Original research papers

Bark beetle infection of spruce differs between Belgium and north France : a remote sensing analysis of 2016-2021 dieback

Gilles Arthur[1], Lisein Jonathan[1], Lemaire Jean[2], Cansel Juliette[2], Claessens Hugues[1]

Abstract

Following the droughts of 2018 to 2020, numerous norway spruce diebacks were caused by bark beetles (Ips typographus/ Pityogenes chalcographus) outbreaks in Wallonia and in the Vosges. 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:

Email address: arthur.gilles@uliege.be (Gilles Arthur)
[1]Liège University - Faculty of Gembloux Agro-Bio Tech - unit of forest ressources managment
[2]Centre National de la propriété forestière

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 (Lindner et al., 2010). Since one decade,principals timber species are affected by sanitary crisis. Norway spruce (*Picea abies L. Karst*)occurs widespread throughout central and western Europe.The spruce is one of the most important economic plant species in Europe (Nystedt et al., 2013). Since the beginning of the 19 th century, this species has been used to reforest European forests (von Teuffel et al., 2004).These massive reforestations have generally led to the formation of pure 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 (Noirfalise and Thill, 1975). This resinous species has taproot sytem with fine roots in shallow depth adapted to intercept rainfall. The precipitation are its primary water source. In the contexte 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 repartition of species in Europe central (Hanewinkel et al., 2013). This climate evolution is unfavorable for the norway spruce in summer that assimilates the major part of his need of water by intercepting precipitation. The lack of water for norway spruce involves stress. When this species is stressed, it produces volatile compounds. This very important species for wood industry surfer of drought. 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 (seidle) 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(Raffa et al., 2015).In fact, the cycle of life of *Ips typographus* depend of temperature and the photoperiod (Baier et al., 2007) and (Annila, 1969). According to (Baier et al., 2007), the swarming begin when thermal sum (with daily maximum temperature of 140 +- 23,68 dd (with Temperture minimum of 8,3°C) is reached after 1 april. 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 (Hlásny et al., 2021). The development of the larvae to adult need to cumulate 557 dd (Baier et al., 2007). After the maturation the new beetle emerge to attack new norway spruce. The old adult can re-emerge and produce one sister brood. The distance of fly of this old beetle is small (Zolubas and Byers, 1995). The level of population for species can be in endemic phasis. This level can be evoluate in a epidemic phasis when droughts or winthrows happen. During epidemic phases all health levels of trees can be attacked. The forest site condition are important for the good growth and health of the tree. We decide to work on two important factors of the forest site: elevation and radiative sub-sector.The aim of this paper is to characterize bark beetle attacks for two important forest sites factor (altitude and radiative sub-sector) between 2017 and 2021.

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. This two regions are covered by 14 Sentinel-2 tiles (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 (Alderweireld et al., 2015-04). For this study, we selected only spruce trees over 15 m and we have worked on 90 500 Ha in Wallonia. Two thirds of the Walloon spruce forest is located above 400m altitude. The Walloon climate is located in the temperate oceanic bioclimatic zone(Lindner et al., 2010). Over the 1989-2020 period, the average temperature vary between 8,7°C and 10,7°C et the average sum of rainfall range from 800m and

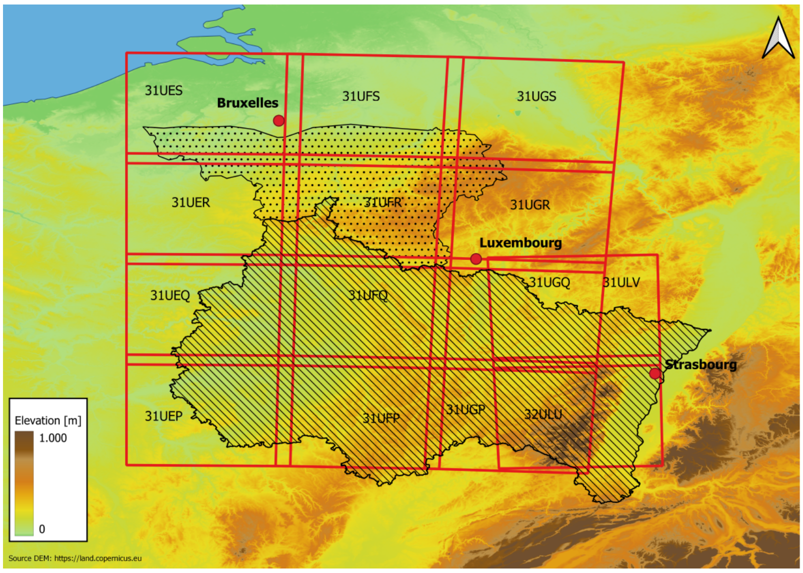

Fig. 1: Zones d'études avec le MNT (XXX) et les tuiles du satellite Sentinelle 2 employées(XXX légende carré rouge).

1120mm. During 2018, the average temperature was 9°C between 11,7°C et 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 ha. The norway spruce forest covers 136 000 Ha (Inventaire forestier national français, 2022). In this study, we worked on 125 800 ha of spruce in this region. 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). 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. The 3 primary regions of production of norway spruce in Wallonia are the "Basse et Moyenne Ardenne", "Ardenne centro oriental" and the "Haute ardenne" (Van der Perre et al., 2015). In the Grand-Est, the major part of the norway spruce stand is located in the 3 naturals regions of the Vosges (Vosges Gréseuses, Vosges cristallines, les collines sous-vosgiennes). For the growing season, in this 2 primary regions of production of noraway spruce, there are a lack of 100 mm of water for 2018 and there is a increasing of 1,7 °C compared to 30-year temperatures.(Figure 2).

2.2. DEM and Slope orientation

We have used the digital surface model (DEM) data from the Copernicus Land Monitoring Service (Union, 2022) at a resolution of 25mX25m for all elevation data and slope calculations. Solar orientation influences bark beetle capture in pheromone traps (Mezei et al., 2012). We determined this solar orientation using the Delvaux and Galoux (1962) definition of the 3 radiative sub-sectors. Plateau and low slope are slopeq less than 12° or 20% that does not create a particular microclimate. Cold slopes are slopes greater than 12° or 20% facing north and valley bottom. These are shady, cool and humid areas. Warm slopes are slope greater than 12° or 20% facing south. In this sub-sector 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 radiative sub-sector maps for Wallonia and the Grand-Est.

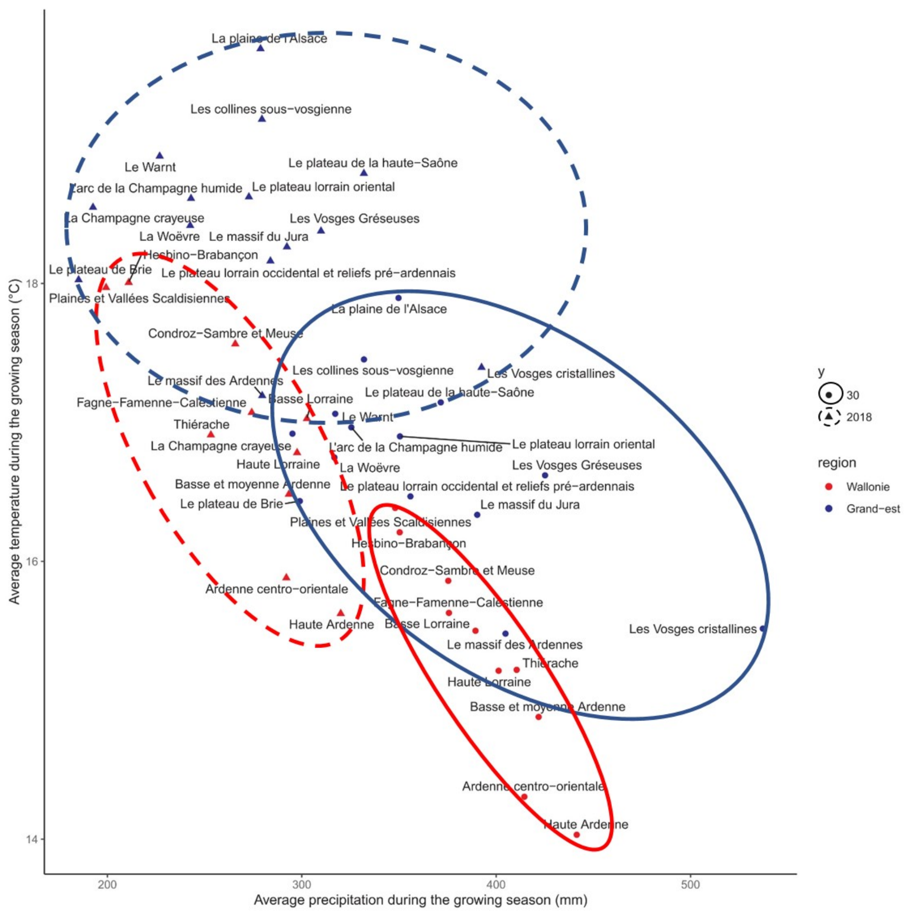
Average temperature during the growing season (°C)
Average precipitation during the growing season (mm)
y
30
2018
region
Wallonie
Grand-est
La plaine de l'Alsace
Les collines sous-vosgienne
Le Warnt
Le plateau de la haute-Saône
L'arc de la Champagne humide
Le plateau lorrain oriental
La Champagne crayeuse
Les Vosges Gréseuses
La Woëvre
Le massif du Jura
Hesbino-Brabançon
Le plateau de Brie
Le plateau lorrain occidental et reliefs pré-ardennais
Plaines et Vallées Scaldisiennes
Condroz-Sambre et Meuse
Les Vosges cristallines
Le massif des Ardennes
Basse Lorraine
Fagne-Famenne-Calestienne
Thiérache
Haute Lorraine
Basse et moyenne Ardenne
Ardenne centro-orientale
Haute Ardenne

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 (Löw and Koukal, 2020) have modelled phenology courses of vegetation indices to detect forest disturbances. They have properly mapped Bark beetle infestation in Austrian spruce stands. Ali et al. (2021) 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. Bárta et al. (2021) 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 DUTRIEUX et al. (2021). 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 (Team, 2022) for all the 6 granules, which are tiles of 100km x 100km, that covers Wallonia. For north France, one single granule covers the Vosges mountains. 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 (Bolyn et al., 2018) computed from remote sensing data in order to restrict our analysis to spruces.

In Vosges mountains, 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

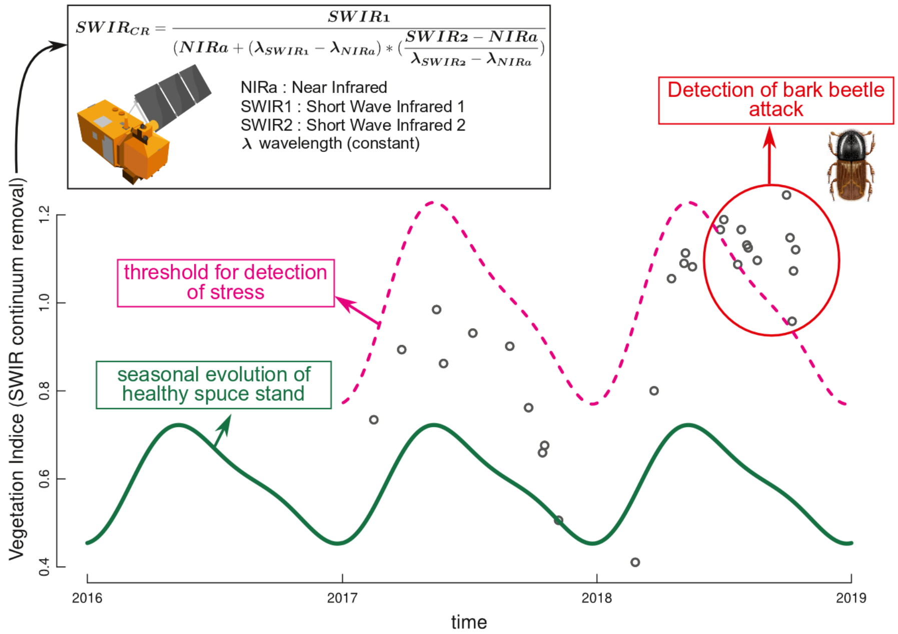

Fig. 3: Bark beetle infestation map are computed by detecting change in the $SWIR_{CR}$ phenology metric. The *SWIR Continuum Removal* is computed using three bands from Sentinel-2 imagery for every single acquisition date and his value is compared to a threshold (purple dashed line) in order to detect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

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.

2.4. Data analysis

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. 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 sub-radiation. We broke down the altitude by 100m classes and kept the three sub-sector 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 2016-2021.

3. Results

3.1. Elevation vs bark beetle presence

The variation of the probability of presence of bark beetles for Wallonia and Grand-Est for the period 2017-2021 is described in the figure 4. 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.

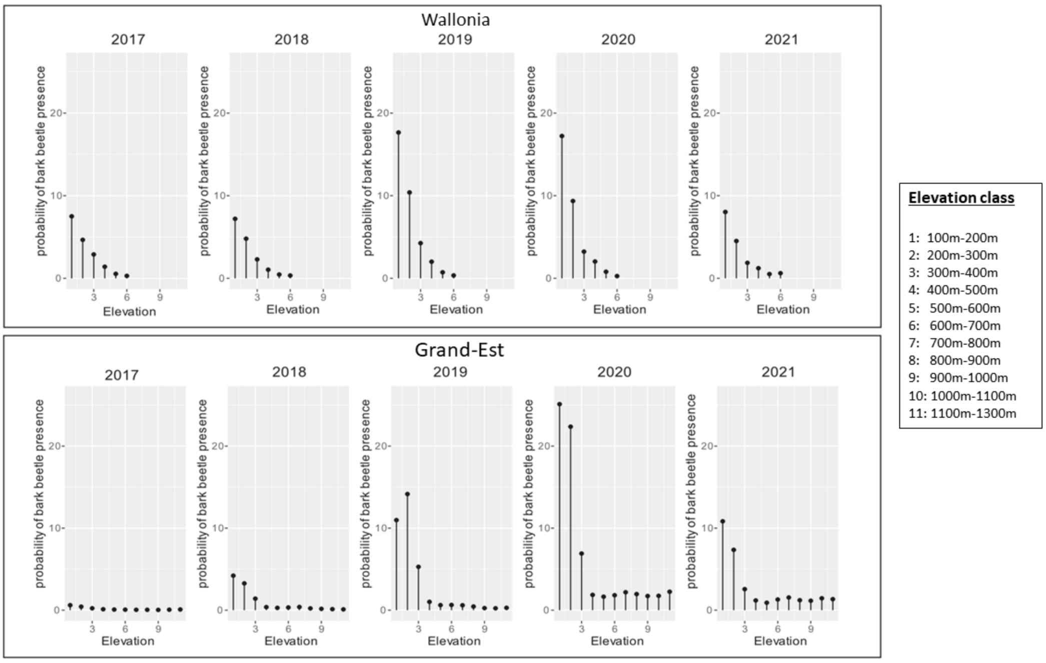

Fig. 4: XXXXAPragrapheprecedent.

For the Walloon spruce stand, there is an increase of the probability de presence of bark beetle for all altitude classes until 2020. In 2021, the probabilty of bark beetle presence decrease for all altitude classes. This figure also shows that the bark beetle crisis started in 2018. 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 decrease the probabilty of bark beetle presence follow an altitudinal gradient. The higher the norway spruce stand grows at an altitude, the lower the the probabilty of bark beetle presence. For the Grand-Est region, there is an increase in the probability of bark beetle presence between 2019 and 2021. Unlike the Walloon spruce forest, there is no clear altitudinal gradient in the Vosges. As in Wallonia, the 200-300m altitude class is strongly affected by the bark beetle. The probability of presence decreases along an altitudinal gradient between the altitude classes 200-300 and 400-500m. However, above 500m the probability of bark beetle increases up to the altitude class 700-800m.

3.2. Radiative sub-sector vs bark beetle presence

As the bark beetle develops more rapidly in warmer areas (Annila, 1969), we studied the evolution of the surface area of spruce affected by bark beetles as a function of the radiative sub-sector. The peak of bark beetle affected area is reached in 2019 for Wallonia and in 2020 for the Grand-Est. This graph also shows that proportionally the spruce forests of the plains of the Great East were more affected than the other sub-sectors in both the Grand-Est and Wallonia. In Wallonia, the most significantly affected sub-sectors are the slopes, and there is also a significant difference between the southern and northern slopes. Conversely, in the Grand Est it is the plateaus that are significantly more affected than the slopes.

4. Discussion

4.1. Différence entre Vosges et Wallonie

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

5. Conclusion

6. Figure

7. Acknowledgements

This research has been funded thanks to the *RegioWood II* project.

References

Alderweireld, M., Burnay, F., Pitchugin, M., and Lecomte, H., 2015-04. *Inventaire Forestier Wallon - Résultats 1994 - 2012*. Bilans et perspectives - Ressources naturelles. SPW. ISBN 978-2-8056-0171-2.

Ali, A. M., Abdullah, H., Darvishzadeh, R., Skidmore, A. K., Heurich, M., Roeoesli, C., Paganini, M., Heiden, U., and Marshall, D., 2021. Canopy chlorophyll content retrieved from time series remote sensing data as a proxy for detecting bark beetle infestation. *Remote Sensing Applications: Society and Environment*, 22:100524.

Annila, E., 1969. Influence of temperature upon the development and voltinism of Ips typographus L.(Coleoptera, Scolytidae). In *Annales Zoologici Fennici*, pages 161–208. JSTOR.

Baier, P., Pennerstorfer, J., and Schopf, A., September 2007. PHENIPS—A comprehensive phenology model of Ips typographus (L.) (Col., Scolytinae) as a tool for hazard rating of bark beetle infestation. *Forest Ecology and Management*, 249(3):171–186. ISSN 03781127. doi: 10.1016/j.foreco.2007.05.020. URL `https://linkinghub.elsevier.com/retrieve/pii/S0378112707004057`.

Bolyn, C., Michez, A., Gaucher, P., Lejeune, P., and Bonnet, S., 2018. Forest mapping and species composition using supervised per pixel classification of Sentinel-2 imagery. *Biotechnologie, Agronomie, Société et Environnement*, 22(3):16.

Bárta, V., Lukeš, P., and Homolová, L., 2021. Early detection of bark beetle infestation in Norway spruce forests of Central Europe using Sentinel-2. *International Journal of Applied Earth Observation and Geoinformation*, 100: 102335.

Delvaux, J. and Galoux, A., 1962. *Les territoires écologiques du Sud-Est belge*. Centre d'écologie générale.

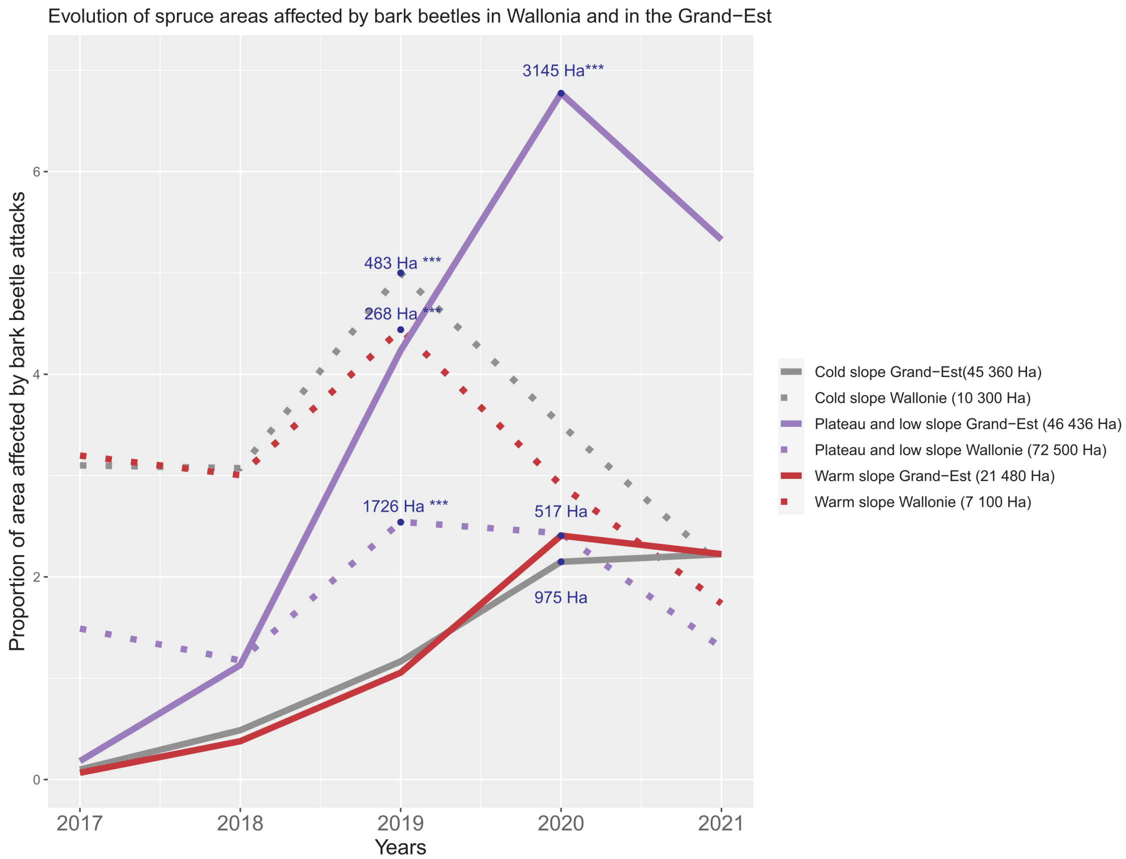

Fig. 5: XXXXAPragrapheprecedent.

DUTRIEUX, R., FERET, J.-B., OSE, K., and DE BOISSIEU, F., 2021. Package Fordead. URL https://doi.org/10.15454/4TE06H.

Grabska, E., Hostert, P., Pflugmacher, D., and Ostapowicz, K., 2019. Forest stand species mapping using the Sentinel-2 time series. *Remote Sensing*, 11(10):1197.

Hanewinkel, M., Cullmann, D. A., Schelhaas, M.-J., Nabuurs, G.-J., and Zimmermann, N. E., 2013. Climate change may cause severe loss in the economic value of european forest land. *Nature climate change*, 3(3):203–207.

Hlásny, T., König, L., Krokene, P., Lindner, M., Montagné-Huck, C., Müller, J., Qin, H., Raffa, K. F., Schelhaas, M.-J., Svoboda, M., Viiri, H., and Seidl, R., September 2021. Bark Beetle Outbreaks in Europe: State of Knowledge and Ways Forward for Management. *Current Forestry Reports*, 7(3):138–165. ISSN 2198-6436. doi: 10.1007/s40725-021-00142-x. URL https://link.springer.com/10.1007/s40725-021-00142-x.

Inventaire forestier national français, 2022. Données brutes, Campagnes annuelles 2005 et suivantes. URL https://inventaire-forestier.ign.fr/dataIFN/.

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., Lexer, M. J., and Marchetti, M., 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management*, 259(4):698–709. ISSN 0378-1127. doi: https://doi.org/10.1016/j.foreco.2009.09.023. URL https://www.sciencedirect.com/science/article/pii/S0378112709006604.

Lisein, J., Michez, A., Claessens, H., and Lejeune, P., 2015. Discrimination of deciduous tree species from time series of unmanned aerial system imagery. *PLoS One*, 10(11):e0141006.

Löw, M. and Koukal, T., 2020. Phenology Modelling and Forest Disturbance Mapping with Sentinel-2 Time Series in Austria. *Remote Sensing*, 12(4191).

Ma, M., Liu, J., Liu, M., Zeng, J., and Li, Y., 2021. Tree Species Classification Based on Sentinel-2 Imagery and Random Forest Classifier in the Eastern Regions of the Qilian Mountains. *Forests*, 12(12):1736.

Mezei, P., Jakuš, R., Blaženec, M., Belánová, S., and Šmídt, J., 2012. The relationship between potential solar radiation and spruce bark beetle catches in pheromone traps. *Annals of Forest Research*, 55(2). ISSN 20652445. URL https://afrjournal.org/index.php/afr/article/view/64.

Noirfalise, A. and Thill, A., 1975. Spruce woods and their pedobotanical types in ardenne (belgium). *Beiträge zur naturkundlichen Forschung in Südwestdeutschland*, 34:251–257.

Nystedt, B., Street, N. R., and Wetterbom, May 2013. The Norway spruce genome sequence and conifer genome evolution. *Nature*, 497(7451):579–584. ISSN 0028-0836, 1476-4687. doi: 10.1038/nature12211. URL http://www.nature.com/articles/nature12211.

Raffa, K. F., Grégoire, J.-C., and Staffan Lindgren, B., 2015. Natural History and Ecology of Bark Beetles. In *Bark Beetles*, pages 1–40. Elsevier. ISBN 978-0-12-417156-5. doi: 10.1016/B978-0-12-417156-5.00001-0. URL https://linkinghub.elsevier.com/retrieve/pii/B9780124171565000010.

Team, T., 2022. Value-added data processed by CNES for the Theia data cluster www.theia.land.fr from Copernicus data. The processing uses algorithms developed by Theia's Scientific Expertise Centers.

Union, E., 2022. Copernicus land monitoring service. URL https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1.

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

von Teuffel, K., Heinrich, B., and Baumgarten, M., 2004. *3 Present Distribution of Secondary Norway Spruce in Europe*, pages 63 – 96. Brill, Leiden, The Netherlands. ISBN 9789047412908. doi: https://doi.org/10.1163/9789047412908_007. URL https://brill.com/view/book/edcoll/9789047412908/B9789047412908_s007.xml.

Zolubas, P. and Byers, J. A., 1995. Recapture of dispersing bark beetle ips typographus l. (col., scolytidae) in pheromone-baited traps: regression models. *Journal of Applied Entomology*, 119(1-5):285–289. doi: https://doi.org/10.1111/j.1439-0418.1995.tb01287.x. URL https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1439-0418.1995.tb01287.x.