Original research papers

Spruce vulnerability to bark beetle attack vary with altitude and topographic position: a remote sensing analysis in Belgium and 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 (fire, storm, drough) and biotic (pest invasion) will be more recurrent (Lindner et al., 2010). In Western Europe, we expect a decrease of precipitation and a increase of drought events during the vegetation period, which will impact the actual geographic distribution of tree species (Hanewinkel et al., 2013). Due to the long time required to complete a forest revolutions, forest managers have to anticipate likely changes in climate conditions by modifying the forest tree species they used to regenerate at a particular location, in a way that the future environmental conditions of the forest site still meet the species requirements. Norway spruce (*Picea abies L. Karst*) is one of the most important economic plant species in Europe (Nystedt et al., 2013). Its productivity comes with a demanding amount of precipitation, thus making it sensitive to climate changes. Plus, its major pest is bark beetle that cause important outbreak after storm, which provide breeding material e.g. windfalls, candle, or after severe drougth 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 urged the need of adapting forest management practices. Indeed, forest practitioners have to decide now which species will replace Norway spruce in the thousands of clear-cutted hectares decimated by bark beetle attacks. The decision-making of replanting spruce requires a proper understanding of both Norway spruce and bark beetle autecology.

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The Norway spruce is adapted to wide range of environmental conditions, although it prefers cold and humid climate. It is naturally present in part of the Grand-Est (Vosges mountains) and artificially in Wallonia, where it was introduced during the second half of the 19th century (Noirfalise and Thill, 1975). The massive reforestations occurring at this time have led to the formation of large pure even-aged stands. Moist and reasonably fertile soils are favourable for its productive cultivation (Horgan et al., 2003). It usually develops a taproot system with fine roots in shallow depth, although the roots go deeper on restrictive soil conditions (Puhe, 2003). The precipitation are its primary water source (Modrzyński, 2007) and lack of water induces stress that affect growth and health of the tree. The most important pest for Norway spruce are bark beetles species. The bark beetle species *Ips typographus* causes the most important damages. In this paper, bark beetle refers to the species *Ips typographus*. Stressed Norway spruce produce volatile compounds which attract bark beetles, making himself more susceptible to pest attack (Netherer et al., 2015, 2021). Bark beetles are ubiquitous in the forest and their populations are usually low (endemic phasis). Many stressed trees cause 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 (Baier et al., 2007; 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 int the phloem (Hlásny et al., 2021). In North 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). 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, the new generation of beetles emerge and attack 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 the decline and rapid death. The Norway spruce dieback goes through three physiological stages which are denominated green, red and grey stage. In 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 cause 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 solutions are limited. The use of phytosanitary product is forbidden in Belgian and French forest. There is a pheromone trap system but it is not efficient to limit the damage in case of bark beetle outbreak (Kuhn et al., 2022). The only solution to limit the outbreak its to remove felled tree before the swarming to limit the presence of ideal breeding material and realize sanitary cutting when the tree is attacked by bark beetle at the green stage to decrease the bark beetle population.

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 that 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 at studying the extent and the dynamic of the 2017-2021 bark beetle outbreak in Wallonia (Belgium) and in the Grand-Est (France). To this end, we map Norway spruce dieback using S2 time series. Then, we analyse the relationship between forest stands, bark beetle and environmental conditions in order to determine the most sensitive forest sites where Norway spruce should not be regenerated.

2. Material and methods

2.1. Study area

The study area was located in Wallonia (south of Belgium) and in the Grand-Est (north-east of France).

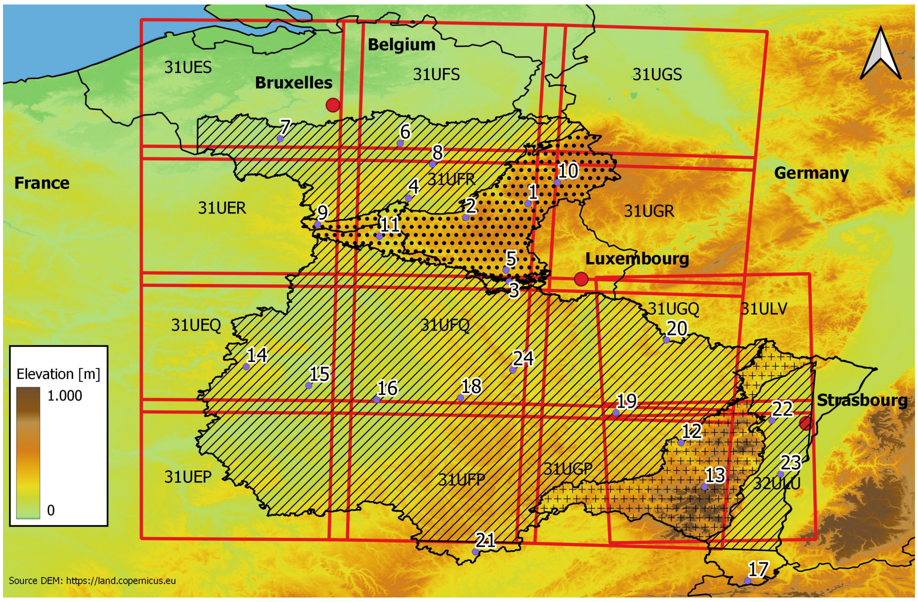

Fig. 1: Study area: Plains (hashed, altitude varying between 100 and 500 meters above see level), Ardenne (black dot, altitude between 100 and 700 m) and Vosges (cross, altitude ranging from 300 to 1300 m). Red squares illustrates the extend of Sentinel satellite 2 tiles which are used for the detection of bark beetle attack.

The walloon forest covers 554 600 Ha. The Norway spruce stand occuped a quarter of Walloon forest (Alderweireld et al., 2015).

Two thirds of the Walloon spruce forest is located above 400m altitude. The Walloon climate is included in the temperate oceanic bioclimatic zone (Lindner et al., 2010).

The Grand-est forest occupies 1 939 000 ha. The Norway spruce covers seven percent of the forest of this region (Inventaire forestier national français, 2022). The majority of Norway spruce stand of this region grow between 400m and 900m. The Grand-est is included in the temperate oceanic bioclimatic zone(Lindner et al., 2010).

We have used the digital surface model data from the Copernicus Land Monitoring Service (European Union, 2022) at a resolution of 25mX25m for all altitude data and slope calculations. We determined the solar orientation using the Delvaux and Galoux (1962) definition of the three topography orientations. Plateau and low slope are slope less than 20% that does not create a particular micro-climate. North facing slopes are slopes greater than 20% facing north. These are shady, cool and humid areas. South facing slopes are slope greater than 20% facing south. In this orientation the air is warmer and drier and the temperature difference between day and night is greater. Based on this definition and on the DEM, we produced topography orientation maps for Wallonia and the Grand-Est.

Climate data for Wallonia have been provided by the Institut Royal Météorologique(IRM). The resolution of the data is 5km X 5km. Climate data of Grand-est come from the data base Digitalis (Piedallu et al., 2014). The resolution of this data is 1km X 1km.

The French natural region and the Bioclimatic area of Wallonia have been grouped by average temperature and precipitation during the growing season in three climatic areas: Ardenne, Plains

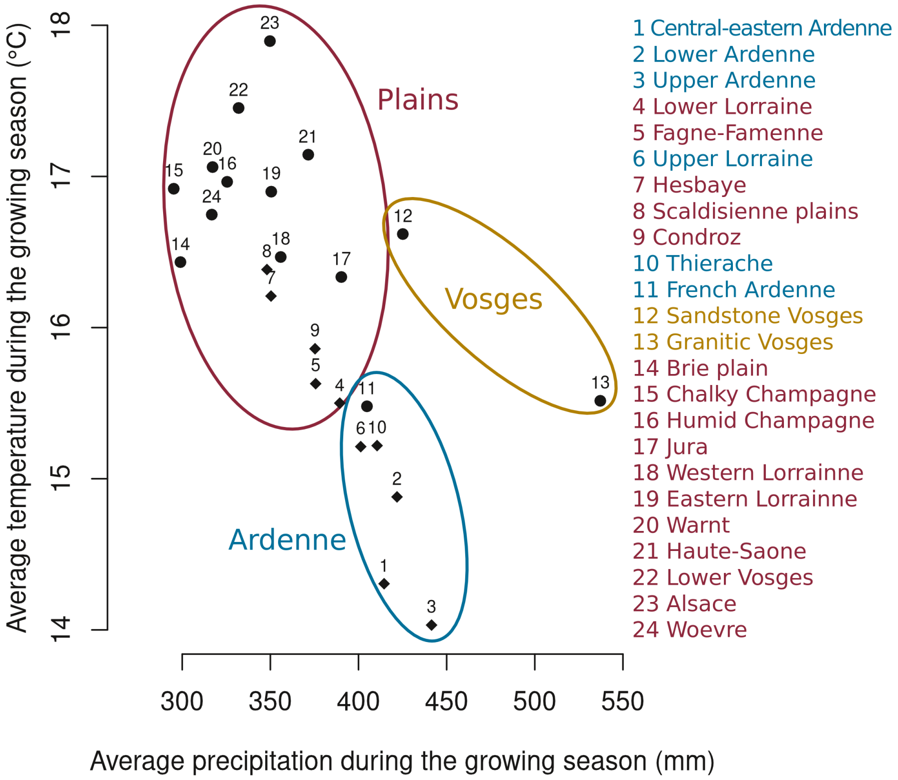

Fig. 2: Grouping of French natural regions according to the temperature and precipitation of the growing season to form three groups: Ardenne (blue), Plains (red) and Vosges (orange). Wallonia natural regions are depicted with diamond-shaped points, and Grand-Est regions are illustrated by rounded points.

and Vosges (Figure 2). The Plains is a group of natural region with growing season temperature between 15.5°C and 18°C and with growing season precipitation between 300mm and 400mm.

The Ardenne is defined a set of natural regions with a temperature of the growing season between 14°C and 15,5°C and a average precipitation during the growing season between 400m and 450 mm. Vosges are natural regions with growing season temperature varies between 15.5°C and 17 °C and the growing season precipitation between 425mm and 600mm. The figure 1 show localisation of the three climatic areas in function of the altitude.

2.2. Mapping of spruce dieback and mortality by analysis of sentinel-2 time-serie

In the present research, the detection of bark beetle infestation is realized by using dense time series of S2 imagery following the methodology developped by Dutrieux et al. (2021). Sentinel-2 (S2) satellites carry multispectral sensor with a ground resolution up to 10 m. The two regions studied are covered by 14 Sentinel-2 tiles (Figure 1). Vegetation changes are tracked by means of a phenology metric, the *SWIR Continuum Removal* ($SWIR_{CR}$) indice. All S2 acquisitions are used in the analyses, provided that the cloud couver do not excess 35 percent. Bottom Of Atmosphere reflectance images (L2A product) are downloaded from the Theia data cluster (Theia Team, 2022) for all the 6 granules, which are tiles of 100km x 100km, that covers Wallonia. For north France, 10 granules cover the Grand-Est. 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 (figure 3). Seasonal variation of $SWIR_{CR}$ for healthy stand is modelled and a bark beetle attack is 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 goes

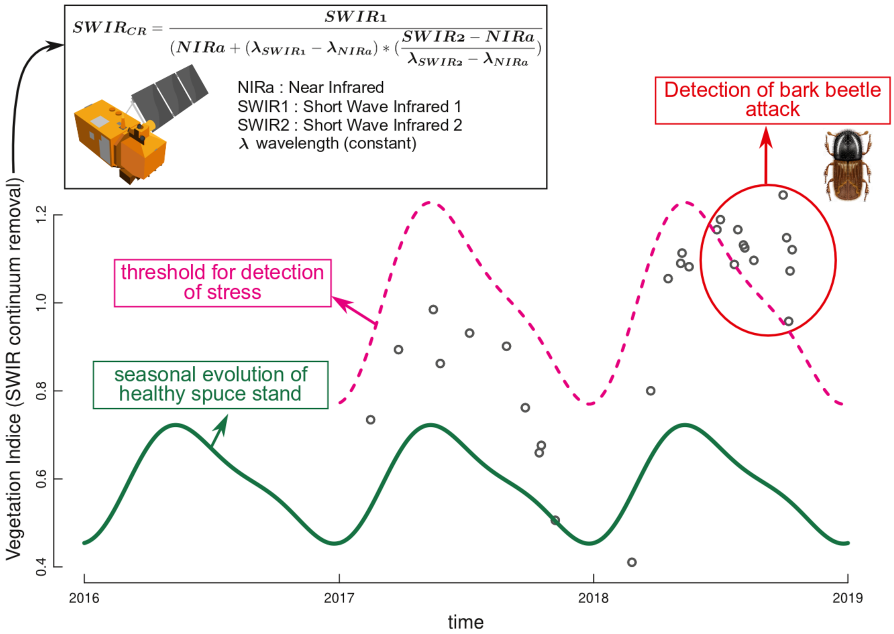

Fig. 3: Bark beetle infestation map are computed by detecting change in the $SWIR_{CR}$ phenology metric. The *SWIR Continuum Removal* is computed using three bands from Sentinel-2 imagery for every single acquisition date and his value is compared to a threshold (purple dashed line) in order to detect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

beyond the threshold represented by the purple-dashed line, which shows that the spruce stand suffer from a serious stress induced by a bark beetle attack. A bark beetle outbreak is confirmed as soon as $SWIR_{CR}$ vegetation indice show a stress for at least three consecutive times. In parallel to the detection of bark beetle stress, stand cutting and thinning are subject of particular attention. Bare soil is detected by using a combination of red, green and shortwave infrared reflectance values. Cutting are thus taken into account and are 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 is thus quite straightforward and is performed individually pixel per pixel starting from the 2016 year, which is the beginning of S2 acquisitions. The dense time-serie covers the 2016-2021 period and count a minimum of 180 acquistion dates. The health status is summarized in annual health maps by means of four classes ; healthy, bark beetle attached, cutted and sanitary thinning.

Our approach of bark beetle detection is only suitable for spruce, as it is closely related to the phenological course of healthy spruce forest. An essential prerequisite is thus to have a proper mapping of spruce stands. For the south of Belgium, we use existing reliable composition maps (Bolyn et al., 2022) computed from remote sensing data in order to restrict our analysis to spruces.

In the Grand-est, the composition map comes from the French Mapping agency (Forest BD version 2). Composition of forest stand is determined by photointerpretation and forest stands identifyed as "spruce or fir" serve as starting point to limit our 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 is to identify and remove every area that are not spruce stand, as pixels located on others species than spruce are 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 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.

2.3. Relation between bark beetle attack and environmental condition

2.3.1. Choice of important variables

To select important variables that influence the Norway spruce dieback, we use the the random forest algorithm (Genuer et al., 2015) in Wallonia. We apply the random forest only in Wallonia. Individual classification trees are trained on a 500 samples of dead spruce stand of 0,25 Ha and 500 samples of healthy stand by randomly selecting a subset of explanatory variables (topographic and climate variable).

2.3.2. Variation of attack along important gradient

For this study, we selected only spruce trees over 15 m and we have worked on 90 500 Ha in Wallonia and on 73 715 ha of spruce in the Grand-est region.

To characterise the bark beetle attacks, we applied the random forest method to select the two topographic factors that most influenced the bark beetle attacks. These two factors are altitude and topography orientation. We broke down the altitude by 100m classes and kept the three topography orientations classes defined by Delvaux and Galoux (1962). Then, in order to determine the classes of these factors most impacted by the bark beetle, we estimated the bark beetle areas for each class of each factor based on the sanitary status maps for each year of the period 2017-2021.

3. Results

3.1. Choice of environmental variable

The altitude and the topographic orientation were selected as explanatory variable by the random forest algorithm. We study the dieback of the Norway spruce in function of this two variables.

3.2. Evolution et importance

The drought touched the western Europe since 2018. However, the outbreaks did not occur at the same time in the different region but the decrease of damage begin in the same year in all of our study area (Figure 4). The first major dieback took place in the Plains in 2018. One year later, the important damage have begun in 2019 in the Vosges and in the Ardenne. The area killed by this resinous pest is detailed in table 1. The area of Norway spruce killed by bark beetle in Ardenne is 13 435 Ha. The maximum of the ratio of area touched by bark beetles during crisis peak in 2019 is 3,4%. A begin of decrease is started in 2021.

In the Vosges, there is 3218 Ha killed by bark beetle. However, the maximum ratio of area affected by this insect is 5,5%. At the peak of the crisis the Vosges are proportionally more affected than the Ardenne.

The Plains group is the group with the most area and proportion of area affected. This regions have three times more area touched by bark beetle than the Vosges. The Plains region reached the maximum of area affected by bark beetles in 2020. The peak of proportion of area impacted is reached at 23,7%. In total, more than half of the spruce stands were affected by bark beetles in this area.

Table 1: Summary table of the crisis

Region	Total Norway spruce area killed by bark beetle (2016-2021)	Total Norway spruce area before crisis
Plains	13665 Ha	25 552 Ha
Ardenne	13435 Ha	101 600 Ha
Vosges	3218,71 Ha	26 327 Ha

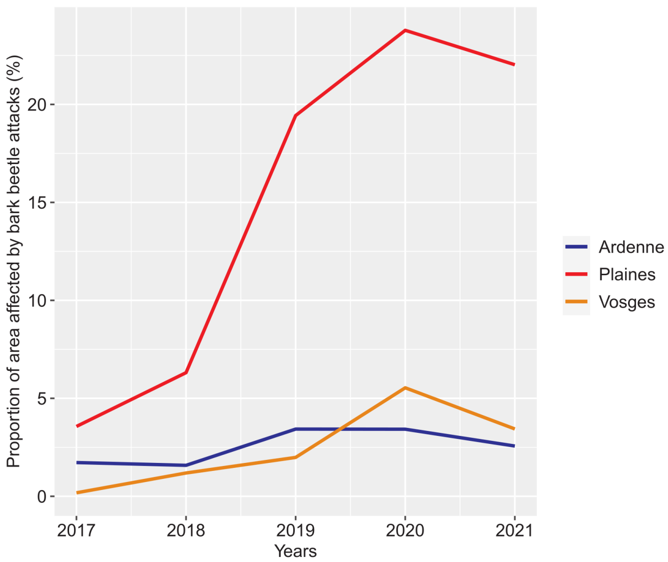

Fig. 4: Proportion of Norway spruce area affected by bark beetle. Plains region in red, Ardenne in blue and Vosges in

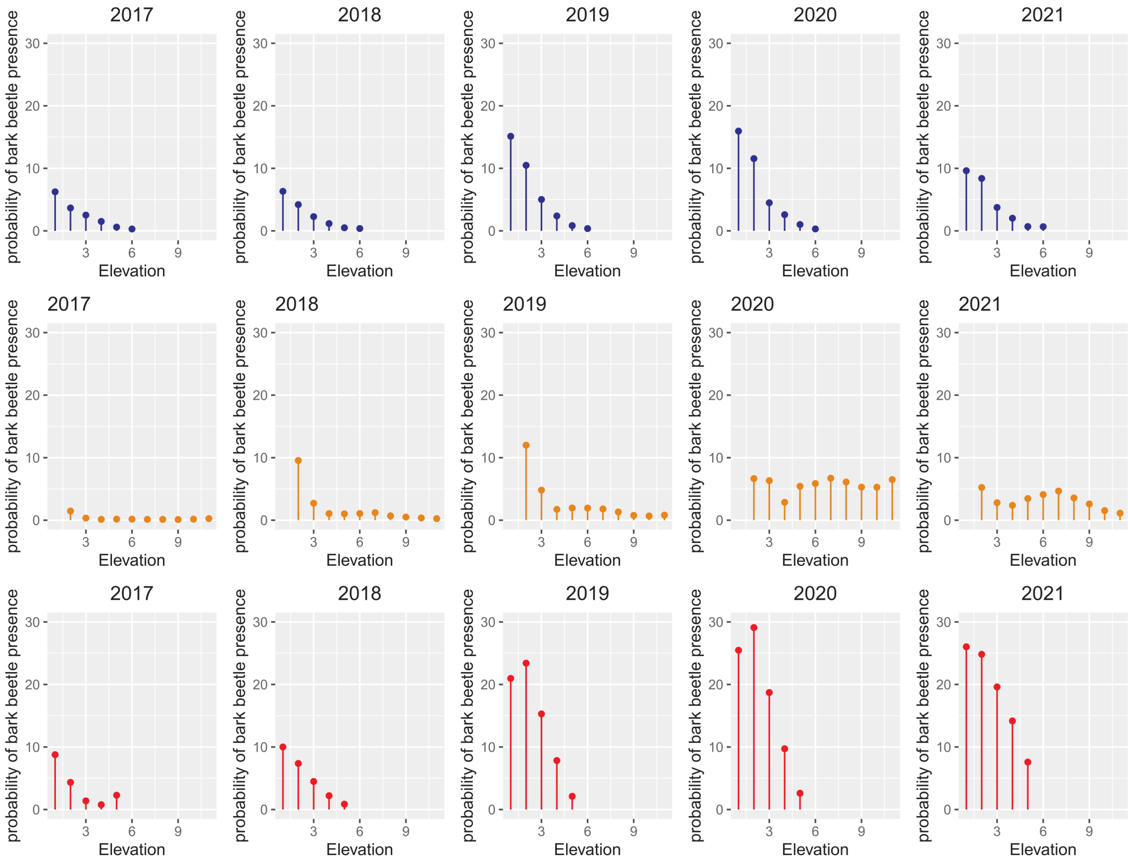

Fig. 5: The altitude has been subdivided into the same 12 altitude classes for both regions. The graphs corresponding to the variation of the probability of presence in Ardenne (blue) are in the upper part of the figure,the Vosges (Orange) in middle part and for the Plains (red) in the lower part.

Climatic area	Thermal sector	Cumulative area affected by bark beetle (Ha).	Norway spruce area before crisis (Ha).	Probability of presence (%)
Plains	North-facing slope	1592	2660	59,8
Plains	Plateau	11337	21450	52,8
Plains	South-facing slope	738	1442	51,1
Ardenne	North-facing slope	2396	14862	16,1
Ardenne	Plateau	9877	79260	12,4
Ardenne	South-facing slope	1165	7475	15,6
Vosges	North-facing slope	1392	35690	3,9
Vosges	Plateau	1280	25052	5,1
Vosges	South-facing slope	546	12975	4,2

3.3. Altitude vs bark beetle presence

The altitude is easily usable for the forest manager. The precipitation in western Europe depend of altitude. The majority of spruce in the Plains is located in low altitude under 400m of altitude in contrast with the Ardenne and the Vosges where the majority of Norway spruce stand grow above 400m. The variation of the probability of presence of bark beetles in the three groups naturals regions for the period 2017-2021 is described in the figure 5.

In Ardenne group, in the begin of the crisis, the low altitude classes are more affect than hight altitude classes. The dieback of Norway spruce occur along a altitudinal gradient. This gradient is confirmed over the 5 years of the study. Indeed, during this year a strong increase in the 100-200m and 200-300m altitude classes is observed. These two altitude classes are more affected during this crisis. The stand located above 400m are weakly attacked with maximum 2,5% of presence.

In Vosges group, there are not altitude classes more affected than other. The low altitude are poorly represent. There are no impact of altitude on the presence of bark beetle. The probability of presence of this insect is inferior of 5 % during the study period.

The Plains group are affected mainly in low altitude with a hight probability of presence of bark beetle. During the crisis the class of altitude 100m-200m et 200m-300m are strongly affected with a probability of presence exceeding 20%. There is also like in the Ardenne group, a diminution of bark beetle attack along altitudinal gradient. The low altitude stand are the more affected stand and are disappearing.

During the five crisis year the trend are similar in the three regions, there is more attack in the low altitude classes.

3.4. Topography orientation vs bark beetle presence

Topography orientation influence the presence of plant and tree species.

This is a parameter easily usable by the forest manager in the field.

In Ardenne, from the beginning of the period to the end, the trend is the same slope are more affected by bark beetles than the plateau. The north and south facing slope are similarly affected until 2020. After 2020, the south facing slope are less impact than the north facing slope. The maximum of attack is reached in 2019 with 4 % in the two orientations slopes.

The Plains group is the most affected. There are not clear trend for the repartition of attack on the topographic orientation. Before 2020, the north facing slope are the most touched by bark beetles. From 2020,the attack in the south facing slopes exceed the attack in north facing slope. The peak of attack is reached during this year.

Before 2019, the Vosges are weakly impacted by bark beetle. The plateau is more affected than the slope. The north-facing slope are more slightly touched than the south-facing slope. However, in 2020 the peak of the crisis is reached. The plateau are always the topographic orientation the most impacted with a proportion of Norway spruce killed by bark beetle of 6,7%. The trend for slopes has reversed. The south-facing slope are more affected.

4. Discussion

4.1. Global trend

In the current study, we found that the plains natural region is most sensible at the attack of bark beetles.

In this natural region, the proportion of attack in 2017 is already over 4 %. This proportion is superior at all maximum of two others regions. The bark beetle is already present in this region because the climate in 2016 was favourable for the development of bark beetle. In fact, the sales data of Department of nature and forest of Wallonia show a increasing volume of Norway spruce infested by bark beetle. The plains region is warmer and with less precipitation than the two others regions. The climate condition are suitable for the multiplication of generation of bark beetle during the year ((Baier et al., 2007) and (Annila, 1969)).

The first major attack of bark beetle have started in the plains in 2018 but the majority of the damage occurred in 2019. The explosion of the ratio of area impacted by bark beetle can be also explain by a non-proactive management of forest in this area.

The sanitation felling allow to limit explosion of bark beetle (Stadelmann et al., 2013). The plains region is not a resinous region and the resinous sawmill are far the forest. The time between the infestation of the stand and the sanitation felling is probably to long and allow more easily a pullulation of bark beetle.

In Ardenne, the peak is reached in 2019. The maximum is 4 %. The climate of ardenne is more suitable for Norway spruce. The climate can explain a the limitation of damage in region. The air masses come to call on the Ardenne massif and important precipitations are created following a foehn effect, allowing the spruce to suffer less from the drought in this region at low altitudes compared to the Vosges massif. At similar altitudes, this foehn effect allows the Ardenne spruce to be less affected by drought than the spruces of the plains.

In the Vosges, the increasing of area impacted by bark beetles is relatively weak. The Norway spruce os a endemic species in the Vosges mountain. The moutain climate protect this resinous species. Besides the vosgian forest is generally mixed with beech (*Fagus sylvatica*) and silver fir (*Abies alba*). Mixed forest are significantly more resitant to pest attack (Jactel et al., 2021).

The difference of proportion affected by bark beetle in Ardenne and Vosges can be expained by type of forest. In Ardenne, the even aged pure stand is predominantly whereas in the Vosges the forest are more mixed.

4.2. Altitude

The Norway spruce is a tree species naturally present on the top of the Vosges mountain (Guinier, 1959). It was introduced in the low altitude Vosges and in all part of the Ardenne and the Plains.

All of spruce species need important amount of water. In the Plains, all classes of altitude are touched more than 10 % during the crisis except for the classe 500-600m. The altitude didn't protect the tree during the drought. All of this stand are artificial stand plant in area not adapted for mountain tree. In the Ardenne from 300m to 700m the forest have been affected to a maximum of 5%.

The weak damage can be explain by increase precipitation with altitude (Kotlarski et al. (2012), Roe (2005)). The Norway spruce is less stressed in hight altitude than in low altitude. The beetle can also affect by this increase of precipitation to swarm.

Besides, in low altitude the temperature are higher than in hight altitude. The number of generation depend of the temperature. And thus higher temperature produce more damage cause by the the supplementary generation.

The altitude influence the choice of the place of overwintering of bark beetle. The quantity of bark beetle that overwinters under the bark decrease with altitude (Kasumović et al., 2019). The litter insulate better the beetle of the freeze (Lombardero et al., 2000) than the bark. However, the metabolism of bark beetle need energy from 5°C (Košťál et al., 2011).

- Différence climat (Climat semicontinental/montagnard vs climat tempéré océanique)
- Différence sylvicole (Wallonie futaie régulière exploitable vs Vosges peuplement + mélangé et moins exploitable en haute altitude)
- Sommet des vosges epicéas endémiques vs épicéas en plantations (résilience peuplement)
- adaptation ep à condition plus rude en versant sud que nord D'après la theorie il devrait y avoir plus de generation sur versant sud car car + chaud et donc pluys touché Seuil letal ou the letargie atteint en versant sud?
- meilleur surveillance des forestiers sur versant sud que nord

4.3. Topography orientation

The orientation of slope influence the presence of vegetation. The north facing slope receive less radiation than south facing slope. The life cycle of the bark beetle is influenced by temperature (Baier et al. (2007), et ...). South facing slope are warmer than north facing slope. Bark beetle make more generation of bark beetles in this area . However in France, Nardi et al. (2022) show that steep slopes and soils with low water availability are less attacked.

In our study, we found that in the Vosges the slope are less impacted than the plateau. For the year 2019, we have the same result that Nardi et al. (2022). The south facing slope are less affected than the north. However, in 2020, the trend has been reversed the south slope are more affected than the north slope. This change is likely to have occurred with the increase of stress with a third dry summer in 2020.

In the plains, before 2020, the north facing slope are also more affected than the others topography orientations. Nevertheless, in 2020 there is a inversion of the trend. The south-facing slope are the most impacted and north facing slope the less.

In Ardenne, the slope are more affected than the plateau. The plateau are probably less affected because the major part of the plateau are located above 400m of altitude. Moreover, this area stay cold in the summer and limit the number of generation of bark beetles and the stress of Norway spruce. The north-facing and south-facing slope are similarly affected until 2021.

4.4. Potential limitations

The detection of bark beetle attack is based on Sentinel 2 satellite imagery. The methodology use Norway spruce mask. In pure even aged Norway spruce, the method works well. However, in mixed forest, the Norway spruce mask is less accurate than in pure even aged. In fact, our sanitary map resolution is 10m and if there some deciduous tree or others resinous in the Norway spruce mask, there is a risk of error. In Ardenne and in the Plains, there is principally pure even aged stand of Norway spruce but in the Vosges the stand are more mixed. In this region, there is more risk of presence of beech and silver fir in our Norway spruce mask.

We overestimated probably the Norway spruce area in the Vosges region.

5. Conclusion and perspective

In the context of global change, the forest manager need to adapt its silvicultural choices. In our study, we try to identify wich are the topographical variable that influence the dieback of Norway spruce. In this study, we show that it is very risky to make new plantation of Norway spruce at low altitude below 400m in the three regions. In the Ardenne, we recommend the plantation of this tree species on the plateau and in the Vosges on slopes. Our data does not support the new plantation of Norway spruce in Plains.

6. Figure

7. Acknowledgements

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