Original research papers

Topographic position effects on Bark beetle damqges on spruce differs between Belgium and north France : a remote sensing analysis of 2016-2021 dieback

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Abstract

Following the droughts of 2018 to 2020, numerous norway spruce diebacks were caused by bark beetles outbreaks in Wallonia and in the Grand-Est. A methodology for detection the health status of spruce was developed based on satellite imagery from the European Union's Earth Observation Programme. The time series of satellite images allowed the modelling of the spectral response of healthy spruce forests over the seasons. Deviations from this seasonal vegetation index trajectory for a healthy spruce stand are caused by a decrease in photosynthetic activity of the forest canopy. This decrease in photosynthesis is caused by a bark beetle attack and is detected automatically. This technique, inspired by the work of INRAe, is robust because of the redundancy of the information from the spatial images, which are repeated every 3-4 weeks. The method results in the production of annual maps of the health status of the Walloon and Grand-Est spruce forests. The most important damage occurred in the years 2018-2019, affecting 2.8% of the total area of spruce stands in Wallonia. Although the main part of the crisis seems to be behind us, it remains to draw the necessary conclusions. The relationship between climatic conditions and the presence of the bark beetle has proven to be complex in Wallonia. Nevertheless, a very strong relationship between altitude and the presence of bark beetle damage could be demonstrated. Stands below 300m in altitude were indeed much more affected. Moreover, forest sites located on steep slopes (¿ 20 %), whether on cold or warm slopes, are more affected than sites located on low slopes (plateaus). In the Grand-Est, the peak of the crisis has been reached in 2019-2020. Altitude and slopes are not strongly influencing factors for spruce dieback.

Keywords:

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1. Introduction

Global changes imply an increase of disturbances in the forest environment. Frequency and intensity of abiotic (fire, wind, drough) and biotic (pest invasion) will be more and more recurrent (**?**). Since one decade, principals timber species are affected by sanitary crisis. Norway spruce (*Picea abies L. Karst*) occurs widespread throughout central and western Europe and is one of the most important economic plant species in Europe (**?**). Since the beginning of the 19 th century, this species has been used to reforest European forests (**?**).These massive reforestations have generally led to the formation of pure even-aged stands.

The norway spruce is a species that is naturally present in part of the Grand-Est (Vosges moutains) and artificially in Wallonia. The norway spruce was introduced into Wallonia in the second half of the 19th century (**?**). This resinous species has taproot sytem with fine roots in shallow depth adapted to intercept rainfall. The precipitation are its primary water source(**?** in **?**). In the context of global change, this two regions will suffer in the future of a diminution of precipitation and a increase of drought period in summer. This climate impact the range of tree species in Europe (**?**). The lack of water for norway spruce involves stress. When this species is stressed, it produces volatile compounds (**?**). This extreme event impact the growth and the health of the tree. In condition of stress, the tree is more susceptible to pest attack (**?**). The two most important pest for this species are two bark beetles species: *Ips typographus* and *Pityogenes chalcographus*. *Ips typographus* cause the most part of damage. Generally the outbreak of bark beetle are linked with windthrow but also with drougth. There are 6 000 species of bark beetle. They play a important role in the cycle of ecosystem. However some species of bark beetles comes into conflict with human because they attack the use the same resource(**?**).The cycle of life of *Ips typographus* depend on temperature and photoperiod (**??**). After swarming, the adult enter in the bark of weakened tree and burrow wood to make brood gallery. They mate and lay the eggs in this gallery. Eggs mature to larvae in the phloem of the tree and will eat the phloem (**?**). After the maturation the new beetle emerge to attack new norway spruce. The old adult can re-emerge and produce one sister brood (**?**). The level of population can be in endemic phasis with low damage but when the condition are favourable for the bark beetle (climate or stressed tree), this level can progress in a epidemic phasis(**?**). During epidemic phases all health levels of trees can be attacked.

The forest site conditions are important for the good growth and health of the tree. The forest site varies with topography and climate (**?**). The non suitability of the tree species for the forest site increase the vulnerability (**?**).

Since 2018, massive bark beetle attacks killing spruce trees have been occurring in Wallonia and in the Grand-Est. Following these events, foresters have asked themselves about certain topographical factors that seem to have strongly influenced bark beetle attacks. The spruce forests located at low altitude seem to have been more affected as well as the stands located on southern slopes. The aim of this paper is to describe bark beetle attacks between 2017 and 2021 and give silvicultural advice to limit damage in the future norway crisis.

2. Material and methods

2.1. Study area

The study area was located in the south of Belgium and in the north east of France. We study 2 regions: Wallonia and Grand-Est (Figure 1). In Wallonia, the altitude varies between 100 and 700m. The walloon forest covers 554 600 Ha. The norway spruce stand occuped 139 600 Ha (**?**). Two thirds of the Walloon spruce forest is located above 400m altitude. The Walloon climate is located in the temperate oceanic bioclimatic zone (**?**). Over the 1989-2020 period, the average temperature vary between 8,7°C and 10,7°C and the average sum of rainfall range from 800m and 1120mm. During 2018, the average temperature was 9°C between 11,7°C and the average sum of rainfall varie between 605 mm and 1015 mm (data of Institut Royal Météorologique). In the Grand-Est, the elevation is between 100m and 1300m. The Grand-est forest occupies 1 939 000

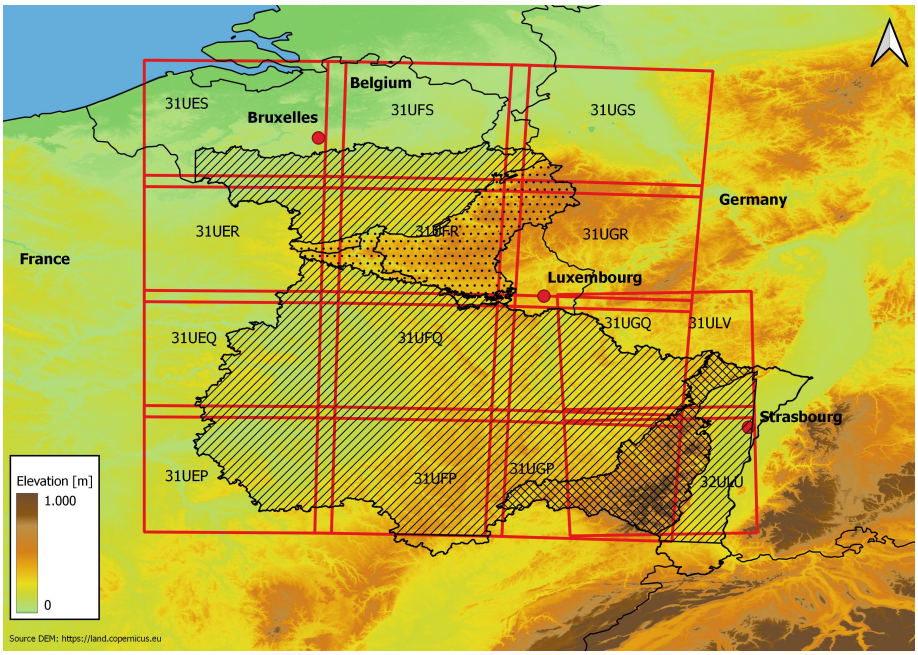


Fig. 1: Study area: Grand-est(hashed) and Wallonia (black dot), tile Sentinel 2 (red square)

ha. The norway spruce forest covers 136 000 Ha (**?**). 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(**?**). During the 1989-2020 period, the average temperature was between 8,4°C and 11,2°C et the average sum of rainfall range from 720 mm and 1475 mm. During the year 2018, the average temperature vary between 10,16°C and 12,4°C et the average sum of rainfall was 640 mm and 1362mm.

This two regions have been divided with natural regions. We form three group in fonction de precipitation and temperature of this natural regions (Figure 2).

The Ardennes group wich temperature of the growing season varies from 14 °C to 15,5°C and average precipitation between 400m and 450 mm. The growing season temperature varies 15.5°C and 17 °C and the growing season precipitation between 425mm and 600mm for the Vosges group. The Plaines group are natural region with growing season temperature between 15.5°C and 18°C and with growing season precipitation between 300mm and 400mm.

2.2. Description of environmental description

We have used the digital surface model data from the Copernicus Land Monitoring Service (**?**) at a resolution of 25mX25m for all elevation data and slope calculations. Solar orientation influences bark beetle capture in pheromone traps (**?**). We determined this solar orientation using the **?** definition of the 3 topography orientations. Plateau and low slope are slope less than 20% that does not create a particular micro-climate. Cold slopes are slopes greater than 20% facing north and valley bottom. These are shady, cool and humid areas. Warm 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 (**?**). The resolution of this data is 1km X 1km.

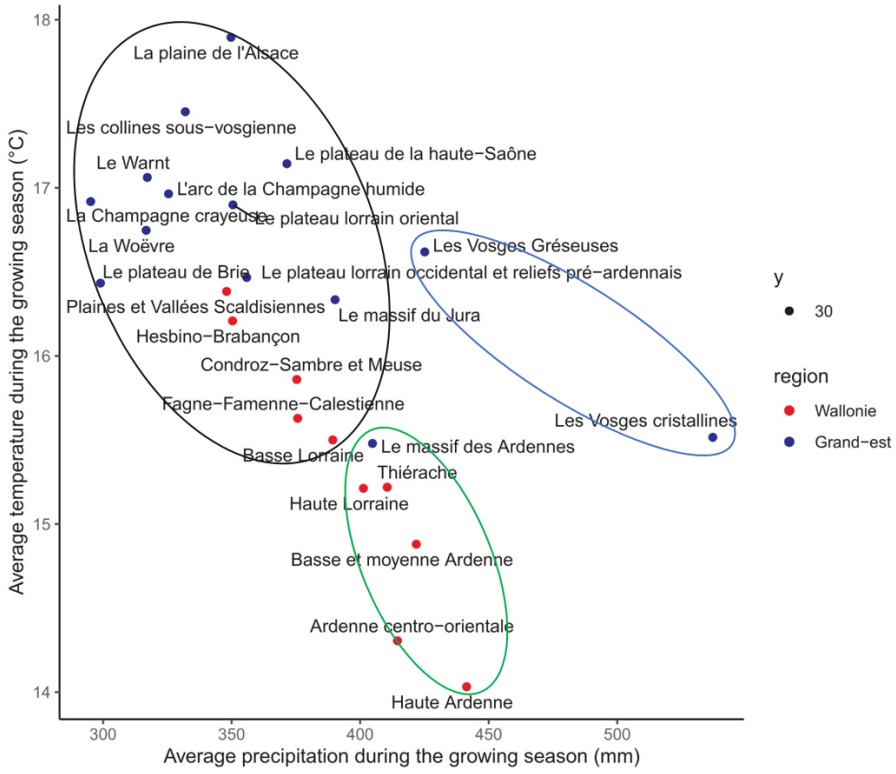

La plaine de l'Alsace
Les collines sous−vosgienne
Le Warnt
Le plateau de la haute−Saône
L'arc de la Champagne humide
La Champagne crayeuse
Le plateau lorrain oriental
La Woëvre
Les Vosges Gréseuses
Le plateau de Brie
Le plateau lorrain occidental et reliefs pré−ardennais
Plaines et Vallées Scaldisiennes
Le massif du Jura
Hesbino−Brabançon
Condroz−Sambre et Meuse
Fagne−Famenne−Calestienne
Les Vosges cristallines
Basse Lorraine
Le massif des Ardennes
Thiérache
Haute Lorraine
Basse et moyenne Ardenne
Ardenne centro−orientale
Haute Ardenne
Average temperature during the growing season (°C)
Average precipitation during the growing season (mm)
18
17
16
15
14
300
350
400
450
500
y
30
region
Wallonie
Grand−est

Fig. 2

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

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. Sentinel-2 (S2) satellites carry multispectral sensor with a ground resolution up to 10 m. S2 imagery have been intensively used recently for forestry purpose, including for the monitoring of bark beetle outbreaks. Low and Koukal (**?**) have modelled phenology courses of vegetation indices to detect forest disturbances. They have properly mapped Bark beetle infestation in Austrian spruce stands. **?** have used multi-years time series remote sensing data in order to detect early bark beetle infestation in Germany. They have highlighted the potential of S2 data for the production of reliable infestation maps. **?** have studied spectral trajectories of nine bands and six vegetation indices from S2 imagery for the 2018 vegetation season. They have confirmed the superiority of multi-date data for the classification by Random Forest of infested stands in the Czech Republic.

In this present research, the detection of bark beetle infestation is realized by using dense time series of S2 imagery following the methodology developped by **?**. 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 (**?**) 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 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 (**?**) 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 (**???**). 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

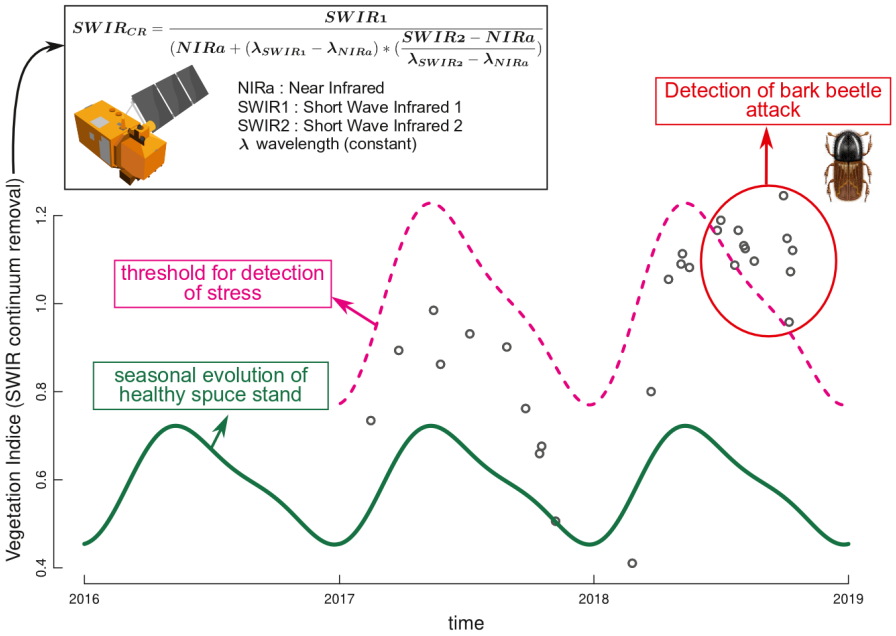


Fig. 3: Bark beetle infestation map are computed by detecting change in the $SWIR_{CR}$ phenology metric. The *SWIR Continuum Removal* is computed using three bands from Sentinel-2 imagery for every single acquisition date and his value is compared to a threshold (purple dashed line) in order to detect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

(**?**). 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.

2.4. Relation between bark beetle attack and environmental condition

2.4.1. Choice of important variables

We try to choice the two most important environmental variable that influence the attack of bark beetle. We make a resample spruce mask in tile of 50mX50m (the minimum area to make productive silviculture). Each tile corresponds to a productive stand. We extract for all of stand the value of environmental variables. To select the important variables influenced the attack of bark beetle, the random forest algorithm is used (**?**). Individual classification trees are trained on a 1000 samples of spruce stand of 0,25 Ha by randomly selecting a subset of explanatory variables.

2.4.2. 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 125 800 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 **?**. 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 2016-2021.

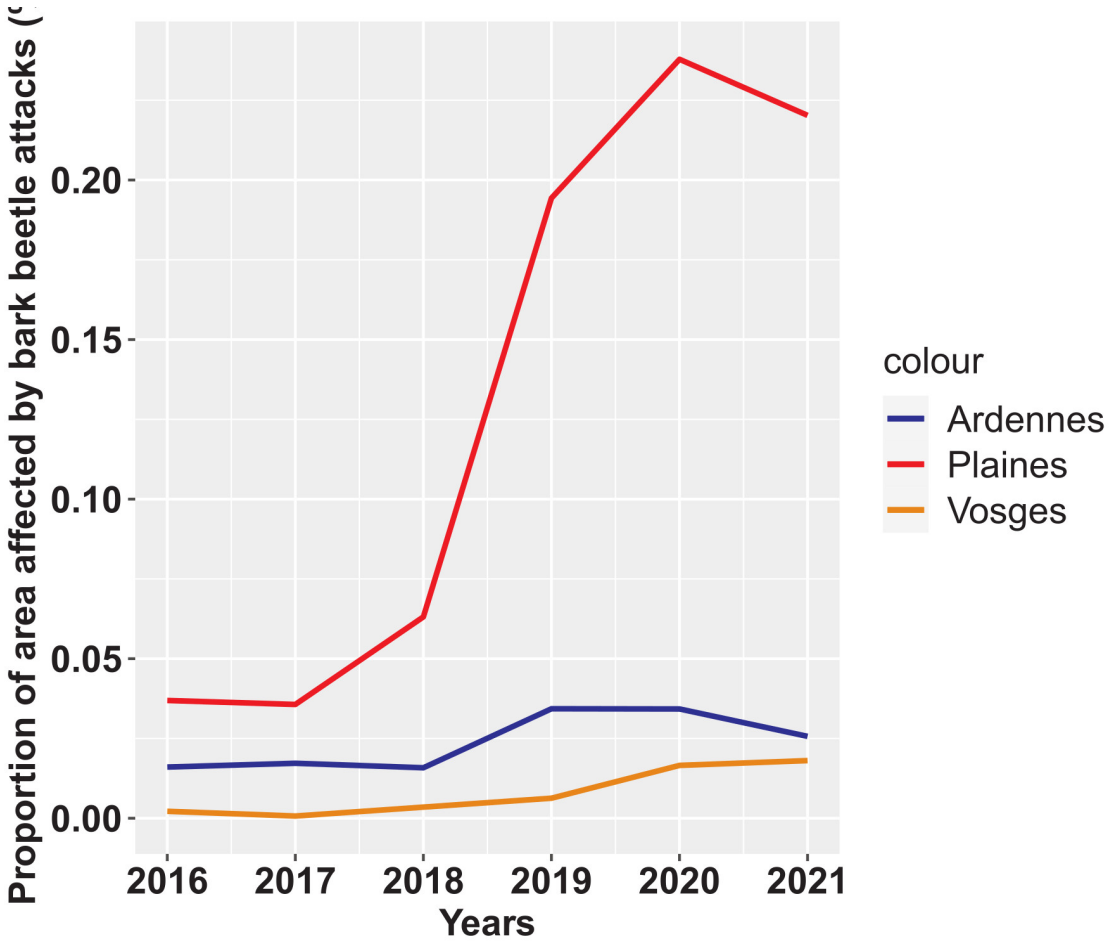


Fig. 4

3. Results

3.1. Choice of environmental variable

3.2. Evolution et importance

The evolution of the crisis differs between these three regions.

In the Ardennes, the peak of attack is reached in 2019. The maximum of the ratio of area touched by bark beetles is 4%. A begin of decrease is started in 2021.

In the Vosges, the peak is not yet reached. However, the maximum ratio of area affected by bark beetlmes is inferior of 2,5%. This group is the less impacted.

The Plains group is the group with the most proportion of area affected by this beetle. The Plains region reached the maximum of area affected by bark beetles in 2020. The peak is 28%.

3.3. Elevation vs bark beetle presence

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 Ardennes 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

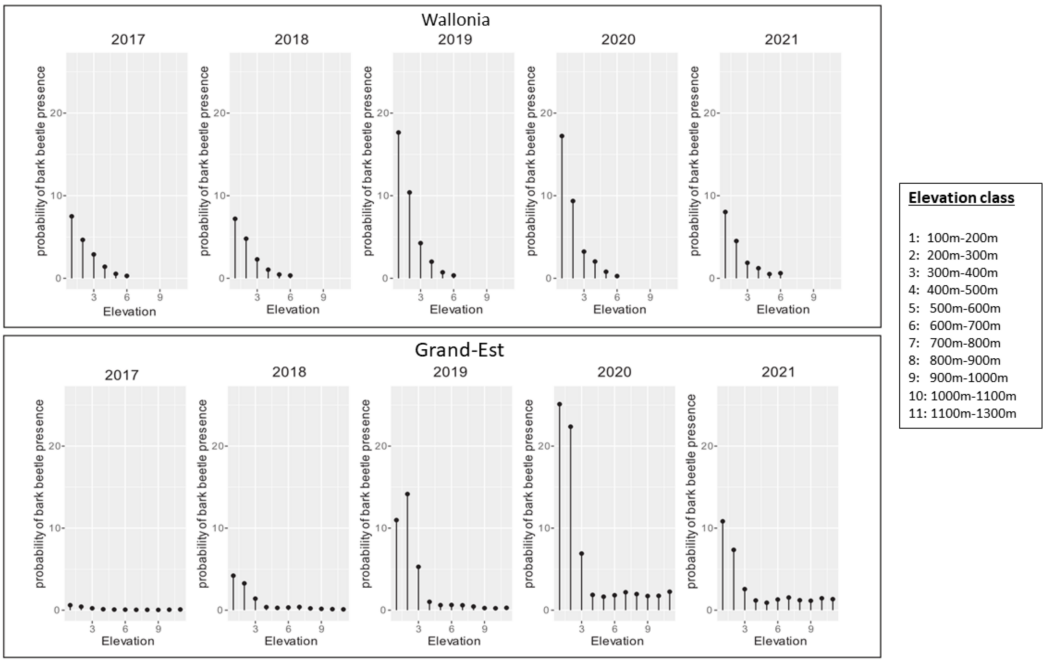
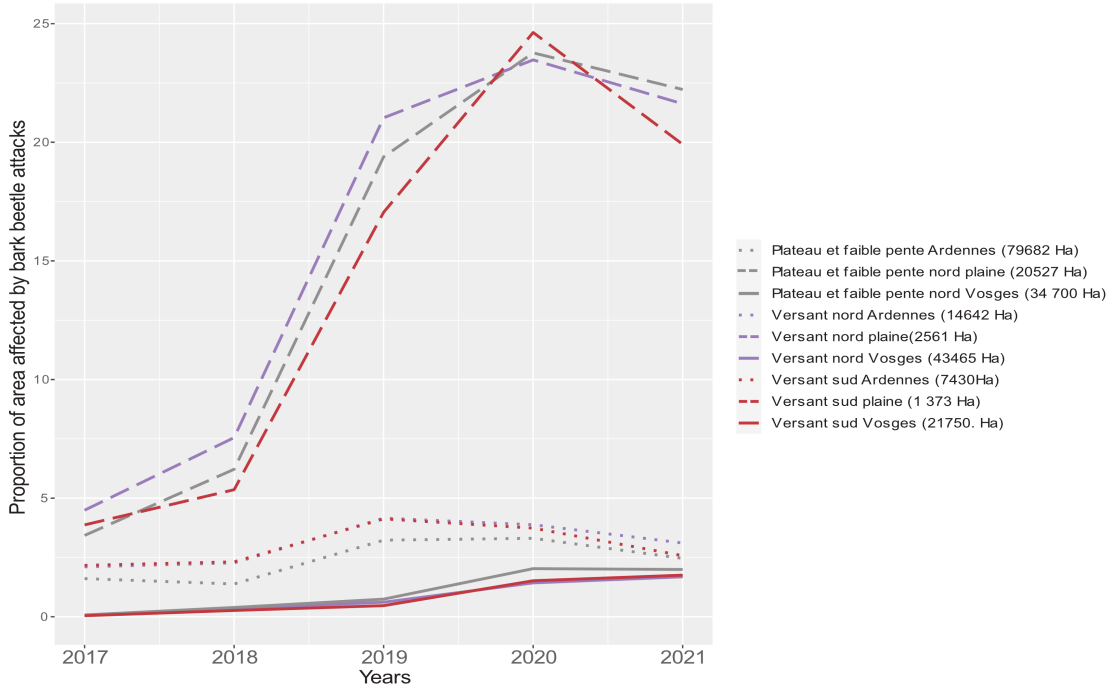


Fig. 5: The altitude has been subdivided into the same 12 elevation classes for both regions. The graphs corresponding to the variation of the probability of presence in Wallonia are in the upper part of the figure and those for the Grand-Est in the lower part.



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 elevation 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 elevation with a hight probability of presence of bark beetle. During the crisis the class of elevation 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.

3.4. topography orientation vs bark beetle presence

In Ardennes, from the beginning of the period to the end, the trend is the same slope are more affected by bark beetles. The north and south slope are similarly affected. 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. Before 2020, the north slope are the most touched by bark beetles. From 2020,the attack in the south slopes exceed the attack in north slope. The peak of attack is reached during this year.

The Vosges group is the group of natural region that are the less infested by bark beetle. Before the peak in 2020, there is no trend. However in 2020, the plateaus are more affected than slopes. The trend seem decrease in 2021.

3.5. Evolution et importance

The evolution of the crisis differs between these two neighbouring regions. In Wallonia, during the year 2017 and 2018, there are already norway spruce affected by bark beetle in low elevation but the probability of presence is under 10%. In 2019, the peak is reached in all of classe of elevation. During this year, the percentage of area of the Wallon norway spruce stand affected by bark beetle is 2.8%. In 2020, there a little diminution of attack. During 2021, there are important diminution of area impacted by bark beetle. The probability of bark beetle presence returns to the same level as begin the crisis.

In Grand-Est, during 2017, the attack of bark beetle are weak. In 2018, there are first attack at low elevation but always below 5%. In 2019, the increasing of attack at low altitude continues. In 2020, in all altitude classes are impacted by bark beetle. Between 100m an 400m of altitude there are a important augmentation of the probability of presence. The maximum of area affected is reached. During 2020, there is 4% of the total area of spruce stand of Grand-est that area affected by bark beetle during 2020.

4. Discussion

4.1. Différence entre Vosges et Wallonie

- 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

4.2. Facteur déterminant l'attaque par l'épicéa ou le scolyte

- Discussion généralisation de modèle scolyte/ dépérissement des épicéas
- est ce la Biologie du scolyte/ ou le stress de l'épicéa qui conditionne le dépérissement massif ?

5. Conclusion

6. Figure

7. Acknowledgements

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