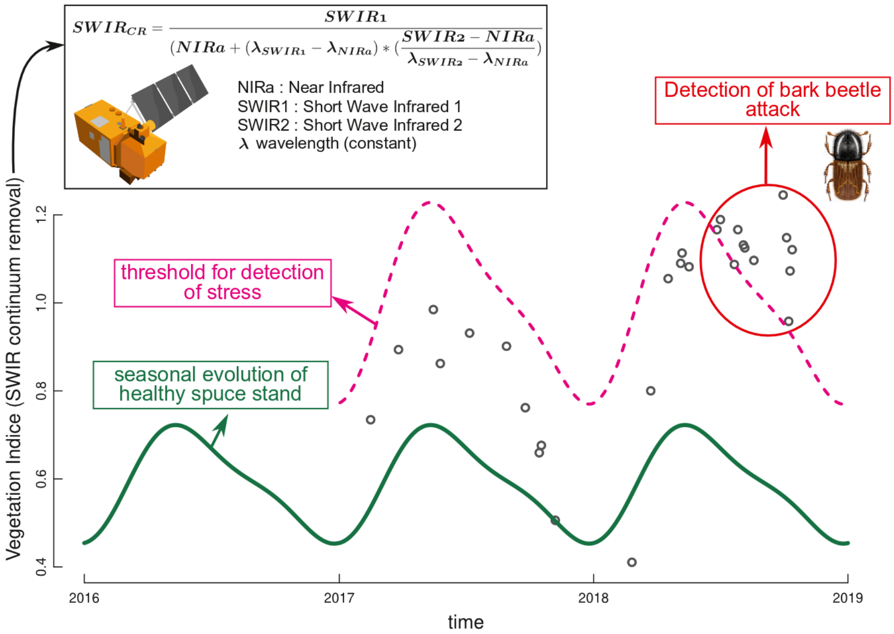

Fig. 3: Bark beetle infestation map are computed by detecting change in the $SWIR_{CR}$ phenology metric. The *SWIR Continuum Removal* is computed using three bands from Sentinel-2 imagery for every single acquisition date and his value is compared to a threshold (purple dashed line) in order to detect vegetation stress. If a stress is detected three consecutive times, we assume that a bark beetle infection occured.

2.3. Relation between bark beetle attack and topographical 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 favor the spruce dieback. This hypothesis match with autecology of spruce, that is known to suffer from heatwaves and low water availability. Indeed, in the study area, precipitation increase with altitude, temperatures decrease the higher the altitude at least within the tree main ecoregions. In addition, the warmer climate of south-facing slopes favours the development of bark beetle population (Annila, 1969; Baier et al., 2007; Jönsson et al., 2009; Marini et al., 2012) and increase the susceptibility of Norway spruce to the attack of bark beetle (Wermelinger, 2004; Netherer et al., 2015). Following this theory, there should be more attacked Norway spruce in low altitude and in south-facing slope in the three climatic areas. Sanitary map have been used to study the relation between the dieback and these two topographic variables. The altitude has been broke down by 100 m classes and kept the three topographic exposures classes. To determine which class of the two topographic variables 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 new dieback rate is the dieback area of a class during one year divided by the total area of Norway spruce of this class at the beginning of the same year. Dieback area is the surface of Norway spruce attacked by bark beetle and the area of sanitary cutting during the year. 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.

3. Results

3.1. Sanitary map validation

The result of photo-interpretation of spruce stand crossed with the sanitary map is present in the table 1. When the sanitary map predicts a decline, the dieback is confirmed by the orthophotoplan in 86.1 % of the verified spots. In 13.9 % this is a false positive because the trees are still healthy.

Table 1: Confusion matrix of the result of the sanitary map validation for 274 spruce stands.

Sanitary map \ Orthophotoplan	Dead trees	Healthy trees
Attacked trees	86.1 %	13.9 %

The field validation in the Vosges confirms the result of the photo-interpretation method. Dead trees is identified correctly in 84.7 %. The healthy tree on the sanitary map are valided in 100 % of the stand in the field (Table 2).

Table 2: Confusion matrix of the result of the field validation for 95 spruce stands.

Sanitary map \ Field	Dead trees	Healthy trees
Dieback trees (=39)	84.7 %	15.3%
Healthy trees (n=56)	0 %	100 %

3.2. Evolution of the crisis

After a slight increase of bark beetle attacks in 2017, the health crisis of spruce really began in 2018 especially in the Plains and in Ardenne. A high level of new damages has been observed each year during four 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 stands seems recover a normal health status in 2022 with respectively 0, 1 and 3% of new attacked trees for Vosges, Ardenne and Plains. During the period 2017-2022, on the study area 29,000 ha of spruce have been destroyed, then 14% of the total spruce area of 2017 (table 3). The three bioclimatic region were not equally touched by spruce mortalities. In terms of impact, the Plains were the most affected by spruce mortality with 52 % of the trees, nearby 10 times more than the Vosges (5.7 %) and four times more than the Ardenne (12.4%). The course of the crisis also differed from region to region (Figure 4). Bark beetles attacks began hardly in 2018 in the Plains and in the Ardenne, but was more progressive in Vosges, where the maximum impact was later observed, in 2020.

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

Region	Total spruce dieback area during the crisis (ha)	Total spruce area before crisis (ha)	Percentage of area with dieback
Plains	11,298	21,720	52,0
Ardenne	13,397	107,926	12,2
Vosges	4,305	75,067	5,7
Total	29,000	204,763	14,2

3.3. Influence of altitude on the Norway spruce mortality

In Western Europe, the altitude is considered as a proxy of the the climate (Faccoli and Bernardinelli, 2014) and is commonly used by the forest managers. The variation of the dieback rate according to altitude during the period 2017-2021 is discribed in the figure 5 for the three bioclimatic regions. The Plains were globally hardly affected, especially in low altitude. At the height of the crisis, the probability of new dieback exceeded 20% each year in the altitude class under 300 m. In Ardenne, since the beginning of the crisis, the dieback rate is gradually decreasing when altitude

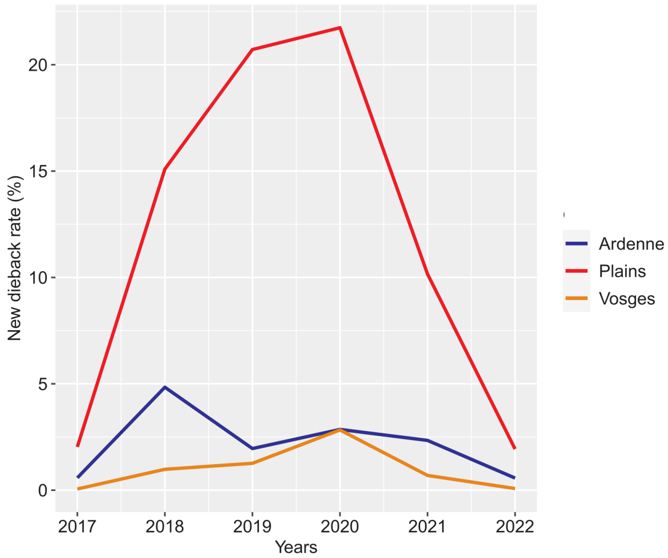

Fig. 4: Proportion of Norway spruce area affected by bark beetle. Plains region in red, Ardenne in blue and Vosges in orange.

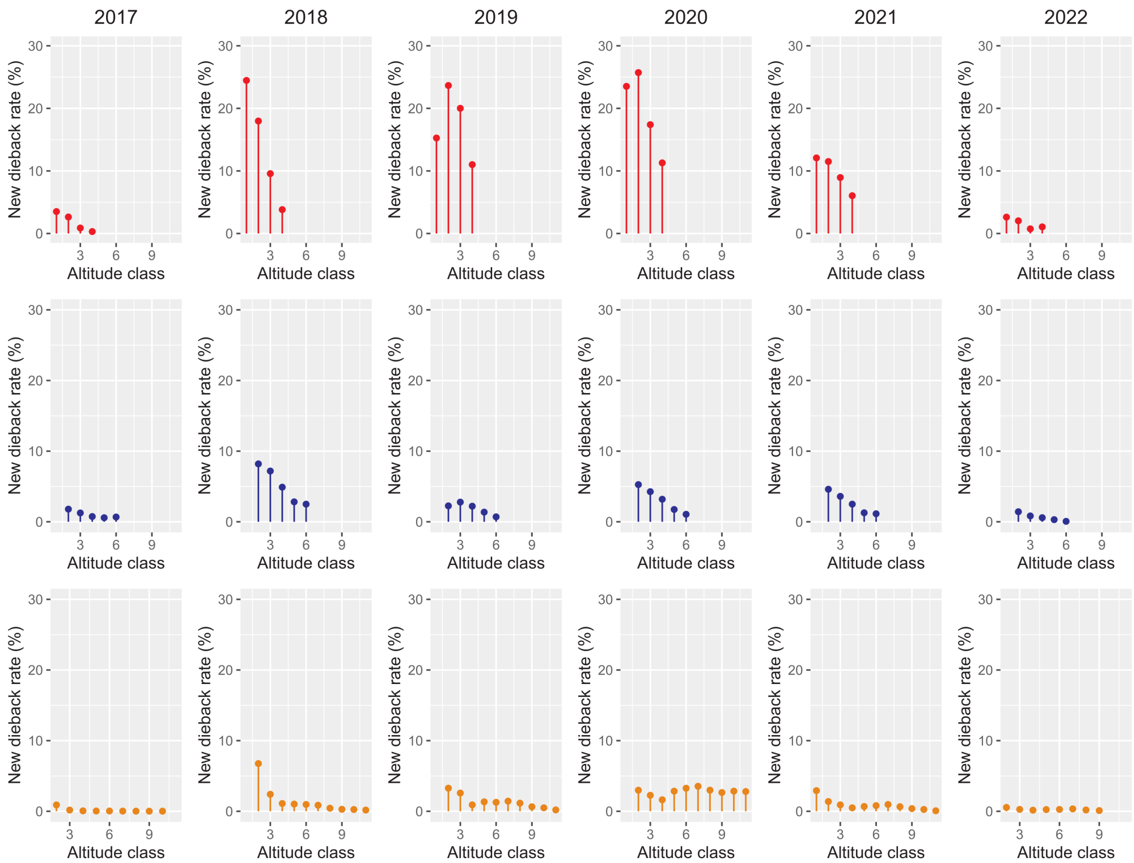

Fig. 5: Variation of the dieback rate from 2017 to 2022 according to the altitude which has been subdivided into 11 altitude classes of 100 m amplitude for the three regions: Plains (red), Ardenne (blue) and Vosges (orange).

is increasing. Except during 2018, at the peak of the crisis, spruce forest above 500 m were not severely affected. In the Vosges, the dieback rate is globally low during the crisis, except for 2020. No clear trend seems to emerge according to the altitude except in the beginning of the crisis in 2018 in the lower stands below 400 m altitude. However,Vosgian spruces are rare below 400 m.

3.4. Influence of topographical exposures on the Norway spruce mortality.

The cumulative killed areas of Norway spruce during five years of crisis according to the topographical exposures is presented in the table 4. The Plains is the most affected bioclimatic area. The north-facing slopes are significantly but slightly more affected than the plateaus or the south-facing slopes. In Ardenne, the plateaus 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 plateaus are significantly more impacted than the north and south-facing slopes.

Table 4: Summary table of area killed by bark beetle in function of topographical exposures during the 2017-2022 period. The same letters (a, b, c) identify homogenous groups with no significant differences for each topographical exposures (based on Pearson's chi-squared test statistic, p-value < 0.05)

	Dieback rate (%)		
	Plains	Ardenne	Vosges
Plateau	51.8^a	11.9^a	7.2^a
South-facing slopes	51.5^a	15.2^b	5.4^b
North-facing slopes	54^b	14.4^c	5.1^c

4. Discussion

4.1. Potential methodological limitations

The detection of bark beetle attack is based on dense time serie of Sentinel 2 satellite imagery. The sanitary map uses a species composition map that depend of the spectral response of the vegetation. This methodology allows to decouple dieback from phenology and other stressors. In pure even-aged Norway spruce stand, the spectral response is stable but at edge of this stand and in mixed stand, this response varies 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 of but in the Vosges forests are more finely mixed. The new dieback rate is influenced by Norway spruce area of the composition map. In Ardenne and in the Plains, the area is correctly estimated. However, in the mixed stands of the Vosges, the area is more difficult to evaluate. An underestimation of dieback rate is not excluded. 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 three correct images are taken by the satellite, the area will be considered as cutted for normal harvesting rather than for a sanitary thinning. On the contrary, some felled trees of sanitary thinnings can be healthy but considered as attacked.

4.2. Dynamic of the dieback

In forest, sanitary crisis lasts on average between three and ten years (Brunier et al., 2020). In our study, the spruce dieback have begun in 2018 and seems to finish in 2022 in all the regions. The new dieback rate has recover the same level than in 2017. The Plains bioclimatic region is the most impacted region. Since the first year of the study, the new dieback rate has increased until it reached its peak in 2020. In the Ardenne, the peak were reached directly in 2018 during the first drought period. A decrease of the dieback occurred during the year 2019. After the peak the dieback rate has stabilised below 3 %. The Vosges were the less impacted bioclimatic area. The peak of the crisis was reached in 2020 with 2.8 % of affected spruce. During the five years of the crisis, the new dieback rate remained below 3 %.

4.3. Regional impact of the bark beetle attacks

The impact of the bark beetle attacks is different between the three main regions. It could be explain through three parameters which differentiate them : the climate, de stand structure and composition, and the current spruce 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) which stressed the spruce. Moreover during warm seasons, the bark beetle produce multiple generations in a year (Annila, 1969; Baier et al., 2007) and can easily attack these stressed trees. At the other hand, pure even-aged spruce stands of the Plains and Ardenne are significantly more sensible to pests attacks (Faccoli and Bernardinelli, 2014; Jactel et al., 2021) then the spruce trees beneficing from continuous cover forestry in mixed stands of the native forest in the Vosges mountains. Rapid harvesting of trees attacked by bark beetles protects stands from severe outbreaks (Stadelmann et al., 2013) but this operation is not systematic in region such as Plains where softwood forestry is not part of the tradition and is not supported by local industry. Faced with these three parameters, the three main regions are not equal. In the Vosges, all parameters are favourable, which could explain the limited outbreak during the crisis (5.7% of 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 52 % 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 then the Vosges. The forest manager generally make the necessary sanitary felling which is part of the silvicultural tradition. However, spruce grows in pure evend-aged stands. These conditions could explain an intermediate situation with damages on 12.2 % of the spruce initial area.

4.4. Influence of the topographical exposures on the dieback of Norway spruce.

The exposure of slopes influences received radiation. 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, there is 50 % less water reserve in south-facing slopes than in north-facing slopes in spring (Rouse and 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 fits not clearly with this hypothesis. In the Plains bioclimatic area, the south-facing slopes and the plateaus are more or less attacked at the same way than the north-facing slopes. In Europe and in north America, Gazol (Gazol et al., 2017) observed that species that grow in drier condition area are more resilient to drought. Piedallu (Piedallu et al., 2022) confirmed this observation in the Vosges during the last outbreak. Moreover in France, a recent study of Nardi et al. (2022) show that Norway spruce stand on the steep slopes and soils with low water availability are less attacked. In this region, spruce trees growing on the southern slopes and plains have suffered of drier conditions throughout their lives 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 could explain the dieback rate difference between de slope and the plateaus. In the Ardenne and in the Vosges, the result are opposed for the plateaus. The damage caused in the

Vosges plateaus could be explain 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 need further investigations. In view of these results, it seems difficult to give global advice for forest managers.

5. Conclusion and perspectives

Our study aimed to assess the evolution of the bark beetle crisis in the spruce forest with remote sensing approach. The methodology used to identify bark beetle damages stands is robust and effective as far as reliable 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 crisis triggered by the dry and warm events from 2018 to 2020 lasted five years and destroyed 14 % (29.000 ha) of the spruce area in Wallonia and Grand-Est of France. In 2022, new bark beetle attacks recover its level of 2017 and seems then over. The damages were not equally distributed on the territory : the Plains are the most impacted regions with more than 50% of the spruce area impacted by bark beetles. The devastated area by this pest is estimated around 11,000 ha. The Ardenne is the second region that has lost the most spruce area with 12,4 % of his spruce area attacked or around 13,400 ha. The Vosges is the less attacked region with 5.7 % of his spruce area killed. The total area impacted in this mountain region is around 4,300 ha. This situation could be linked to the climate, the structure and the composition of the stands, and the current forest monitoring and management which differ between the three regions. Taking account to climate change, which will favour warm and dry events in the near future, our results does not support new plantations of Norway spruce in Plains. In Ardenne, we advise not to plant any more Norway spruce at lower altitude then 400 m except in specific micro-climate. In the Vosges, the trend differs of the two others regions. More investigation specially dedicated to this region is necessary to draw conclusions. A study taking into account 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.

6. Acknowledgements

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