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HAL Authorization

1 **Spatial and remote sensing monitoring shows the end of bark beetle**  
2 **outbreak on Belgian and North-eastern France Norway spruce (*Picea***  
3 ***abies*) stand.**

4

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10 Keywords: Norway spruce, Species vulnerability, Bark beetle, forest management, forest site,  
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15 **Abstract**

16 In 2022, Europe emerged from eight of the hottest years on record, leading to significant  
17 spruce mortality across Europe. The particularly dry weather conditions of 2018 triggered  
18 an outbreak of bark beetles (*Ips typographus*), causing the loss of thousands of hectares of  
19 Norway spruce stands, including in Wallonia and North-eastern France.

20 A methodology for detecting the health status of spruce was developed based on dense time  
21 series of satellite imagery (Sentinel-2). The time series of satellite images allowed the  
22 modelling of the spectral response of healthy spruce forests over the seasons: a decrease in  
23 photosynthetic activity of the forest canopy causes deviations from this normal seasonal  
24 vegetation index trajectory. These anomalies are caused by a bark beetle attack and are  
25 detected automatically. The method leads in the production of annual spruce health map of  
26 Wallonia and Grand-Est. The goal of this paper is to assess the damage caused by bark beetle  
27 using the resulting spruce health maps. A second objective was to compare the influence of  
28 basic variables on the mortality of spruce trees in these two regions.

29 Lasted six years (2017-2022), bark beetle has destroyed 12.2 % (23,674 ha) of the spruce  
30 area in Wallonia and Grand-Est of France. This study area is composed of three bioclimatic  
31 areas: Plains, Ardennes and Vosges, which have not been equally affected by bark beetle  
32 attacks. The plains were the most affected, with 50% of spruce forests destroyed, followed  
33 by the Ardennes, which lost 11.3% of its spruce stands. The Vosges was the least affected

34 bioclimatic area, with 5.6% of spruce stands lost. For the most problematic sites, Norway  
35 spruce forestry should no longer be considered.

36

## 37 **Introduction**

38 Global changes are increasing the risk of disturbances in forest environment: frequency and  
39 intensity of abiotic events (fire, storm, drought) and health problems (diseases and pest  
40 invasion) will be more recurrent (Lindner et al., 2010). In Western Europe, we expect a  
41 decrease of precipitation and an increase of drought events during the vegetation period,  
42 which will impact the actual geographic distribution of tree species (Hanewinkel et al.,  
43 2013). In this context, Norway spruce (*Picea abies* L. Karst) which is one of the most  
44 important economic forest species in Europe (Nystedt et al., 2013) is also one of the most  
45 triggered species. Indeed, this species is very sensitive to water shortage (Modrzyński, 2007)  
46 and lack of water induces stress that affect growth and health of the tree. Moreover, its major  
47 pest, the bark beetle, causes important outbreaks after storm, which provide breeding  
48 material, e.g. windfalls, or after severe drought that weaken trees. A recent bark beetle  
49 outbreak, triggered by the exceptionally hot and dry weather of 2018, occurred in Western  
50 Europe. It has highlighted the need of improving our understanding of both Norway spruce  
51 and bark beetle autecology and synecology for minimizing the impact of bark beetle on  
52 spruce stands with adapted management methods. It should concern the monitoring of bark  
53 beetle population and early detection of attacks on trees as well as adapted silvicultural  
54 methods and adequate species composition of future forest, especially for the thousand  
55 hectares of clear-cut stands decimated by bark beetle attacks.

56 The Norway spruce is a native species of the boreal or mountainous climates of Europe. It is  
57 naturally present in the highest altitude in the Vosges mountains, but it has also been  
58 successfully planted out of its native range on warmer sites of low altitude in the Grand-Est  
59 (France) and Wallonia (Belgium) during the 19<sup>th</sup> and 20<sup>th</sup> centuries (Guinier, 1959;  
60 Noirfalise & Thill, 1975). The massive reforestations occurring at this period have led to the  
61 formation of large pure even-aged stands. It usually develops a taproot system with fine  
62 roots in shallow depth, although rooting system can adapt its configuration in constrained  
63 soil conditions (Köstler et al., 1968; Puhe, 2003). Stressed Norway spruce produce volatile  
64 compounds which attract bark beetles, making himself more susceptible to pest attack  
65 (Netherer et al., 2015, 2021). Bark beetles, in particular the species *Ips typographus*, are  
66 ubiquitous in the forest and their populations are generally low (endemic phase) without  
67 producing damage to healthy trees. However, the large number of stressed trees causes a  
68 shift to an epidemic phasis with an explosion of bark beetle populations during which even  
69 healthy trees are massively attacked (Kautz et al., 2014).

70 The life cycle of bark beetle depends on temperature and photoperiod (Annala, 1969; Baier  
71 et al., 2007). In Northern Europe, the bark beetle is univoltine (one single generation) but it  
72 is multivoltine (breed two or even three generations) in Western and Central Europe (Annala,  
73 1969). After spring swarming, the adult enters in the bark and burrow wood to make brood  
74 gallery where they mate and lay the eggs that mature to larvae into the phloem (Hlásny et

75 al., 2021). The bark beetle adult can re-emerge and swarm a second time to give birth to one  
76 sister brood (Zolubas & Byers, 1995). After the larvae maturation that last about seven  
77 weeks (Baier et al., 2007), the new generation of beetles emerges and attacks the direct  
78 surrounding trees (Zolubas & Byers, 1995). Attacked trees defend themselves by pulsing  
79 resin to kill the bark beetle but these defences failed to resist again numerous simultaneous  
80 attacks that induce their decline and rapid death.

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

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

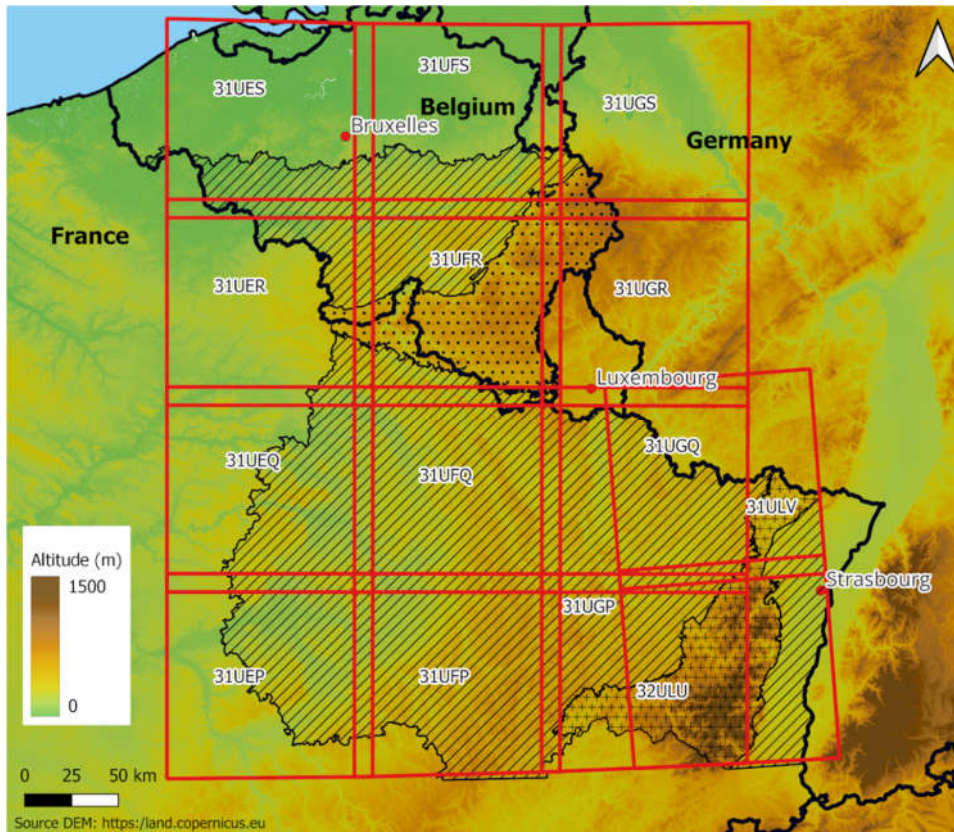
## 106 **Material and methods**

### 107 **Study area**

108 The study area includes Wallonia (south of Belgium) and the Grand-Est region (north-east  
109 of France). The Walloon Forest covers 554,600 ha and Norway spruce stands occupy  
110 quarter of area (Lejeune et al., 2022). The Norway spruce covers seven percent of the  
111 1,939,000 ha of the Grand-Est forest (Inventaire forestier national français, 2022). Both  
112 neighbour countries share some similar environmental conditions. They are included in the  
113 temperate oceanic bioclimatic zone (Lindner et al., 2010). However, at a finest scale, 24  
114 ecoregions have been defined, mainly by climate and soil parameters, influencing tree

115 species distributions (Walthert & Meier, 2017). To better analyse the dieback of Norway  
116 spruce, the French and Walloon ecoregions have been grouped in three main regions  
117 (Figure 1) according to averages of temperature and precipitation during the growing  
118 season (May to September) of the 1991-2020 period and to expert knowledge. The climate  
119 variables were provided by the Royal Meteorological Institute of Belgium for Wallonia and  
120 from the climate maps Digitalis for the Grand-Est (Piedallu et al., 2014). We summarized  
121 the recent climate for these three bioclimatic areas by means of the annual precipitation  
122 and the longest drought events by determining the largest number of consecutive dry days  
123 according to Schulzweida & Quast (2015) with climate data from the ECA-D (Cornes et al.,  
124 2018). The data collection methods in Belgium differ from those employed in France,  
125 making their use complicated. Fortunately, the European Climate Assessment & Dataset  
126 (ECAD) provides harmonized data for the entire Europe. However, the quality of these data  
127 is debatable. Temperature data is consistent, but precipitation data is less precise. Indeed,  
128 the number of weather stations used in Belgium for ECAD precipitation modeling is limited,  
129 and precipitation interpolation provides inadequate results because the precipitation  
130 pattern shows strong spatial variations on a fine scale.

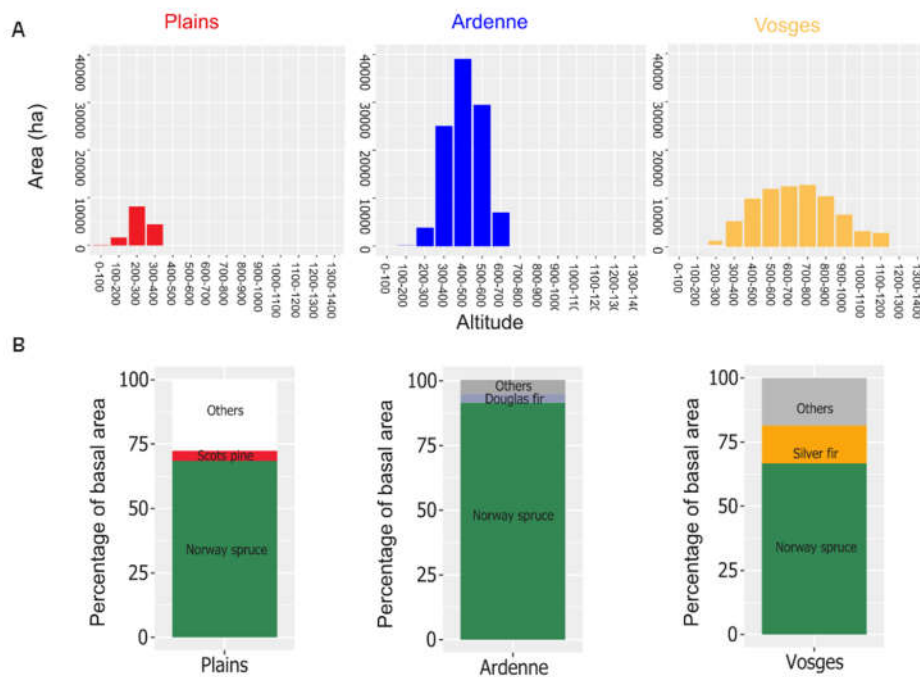
131 The majority of Ardenne and Vosges spruce forests are located above 400 meters in  
132 altitude, while in the plains, they are predominantly found below 300 meters (Figure 2A).  
133 The Ardenne spruce forest is less mixed compared to the Vosges and plains spruce forests  
134 (Figure 2B).



135

136 FIG1 Study area: Plains (black slant lines, altitude between 100 and 500 meters above sea  
 137 level), Ardennes (black dots, altitude between 200 and 700 m) and Vosges (black crosses,  
 138 altitude between 300 and 1500 m). Red squares illustrate the extent of Sentinel-2 tiles which  
 139 are used for the detection of bark beetle attack.

140 The regional climate is locally influenced by topography (De Frenne et al., 2021). South-  
 141 facing slopes are warmer and drier and their temperature difference between day and night  
 142 are higher than the North-facing ones. Three topographic exposures have been determined  
 143 using the Delvaux & Galoux (1962) definition. Flat areas are gentle slope less than 20% and  
 144 valley floor that does not create a particular local climate. Comparatively to flat areas, north-  
 145 facing orientations are slopes higher than 20% facing north (285° to 125°) with colder and  
 146 more shaded conditions. South-facing orientations are slopes higher than 20% facing south  
 147 (125° to 285°) with a warmer local climate. The digital elevation model (DEM) data from the  
 148 Copernicus Land Monitoring Service (European Union 2022) at a resolution of 25 m have  
 149 been used for altitude and topographic exposures maps.



150

151 *FIG2 Altitudinal distribution of spruce (A) and composition (B) of stands with relative basal*  
 152 *area of Norway spruce higher than 25% (Inventaire forestier national français, 2022; Perin,*  
 153 *2021) for the three bioclimatic areas.*

154

## 155 Sentinel 2 imagery

156 S2 satellites carry multispectral sensor with a ground resolution up to 10 m. Bottom of  
 157 Atmosphere reflectance images (L2A product) were downloaded from the Theia data cluster  
 158 (Theia Team, 2022) for all the 14 tiles of 100km x 100km covering our study area (Figure 3),  
 159 from 1st January 2016 to 28 February 2023, provided that the cloud cover does not exceed  
 160 35 percent.

## 161 Focus on spruce stands

162 The first prerequisite to assess spruce dieback was to map the species distribution at a fine  
 163 scale. For the south of Belgium (Wallonia), we used reliable composition maps from Bolyn et  
 164 al., (2022), in order to restrict our analysis to Norway spruce stands. These composition  
 165 maps consist in presence probabilities for eight major species, from which we discriminated  
 166 Norway spruce stands by selecting areas with equals or greater than 80% of probability of  
 167 presence.

168 In the Grand-Est, the determination of species was first determined by photointerpretation  
 169 as spruce or fir or as mixed conifers (performed by National Institute of Geographic and  
 170 Forest Information) and then refined using Sentinel-2 (S2) spectral time series. Phenology  
 171 courses are highly suitable for forest tree species discrimination (Grabska et al., 2019;

172 Lisein et al., 2015; Ma et al., 2021). In order to identify and remove every non-spruce pixel,  
 173 all S2 spectral bands of 10 and 20 m were first summarized for each of the four quarters of  
 174 the year, by averaging all cloud-free observations occurring during the quarter. We used  
 175 the satellite observations from the two years prior to the bark beetle outbreak for  
 176 computing these multi-year quarterly averages, i.e. 2016 and 2017. A Random Forest  
 177 algorithm was then trained on this synthetic time series to discriminate spruce from non-  
 178 spruce pixels, based on a training set of observations from Wallonia consisting in 1000  
 179 sampled pixels (20mx20m) for each of the eight major species (Bolgen et al., 2018). This  
 180 forest species classifier was applied on *spruce or fir or mixed conifers* area of Grand-Est. The  
 181 proportion of pixel detected as spruce in the Vosges was 43 % and corresponds to the level  
 182 of mixture expected for this bioclimatic area (52 %) according to photo-interpreted plots  
 183 from Piedallu et al. (2022) and total spruce surface reached 75,068 ha which is in  
 184 accordance with french National Forest Inventory data (68,000 +- 12,000 ha). Following  
 185 bark beetle detection was carried on only for 10x10 m pixels detected as spruce.

## 186 Vegetation index and health status

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

$$196 \quad (1) \quad SWIR_{CR}(t) = a_1 + b_1 \sin\left(\frac{2\pi}{365.25} t\right) + b_2 \cos\left(\frac{2\pi}{365.25} t\right) + b_3 \sin\left(\frac{2\pi}{365.25} 2t\right) +$$

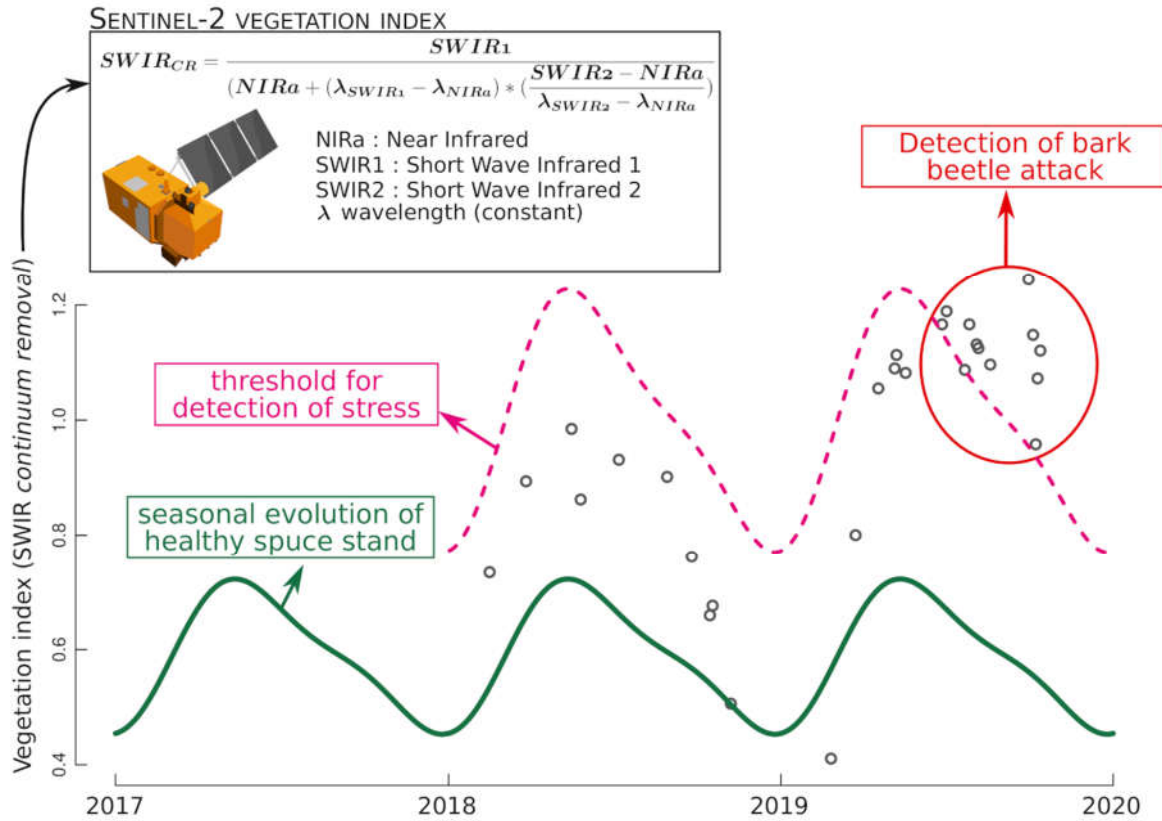
$$197 \quad b_4 \cos\left(\frac{2\pi}{365.25} 2t\right)$$

198 For fitting this equation, we used all cloud-free S2 observations from the two years preceding  
 199 the onset of the bark beetle outbreak, i.e. 2016 and 2017. Then, bark beetle attack was  
 200 detected if the  $SWIR_{CR}$  observations deviate from the healthy phenology trajectory.  
 201 Preliminary investigations have led us to consider a multiplying factor of 1.7 applied to the  
 202  $SWIR_{CR}$  for determining the threshold separating healthy to stressed situation. Figure 3  
 203 illustrates a time series of  $SWIR_{CR}$  observations (grey dots) for one single pixel. When the  
 204 observations exceed the threshold represented by the purple-dashed line (in 2019 in Figure  
 205 3), the spruce stand is probably under severe stress. As soon as  $SWIR_{CR}$  vegetation index  
 206 showed a stress for two consecutive times separated by at least 20 days, we assumed that  
 207 the stress is permanent (leading to death).

208

209 Simultaneously to the detection of bark beetle stress, stand cutting and thinning were subject  
 210 of particular attention: bare soil was detected by using a combination of thresholds for red,  
 211 green, blue and shortwave infrared reflectance values (Band 8A  $\geq$  12% reflectance and Band

212  $2 \leq 6\%$  reflectance and Band 3 + Band 4  $\geq 8\%$  reflectance). Cuttings were classified either  
 213 as normal or sanitary thinning based on the health status determined by the  $SWIR_{CR}$   
 214 vegetation index prior to cutting.



215  
 216 *FIG3 Bark beetle health maps were computed by detecting change in the  $SWIR_{CR}$  phenology*  
 217 *metric. The SWIR Continuum Removal was computed using three bands from Sentinel-2*  
 218 *imagery for every single acquisition date and its value was compared to a threshold (purple*  
 219 *dashed line, which correspond to the healthy situation in green multiplied by 1.7) in order to*  
 220 *detect vegetation stress. If a stress was detected two consecutive times with a minimum of 20*  
 221 *days between the observations, we assumed that the dieback occurred.*

222

223

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

## 229 Annual spruce health maps

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

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

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

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

## 250 Validation

251 The spruce health maps were validated by two different methods.

252 On the one hand, a stratified random sampling based on the size of the bark beetle attack  
253 area on the spruce health map was used for the 2018 vegetation season during which  
254 Wallonia suffered a lot of damage. The dieback area is a combination of bark beetle attacked  
255 area and sanitary cutting area. Adjacent pixels of dieback were first gathered, polygonised  
256 and categorised into six surface categories:  $\leq 200 \text{ m}^2$ ,  $200$  and  $\leq 400 \text{ m}^2$ ,  $400$  and  $\leq 600 \text{ m}^2$ ,  
257  $600$  and  $\leq 1000 \text{ m}^2$ ,  $1000$  and  $\leq 2000 \text{ m}^2$  and  $\geq 2000 \text{ m}^2$ . 48 dieback polygons were selected  
258 for each surface category, a total of 288 located exclusively in Belgian Ardenne. A  
259 photointerpretation was then performed using the annual orthophotoplans of the Wallonia.  
260 The health status from the health map was compared with health status deduced from the  
261 orthophotoplan and false detection were expressed as the proportion of surface wrongly  
262 detected as bark beetle attack area.

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

## 269 **Relation between bark beetle attack and environmental conditions**

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

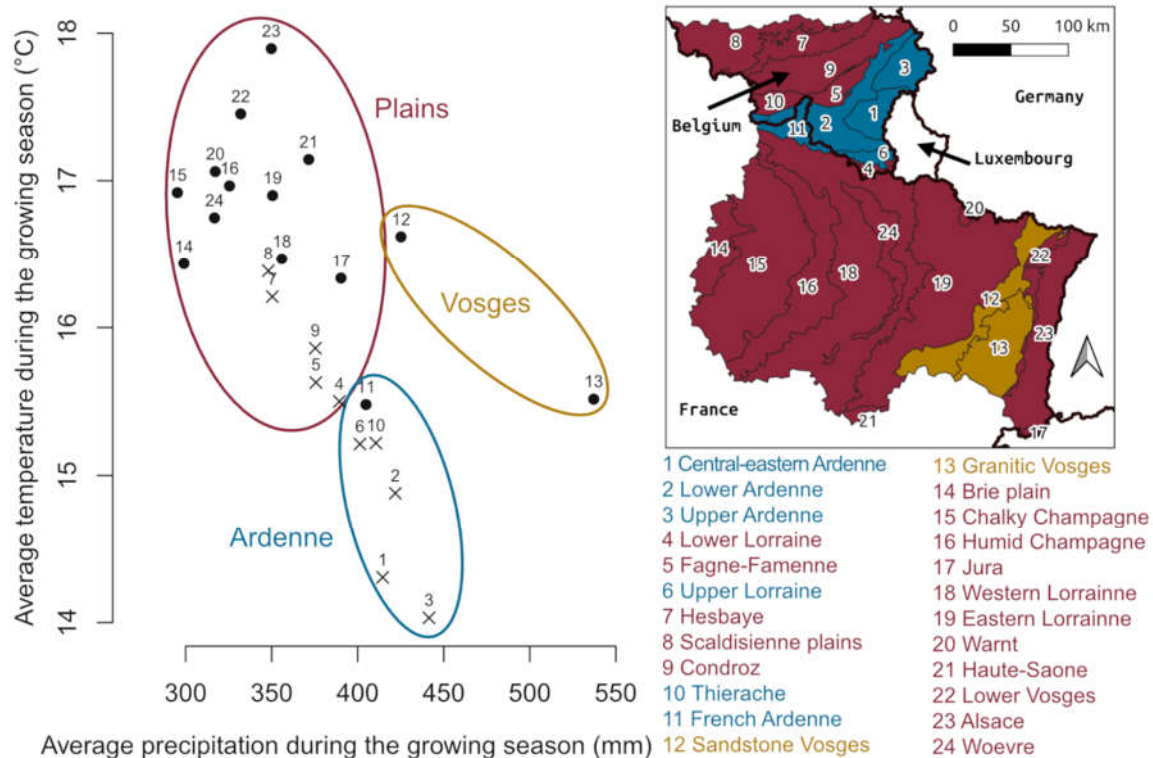
281 The resulting spruce health map has been used to study the relation between the dieback  
282 and these two factors. The altitude has been broken down by 100 m classes and kept the  
283 three topographic exposures classes (flat, north-facing slope and south-facing slope). To  
284 determine which class of the two factors was most affected, we estimated the dieback areas  
285 for each class of each factor based on the health status maps for each year of the period 2017-  
286 2021. The total area of spruce at the beginning of the years is composed of the area of healthy  
287 spruce area at the beginning of the year. The annual dieback rate is the dieback area during  
288 one year divided by the total area of Norway spruce at the beginning of the same year.

## 289 **Results**

### 290 **Bioclimatic areas**

291

292 The study area was divided into 3 bioclimatic zones based on averages of temperature and  
293 precipitation during the growing season (Figure 4). Plains are characterized by the lowest  
294 precipitation during the growing season (400 mm) and among the highest mean  
295 temperature during the growing season (15°C). Ecoregions with rainfall between 400 and  
296 450 mm and temperature lower than 15.5°C correspond to the bioclimatic area of the  
297 Ardenne. Vosges includes ecoregions with the highest rainfall (400 mm) and temperature  
298 between 15.5 °C and 17°C.



299

300 FIG4 Localisation(right) and groups of ecoregions (right) according to the temperature and  
 301 precipitation of the growing season (May-September) during the 1991-2020 period: Ardenne  
 302 (blue), Plains (red) and Vosges (orange). Walloon ecoregions are depicted with cross, and  
 303 Grand-Est regions are illustrated by rounded points.

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

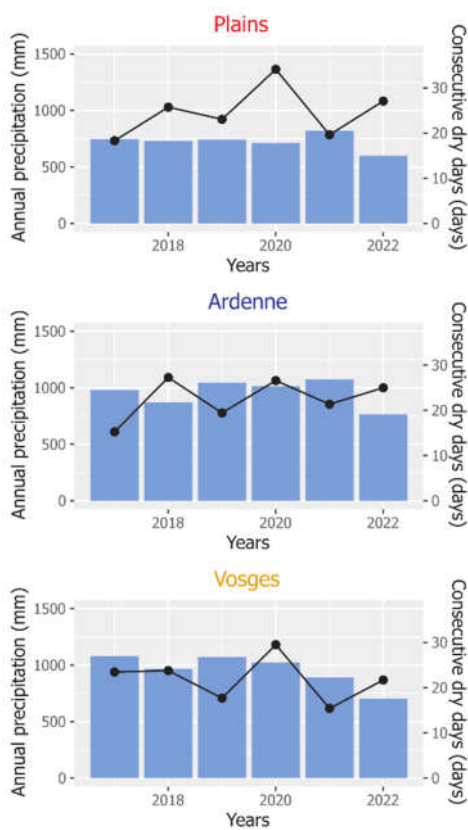
307 The three homogeneous bioclimatic areas, Plains, Ardenne and Vosges, differ in their  
 308 altitude which can be considered as an imperfect proxy for climate. The altitude varies  
 309 between 100 and 500 m for the Plains, between 200 and 700 m for the Ardenne and  
 310 between 300 and 1500 m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

314 Table 1: Description of the three bioclimatics areas.

Area	Precipitation (growing season)	Average temperature (growing season)	Altitude	Area	Country

Plains	<400 mm	>15 °C	100m-500m	6,099,800 ha	Belgium-France
Ardenne	400-450 mm	<15,5°C	200m-700m	724,970 ha	Belgium-France
Vosges	>400m	15,5°C-17°C	300m-1500m	640,930 ha	France

315



316

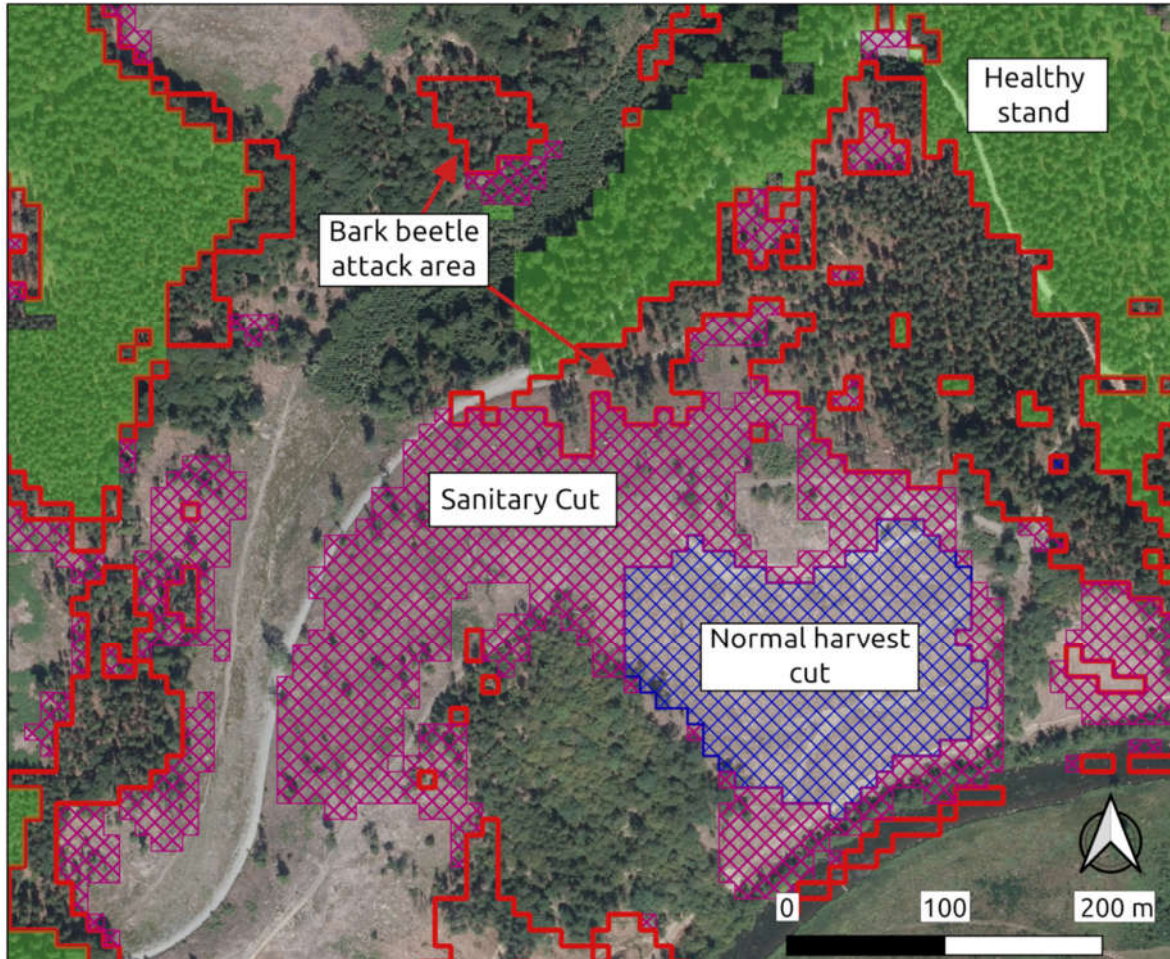
317 *FIG5 The climate summary for the three bioclimatic areas showed different trends during the*  
318 *bark beetle outbreak: annual precipitation (blue areas) and longest drought events (black*  
319 *lines).*

320

### 321 Spruce health map generation and validation

322

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



326  
327 *FIG6 Norway spruce health map of 2018 and Belgian orthophotoplan of 2019 for an Ardenne*  
328 *forest.*

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

333 The field validation in the Vosges confirms the result of the photo-interpretation method.  
334 Dead stands are identified correctly in 84.7 %. The healthy stands on the spruce health map  
335 are validated in 100 % of the stand in the field.

336

337

338

339

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

Region		Belgian Ardenne		Vosges	
Validation type		Photo-interpretation (n=288)		Field survey (n=95)	
Health statut		Attacked stands	Healthy stands	Attacked stands	Healthy stands
Spruce health map	Attacked stands	86,1 %	13,9 %	84.7 %	15.3 %
	Healthy stands	/	/	0%	100 %

342

### 343 **Importance of the evolution of the outbreak**

344 After a low spruce mortality rate in 2017, the sanitary outbreak of spruce really began in  
345 2018 especially in the Plains and in Ardenne (Figure 7). A high level of annual mortality rate  
346 has been observed each year during four years with a maximum of 2.5 % of the spruces in  
347 the Vosges, 5% in Ardenne and 22 % in the Plains after three critical years (2018-2020).  
348 Spruce mortality rates decreased in 2022 and returned to a similar situation as in 2017 with  
349 respectively 0, 1 and 3% of new attacked stands for Vosges, Ardenne and Plains. During the  
350 period 2017-2022, 23,674 ha of spruce have been destroyed on the study area, then  
351 representing 12% of the total spruce area of 2017 (Table 3). The three bioclimatic areas were  
352 not equally impacted by spruce mortality: Plains were the most affected with 50.1 % of the  
353 stands, nearby 10 times more than the Vosges (5.6 %) and four times more than the Ardenne  
354 (11.3%). The evolution of the outbreak also differed by bioclimatic areas (Figure 7). Bark  
355 beetle attacks began hardly in 2018 in the Plains and in the Ardenne, but was more  
356 progressive in the Vosges, where the maximum impact was later observed, in 2020.

357

358

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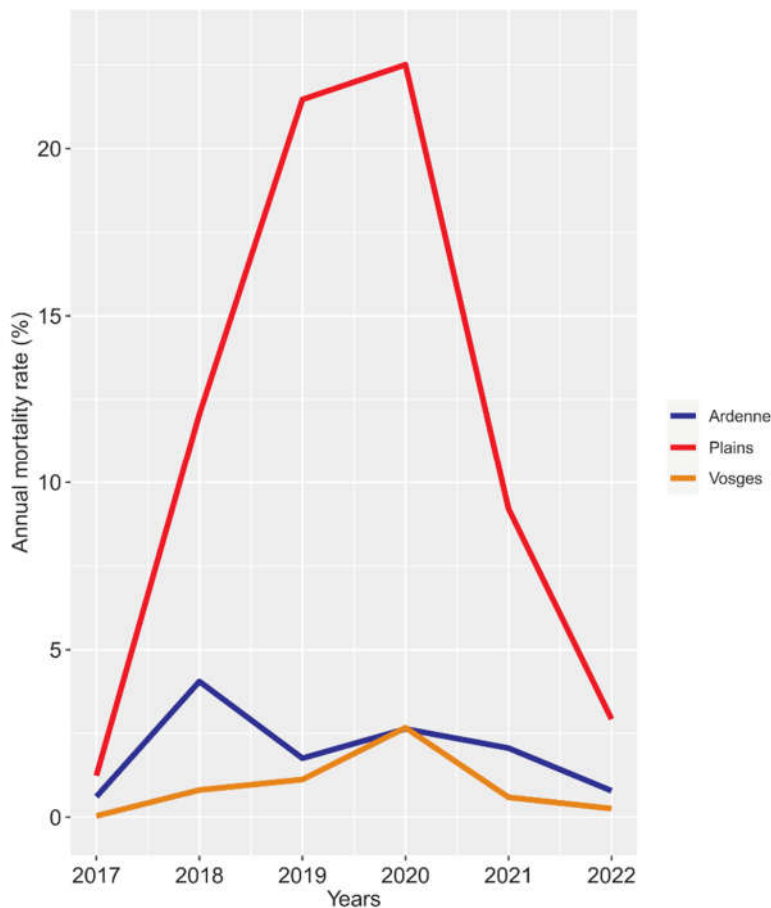
360

361

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

Bioclimatic areas	Total spruce dieback area during the outbreak (ha)	Total spruce area before outbreak (ha)	Rate of area with dieback (%)	Rate of sanitary cut/normal cut
Plains	7,634	15,028	50.1	1.24
Ardenne	11,822	104,723	11.3	0.57
Vosges	4,218	75,068	5.6	0.92
Total	23,674	194,819	12.2	0.77

364



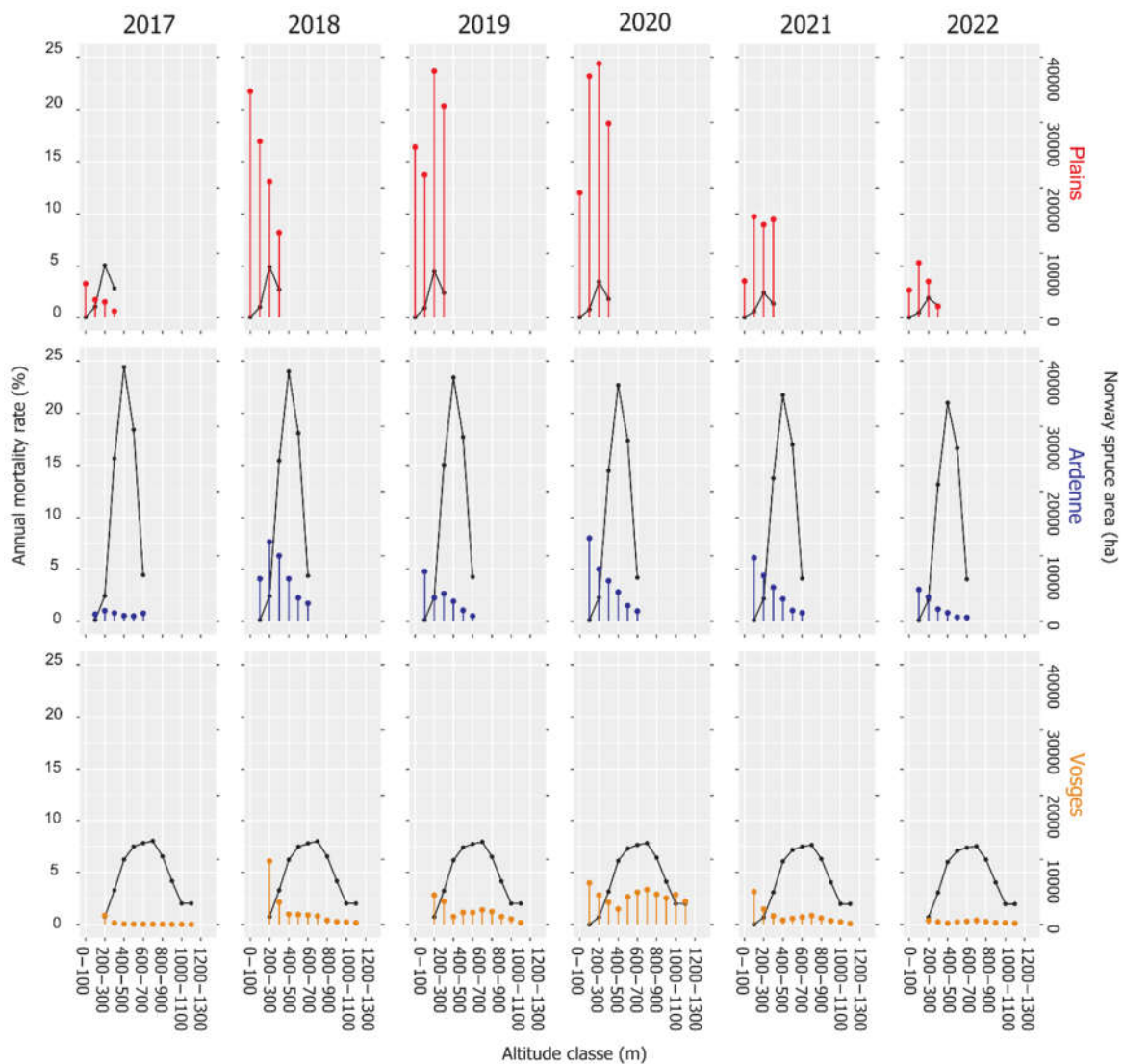
365

366 *FIG7 Evolution of the annual mortality rate during the outbreak (2017-2022).*

### 367 **Influence of altitude on the Norway spruce mortality**

368 Because spruce was planted outside its distribution range in low altitude and according to  
 369 studies showing a shift of species distribution along the altitudinal gradient (Lenoir et al.,  
 370 2008), more mortality was expected at lower altitude. The variation of the dieback rate

371 during 2017-2022 for the three bioclimatic areas shows an important effect of altitude but  
 372 with some difference according to the region (Figure 8). More dieback was observed at low  
 373 altitude: at the peak of the outbreak, the annual mortality rate exceeded 20% each year in  
 374 the altitude class under 300 m. In Ardenne, since the beginning of the outbreak, the dieback  
 375 rate is gradually decreasing when altitude is increasing. Except during 2018, at the peak of  
 376 the outbreak, spruce forest above 500 m were not severely affected. In the Vosges, the  
 377 dieback rate is globally low during the outbreak comparatively to the other bioclimatic areas,  
 378 except for 2020. No clear trend seems to emerge according to the altitude except in the  
 379 beginning of the outbreak in 2018 in the lower stands below 400 m altitude. However,  
 380 Vosgian spruces are rare below 400 m (less than 6,500 ha).



381

382 *FIG8 Variation of the dieback rate from 2017 to 2022 according to the altitude divided into 14*  
 383 *classes of 100 m amplitude for the three bioclimatic area: Plains (red), Ardenne (blue) and*  
 384 *Vosges (orange). The spruce area per altitude class is represented in black.*

## 385 Influence of exposures on the Norway spruce mortality.

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

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

Plains		Ardenne		Vosges	
Exposure	Rate (%)	Exposure	Rate (%)	Exposure	Rate (%)
Flat areas	50,2 <sup>a</sup>	Flat areas	10,7 <sup>a</sup>	Flat areas	<b>6,8<sup>a</sup></b>
South-facing slopes	52,8 <sup>b</sup>	South-facing slopes	<b>13,8<sup>b</sup></b>	South-facing slopes	5,1 <sup>b</sup>
North-facing slopes	<b>54<sup>c</sup></b>	North-facing slopes	13,1 <sup>c</sup>	North-facing slopes	5,0 <sup>c</sup>

397

398

## 399 Discussion

### 400 Dynamic of the dieback

401 In forest, sanitary outbreak lasts on average between three and ten years (Brunier et al.,  
402 2020). In our study, the spruce dieback has begun in 2018 and decrease in 2022 in all  
403 regions. The annual dieback rate has recovered in the 2022 the same level than in 2017. We  
404 found that the Vosges lost 5.4% of their spruce area. According to Piedallu et al. (2022), 33%  
405 of Vosgian spruce stands are in areas at high risk of dieback. It is therefore likely that new  
406 stands will dieback in the years to come. Even if all results show a decrease in mortality, the  
407 forestry community should remain vigilant for a new explosion of mortality. The experience  
408 gained in remote sensing in previous years should help to detect new bark beetle outbreaks  
409 and to contain a potential new outbreak.

410 The outbreak peaks seem to be linked to the maximum number of consecutive dry days and  
411 to the total rainfall of the year. Indeed, for three areas, the outbreak peak is reached in the  
412 year with the maximum of consecutive dry day. These annual mortality results can be linked  
413 to the climate data of ECAD (Cornes et al., 2018), in particular, the consecutive dry days  
414 (NCDD), which correspond the largest number of consecutive days with less than 1 mm of  
415 precipitation. During the 6 years of monitoring, the mortality peaks occurred in the same  
416 years as NCDD peaks, regardless of bioclimatic areas (Figure 5).

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

424 Our results of total dieback area can be compared to the estimates of annual bark beetle  
425 damage made at the scale of administrative regions. According to Nardi et al. (2022), the  
426 damage during 2018 is assessed at 1185 ha for the Grand-Est based on remote sensing  
427 methodology. From our health map for the vegetation season of 2018, we found a total  
428 1360 ha attacked in this administrative region. In Wallonia, Saintonge et al. (2022)  
429 estimate from sales catalogues that the area of spruce attacked by bark beetle between  
430 2018 and 2021 in Wallonia is around 5,000 ha. For this very same area and period, we  
431 determined that 13,000 ha of spruce were killed by bark beetle. We suppose Saintonge et  
432 al. (2022) underestimated the impact of the bark beetle outbreak, because their estimate  
433 does not consider unharvested dead spruce. Our method enables us to provide reliable  
434 damage area information to politicians and information on the location of bark beetle  
435 infestations to foresters and scientists.

## 436 **Regional impact of the bark beetle attacks**

437 The impact of the bark beetle attacks is different between the three main bioclimatic areas.  
438 It could be explained through three parameters: climate, stand structure and composition,  
439 and forest management. Warm and dry climate, as in the Plains, does not meet the  
440 autecological requirements of the spruce species, especially during extreme dry or warm  
441 events as in the period 2018-2020 (Rousi et al., 2022). Moreover, during warm seasons, the  
442 bark beetle produces multiple generations in a year (Annala, 1969; Baier et al., 2007) that  
443 can easily attack these stressed trees. In furthermore, the relations between bark beetle  
444 attacks, spruce trees, and environmental conditions are very complex (König et al., 2023;  
445 Lausch et al., 2011). According to the literature, three parameters could explain the dieback:  
446 climate (Baier et al., 2007; Trubin et al., 2022; Wermelinger & Seifert, 1998), stand structure  
447 and composition (Kamińska et al., 2021), and forest management (Faccoli & Bernardinelli,  
448 2014; Jactel et al., 2021).

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

460 generally makes the necessary sanitary felling which is part of the silvicultural tradition.  
461 However, spruce grows in pure even-aged stands. These conditions could explain an  
462 intermediate situation with damages on 11.3 % of the spruce initial area.

### 463 **Influence of the exposures on the mortality of Norway spruce.**

464 The exposure influences received radiation and water balance. South facing slopes are  
465 warmer than north facing ones. As the life cycle of the bark beetle is influenced by  
466 temperature (Baier et al., 2007), this insect should produce more generations in south-facing  
467 slopes and thus cause more damage in this exposure (Jakuš, 1995). Moreover, the south-  
468 facing slopes store until 50 % less water than in north-facing slopes in early spring (Rouse &  
469 Wilson, 1969). Thus, Norway spruces that growth in this orientation should be more often  
470 in a situation of water stress and should be more attacked than the north-facing slopes.  
471 However, our results do not clearly fit with this hypothesis. In the Plains, the south-facing  
472 slopes and the flat areas are less attacked than the north-facing slopes. In Europe and in  
473 north America, Gazol et al. (2017) observed that species that grow in drier condition area  
474 are more resilient to drought. Piedallu et al. (2022) confirmed this observation in the Vosges  
475 during the last outbreak. Moreover, in France, a recent study of Nardi et al. (2022) showed  
476 that Norway spruce stand on the steep slopes and soils with low water availability are less  
477 attacked. In the Vosges, spruce trees growing on the southern slopes and plains have suffered  
478 of drier conditions throughout their life and therefore have been less stressed than spruce  
479 trees growing on the north-facing slopes. In Ardenne, the south-facing slopes are more  
480 affected by bark beetle than other position. Norway spruce that growth in south-facing  
481 slopes should be more often in a situation of water stress and should be more attacked than  
482 the north facing-slopes. However, the north-facing slopes are not the less attacked. The  
483 shallow soil depth on the slopes of Ardenne could explain the dieback rate difference  
484 between de slope and the flat areas. In the Ardenne and in the Vosges, the result is opposed  
485 for the flat areas. The damage caused in the Vosgian flat areas could be explained by the more  
486 important presence of pure even-aged stand in this topographical orientation than in the  
487 slope. This stand structure is more sensible to bark beetles.

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

### 491 **Potential methodological limitations**

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

497 Calculating the spruce health map requires a species composition map, in order to limit the  
498 analysis to the spruce area. In pure even-aged Norway spruce stand, the spectral response is  
499 stable in absence of mortality but at edge of this stand and in mixed stand, this response can  
500 vary with season due to the deciduous tree or herbaceous species. In mixed forest and in the

501 border of the stands, the species composition map is less accurate than in pure even aged  
502 stand. In Ardenne and in the Plains, Norway spruce occurs principally in pure even-aged  
503 stands. In the Vosges, spruce forests are intimately mixed with silver fir (*abies alba*), and we  
504 suppose thus that the species composition map is less accurate than in the others bioclimatic  
505 areas. The annual dieback rate is influenced by Norway spruce area of the composition map.  
506 In Ardenne and in the Plains, the area is correctly estimated because spruce stands are purely  
507 even aged. On the other hand, in the mixed stands of the Vosges, the surface area is more  
508 difficult to evaluate because of the strong variation of tree species that influence the  
509 composition of the canopy. An underestimation of dieback rate is not excluded in this type  
510 of stand.

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

## 522 **Conclusion and perspectives**

523 Our study aimed to assess the evolution of the bark beetle outbreak in the spruce forest by  
524 analysing time series of sentinel-2 satellite images. To our knowledge, only König et al., 2023  
525 dealt with such comprehensive time series : in theirs study, they used multi-sensor satellite  
526 data with all available acquisitions from january 2015 to 30 april 2021, totalizing 662  
527 Sentinel-2 images. We focused on cloudless acquisition, which end up with a total of 275  
528 acquisitions dates in 6 years. The methodology used to identify the damaged stands is robust  
529 and effective as far as reliable species composition maps are available. Indeed, to improve  
530 the result in the Vosges, a new Norway spruce map is necessary to better distinguish spruce  
531 from fir. Taking this limitation into account, remote sensing could be the basis for monitoring  
532 bark beetle attacks in spruce forest. This outbreak triggered by the dry and warm events  
533 from 2018 to 2020 lasted five years and destroyed 12.2 % (23,674 ha) of the spruce area in  
534 Wallonia and Grand-Est of France. After a rainy year in 2021, new bark beetle attacks in 2022  
535 return to their 2017 level. The outbreak seems to be over. However, foresters must remain  
536 vigilant in the face of a resurgence of attacks in the years to come. The damages were not  
537 equally distributed on the territory: the Plains are the most impacted bioclimatic area with  
538 more than 50% of the spruce area impacted by bark beetles. The devastated area by this pest  
539 is estimated around 7,634 ha. The Ardenne is the second region that has lost the most spruce  
540 areas with 11.3 % of his spruce area attacked or around 13,400 ha. The Vosges is the less  
541 attacked region with 5.6 % of his spruce area killed. The total area impacted in this mountain  
542 region is around 4,200 ha. This situation could be linked to the climate, the structure and the  
543 composition of the stands, and the current forest management which differ between the

544 three bioclimatic areas. Taking into account the climate change, which will favour warm and  
545 dry events in the near future, our results does not support new plantations of Norway spruce  
546 in Plains. In Ardenne, we advise not to plant any more Norway spruce at lower altitude then  
547 400 m except in specific micro-climate. In the Vosges, the trend differs of the two other  
548 regions. More investigation specially dedicated to this region is necessary to draw  
549 conclusions. A study considering the effects of environment, climate and silvicultural factors  
550 would be interesting to better understand the determining factors of these bark beetle  
551 attacks of this important species for the wood industry.

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## 556 **Data availability**

557 Source codes are available on <https://github.com/JoLeBelge/s2-spruce-dieback/>

## 558 **Conflict of interest**

559 The authors declare no competing interests.

## 560 **Contributions**

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

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## 568 **Declarations**

569 All authors have read, understood, and have complied as applicable with the statement on  
570 "Ethical responsibilities of Authors" as found in the Instructions for Authors.

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## 574 **References**

- 575 Abdullah, H., Darvishzadeh, R., Skidmore, A. K., Groen, T. A., & Heurich, M. (2018). European  
576 spruce bark beetle (*Ips typographus*, L.) green attack affects foliar reflectance and  
577 biochemical properties. *International journal of applied earth observation and*  
578 *geoinformation*, *64*, 199-209.
- 579 Ali, A. M., Abdullah, H., Darvishzadeh, R., Skidmore, A. K., Heurich, M., Roeoesli, C., Paganini,  
580 M., Heiden, U., & Marshall, D. (2021). Canopy chlorophyll content retrieved from  
581 time series remote sensing data as a proxy for detecting bark beetle infestation.  
582 *Remote Sensing Applications: Society and Environment*, *22*, 100524.
- 583 Annala, E. (1969). Influence of temperature upon the development and voltinism of *Ips*  
584 *typographus* L.(Coleoptera, Scolytidae). *Annales Zoologici Fennici*, 161-208.
- 585 Baier, P., Pennerstorfer, J., & Schopf, A. (2007). PHENIPS—A comprehensive phenology  
586 model of *Ips typographus* (L.) (Col., Scolytinae) as a tool for hazard rating of bark  
587 beetle infestation. *Forest Ecology and Management*, *249*(3), 171-186.
- 588 Bárta, V., Lukeš, P., & Homolová, L. (2021). Early detection of bark beetle infestation in  
589 Norway spruce forests of Central Europe using Sentinel-2. *International Journal of*  
590 *Applied Earth Observation and Geoinformation*, *100*, 102335.
- 591 Bolyn, C., Lejeune, P., Michez, A., & Latte, N. (2022). Mapping tree species proportions from  
592 satellite imagery using spectral-spatial deep learning. *Remote Sensing of*  
593 *Environment*, *280*, 113205.

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

597 Brunier, L., Delpont, F., & Gauquelin, X. (2020). *Guide de gestion des crises sanitaires en forêt*.  
598 188.

599 Cornes, R. C., van der Schrier, G., van den Besselaar, E. J. M., & Jones, P. D. (2018). An  
600 Ensemble Version of the E-OBS Temperature and Precipitation Data Sets. *Journal of*  
601 *Geophysical Research: Atmospheres*, 123(17), 9391-9409.

602 Dalponte, M., Solano-Correa, Y. T., Frizzera, L., & Gianelle, D. (2022). Mapping a European  
603 Spruce Bark Beetle Outbreak Using Sentinel-2 Remote Sensing Data. *Remote Sensing*,  
604 14(13), 3135.

605 De Frenne, P., Lenoir, J., Luoto, M., Scheffers, B. R., Zellweger, F., Aalto, J., Ashcroft, M. B.,  
606 Christiansen, D. M., Decocq, G., De Pauw, K., Govaert, S., Greiser, C., Gril, E., Hampe, A.,  
607 Jucker, T., Klinges, D. H., Koelemeijer, I. A., Lembrechts, J. J., Marrec, R., ... Hylander,  
608 K. (2021). Forest microclimates and climate change : Importance drivers and future  
609 research agenda. *Global Change Biology*, 27(11), 2279-2297.

610 Delvaux, J., & Galoux, A. (1962). *Les territoires écologiques du Sud-Est belge*. Centre  
611 d'écologie générale.

612 Dutrieux, R., Feret, J.-B., Ose, K., & De Boissieu, F. (2021). *Package Fordead*. Portail Data  
613 INRAE. <https://doi.org/10.15454/4TEO6H>

614 Faccoli, M., & Bernardinelli, I. (2014). Composition and Elevation of Spruce Forests Affect  
615 Susceptibility to Bark Beetle Attacks : Implications for Forest Management. *Forests*,  
616 5(1), 88-102.

617 Gazol, A., Camarero, J. J., Anderegg, W. R. L., & Vicente-Serrano, S. M. (2017). Impacts of  
618 droughts on the growth resilience of Northern Hemisphere forests. *Global Ecology*  
619 *and Biogeography*, 26(2), 166-176.

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

622 Guinier, Ph. (1959). Trois Conifères de la flore vosgienne. *Bulletin de la Société Botanique de*  
623 *France*, 106(sup2), 168-183.

624 Hanewinkel, M., Cullmann, D. A., Schelhaas, M.-J., Nabuurs, G.-J., & Zimmermann, N. E.  
625 (2013). Climate change may cause severe loss in the economic value of European  
626 forest land. *Nature climate change*, 3(3), 203-207.

627 Hlásny, T., König, L., Krokene, P., Lindner, M., Montagné-Huck, C., Müller, J., Qin, H., Raffa, K.  
628 F., Schelhaas, M.-J., Svoboda, M., Viiri, H., & Seidl, R. (2021). Bark Beetle Outbreaks in  
629 Europe : State of Knowledge and Ways Forward for Management. *Current Forestry*  
630 *Reports*, 7(3), 138-165.

631 Inventaire forestier national français. (2022). *Données brutes, Campagnes annuelles 2005 et*  
632 *suivantes*. <https://inventaire-forestier.ign.fr/dataIFN/>

633 Jactel, H., Moreira, X., & Castagneyrol, B. (2021). Tree Diversity and Forest Resistance to  
634 Insect Pests : Patterns, Mechanisms, and Prospects. *Annual Review of Entomology*,  
635 66(1), 277-296.

636 Jakuš, R. (1995). Bark beetle (Col., Scolytidae) communities and host and site factors on  
637 tree level in Norway spruce primeval natural forest. *Journal of Applied Entomology*,  
638 119(1-5), 643-651.

639 Jönsson, A. M., Appelberg, G., Harding, S., & Barring, L. (2009). Spatio-temporal impact of  
640 climate change on the activity and voltinism of the spruce bark beetle, *Ips*  
641 *typographus*. *Global Change Biology*, 15(2), 486-499.

642 Kamińska, A., Lisiewicz, M., Kraszewski, B., & Stereńczak, K. (2021). Mass outbreaks and  
643 factors related to the spatial dynamics of spruce bark beetle (*Ips typographus*)  
644 dieback considering diverse management regimes in the Białowieża forest. *Forest*  
645 *Ecology and Management*, 498, 119530.  
646 <https://doi.org/10.1016/j.foreco.2021.119530>

647 Kautz, M., Schopf, R., & Imron, M. A. (2014). Individual traits as drivers of spatial dispersal  
648 and infestation patterns in a host–bark beetle system. *Ecological Modelling*, 273,  
649 264-276.

650 König, S., Thonfeld, F., Förster, M., Dubovyk, O., & Heurich, M. (2023). Assessing  
651 Combinations of Landsat, Sentinel-2 and Sentinel-1 Time series for Detecting Bark  
652 Beetle Infestations. *GIScience & Remote Sensing*, 60(1), 2226515.  
653 <https://doi.org/10.1080/15481603.2023.2226515>

654 Köstler, J. N., Brückner, E., & Bibelriether, H. (1968). Die Wurzeln der Waldbäume.  
655 *Zeitschrift für Pflanzenernährung und Bodenkunde*, 120.

656 Kuhn, A., Hautier, L., & San Martin, G. (2022). Do pheromone traps help to reduce new  
657 attacks of *Ips typographus* at the local scale after a sanitary cut? *PeerJ*, 10, e14093.

658 Lausch, A., Fahse, L., & Heurich, M. (2011). Factors affecting the spatio-temporal dispersion  
659 of *Ips typographus* (L.) in Bavarian Forest National Park : A long-term quantitative  
660 landscape-level analysis. *Forest Ecology and Management*, 261(2), 233-245.  
661 <https://doi.org/10.1016/j.foreco.2010.10.012>

- 662 Lejeune, P., Michez, A., Perin, J., Gilles, A., Latte, N., Ligot, G., Lisein, J., & Claessens, H. (2022).  
663 L'épicéa wallon : État de la ressource en 2021. *Silva Belgica*, 2, 7.
- 664 Lenoir, J., Gégout, J. C., Marquet, P. A., de Ruffray, P., & Brisse, H. (2008). A Significant  
665 Upward Shift in Plant Species Optimum Elevation During the 20th Century. *Science*,  
666 320(5884), 1768-1771. <https://doi.org/10.1126/science.1156831>
- 667 Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R.,  
668 Delzon, S., Corona, P., Kolström, M., Lexer, M. J., & Marchetti, M. (2010). Climate  
669 change impacts, adaptive capacity, and vulnerability of European forest ecosystems.  
670 *Forest Ecology and Management*, 259(4), 698-709.
- 671 Lisein, J., Michez, A., Claessens, H., & Lejeune, P. (2015). Discrimination of deciduous tree  
672 species from time series of unmanned aerial system imagery. *PLoS One*, 10(11),  
673 e0141006.
- 674 Löw, M., & Koukal, T. (2020). Phenology Modelling and Forest Disturbance Mapping with  
675 Sentinel-2 Time Series in Austria. *Remote Sensing*, 12(4191).
- 676 Ma, M., Liu, J., Liu, M., Zeng, J., & Li, Y. (2021). Tree Species Classification Based on Sentinel-  
677 2 Imagery and Random Forest Classifier in the Eastern Regions of the Qilian  
678 Mountains. *Forests*, 12(12), 1736.
- 679 Marini, L., Ayres, M. P., Battisti, A., & Faccoli, M. (2012). Climate affects severity and  
680 altitudinal distribution of outbreaks in an eruptive bark beetle. *Climatic Change*,  
681 115(2), 327-341.
- 682 Modrzyński, J. (2007). Outline of Ecology. In M. G. Tjoelker, A. Boratyński, & W. Bugała  
683 (Éds.), *Biology and Ecology of Norway Spruce* (Vol. 78, p. 195-253).

684 Müller, M., Olsson, P.-O., Eklundh, L., Jamali, S., & Ardö, J. (2022). Features predisposing  
685 forest to bark beetle outbreaks and their dynamics during drought. *Forest Ecology*  
686 *and Management*, 523, 120480.

687 Nardi, D., Jactel, H., Pagot, E., Samalens, J., & Marini, L. (2022). Drought and stand  
688 susceptibility to attacks by the European spruce bark beetle : A remote sensing  
689 approach. *Agricultural and Forest Entomology*.

690 Netherer, S., Kandasamy, D., Jirosová, A., Kalinová, B., Schebeck, M., & Schlyter, F. (2021).  
691 Interactions among Norway spruce, the bark beetle *Ips typographus* and its fungal  
692 symbionts in times of drought. *Journal of Pest Science*, 94(3), 591-614.

693 Netherer, S., Matthews, B., Katzensteiner, K., Blackwell, E., Henschke, P., Hietz, P.,  
694 Pennerstorfer, J., Rosner, S., Kikuta, S., Schume, H., & Schopf, A. (2015). Do water-  
695 limiting conditions predispose Norway spruce to bark beetle attack? *New*  
696 *Phytologist*, 205(3), 1128-1141.

697 Noirfalise, A., & Thill, A. (1975). Spruce woods and their pedobotanical types in Ardenne  
698 (Belgium). *Beiträge zur naturkundlichen Forschung in Südwestdeutschland*, 34,  
699 251-257.

700 Nystedt, B., Street, N. R., & Wetterbom. (2013). The Norway spruce genome sequence and  
701 conifer genome evolution. *Nature*, 497(7451), 579-584.

702 Perin, J. (2021). *Inventaire permanent des ressources forestières de Wallonie*.  
703 <http://iprfw.spw.wallonie.be/>

704 Piedallu, C., Dallery, D., Bresson, C., Legay, M., Gégout, J.-C., & Pierrat, R. (2022). Spatial  
705 vulnerability assessment of silver fir and Norway spruce dieback driven by climate  
706 warming. *Landscape Ecology*.

707 Piedallu, C., Perez, V., Seynave, I., Gasparotto, D., & Gégout, J.-C. (2014). Présentation du  
708 portail web SILVAE: système d'informations localisée sur la végétation, les arbres et  
709 leur environnement. *Revue Forestière Française*, 1, 41.

710 Puhe, J. (2003). Growth and development of the root system of Norway spruce (*Picea*  
711 *abies*) in forest stands-a review. *Forest Ecology and Management*, 175, 253-273.

712 Pureswaran, D. S., Meurisse, N., Rassati, D., Liebhold, A. M., & Faccoli, M. (2022). Climate  
713 change and invasions by nonnative bark and ambrosia beetles. In *Bark Beetle*  
714 *Management, Ecology, and Climate Change* (p. 3-30). Elsevier.  
715 <https://doi.org/10.1016/B978-0-12-822145-7.00002-7>

716 Rouse, W. R., & Wilson, R. G. (1969). Time and Space Variations in the Radiant Energy  
717 Fluxes Over Sloping Forested Terrain and Their Influence on Seasonal Heat and  
718 Water Balances at a Middle Latitude Site. *Geografiska Annaler: Series A, Physical*  
719 *Geography*, 51(3), 160-175.

720 Rousi, E., Kornhuber, K., Beobide-Arsuaga, G., Luo, F., & Coumou, D. (2022). Accelerated  
721 western European heatwave trends linked to more-persistent double jets over  
722 Eurasia. *Nature Communications*, 13, 3851.

723 Saintonge, F.-X., Gillette, M., Blaser, S., Queloz, V., & Leroy, Q. (2022). Situation et gestion de  
724 la crise liée aux scolytes de l'Épicéa commun fin 2021 dans l'est de la France, en  
725 Suisse et en Wallonie. *Revue forestière française*, 73(6), 619-641.  
726 <https://doi.org/10.20870/revforfr.2021.7201>

727 Schulzweida, U., & Quast, R. (2015). *Climate indices with CDO* (p. 1-34).  
728 [https://earth.bsc.es/gitlab/ces/cdo/raw/b4f0edf2d5c87630ed4c5ddee5a4992e3e](https://earth.bsc.es/gitlab/ces/cdo/raw/b4f0edf2d5c87630ed4c5ddee5a4992e3e08b06a/doc/cdo_eca.pdf)  
729 [08b06a/doc/cdo\\_eca.pdf](https://earth.bsc.es/gitlab/ces/cdo/raw/b4f0edf2d5c87630ed4c5ddee5a4992e3e08b06a/doc/cdo_eca.pdf)

730 Stadelmann, G., Bugmann, H., Meier, F., Wermelinger, B., & Bigler, C. (2013). Effects of  
731 salvage logging and sanitation felling on bark beetle (*Ips typographus* L.)  
732 infestations. *Forest Ecology and Management*, 305, 273-281.

733 Theia Team. (2022). *Value-added data processed by CNES for the Theia data cluster*  
734 *www.theia.land.fr from Copernicus data. The processing uses algorithms developed by*  
735 *Theia's Scientific Expertise Centers.*

736 Thonfeld, F., Gessner, U., Holzwarth, S., Kriese, J., Da Ponte, E., Huth, J., & Kuenzer, C. (2022).  
737 A First Assessment of Canopy Cover Loss in Germany's Forests after the 2018–2020  
738 Drought Years. *Remote Sensing*, 14(3), 562.

739 Trubin, A., Mezei, P., Zabihi, K., Surovỳ, P., & Jakuš, R. (2022). Northernmost European  
740 spruce bark beetle *Ips typographus* outbreak : Modelling tree mortality using  
741 remote sensing and climate data. *Forest Ecology and Management*, 505, 119829.

742 Walthert, L., & Meier, E. S. (2017). Tree species distribution in temperate forests is more  
743 influenced by soil than by climate. *Ecology and Evolution*, 7(22), 9473-9484.

744 Wermelinger, B. (2004). Ecology and management of the spruce bark beetle *Ips*  
745 *typographus*—A review of recent research. *Forest Ecology and Management*,  
746 202(1-3), 67-82.

747 Wermelinger, B., & Seifert, M. (1998). Analysis of the temperature dependent development  
748 of the spruce bark beetle *Ips typographus* (L) (Col., Scolytidae). *Journal of Applied*  
749 *Entomology*, 122(1-5), 185-191. [https://doi.org/10.1111/j.1439-](https://doi.org/10.1111/j.1439-0418.1998.tb01482.x)  
750 [0418.1998.tb01482.x](https://doi.org/10.1111/j.1439-0418.1998.tb01482.x)

751 Zolubas, P., & Byers, J. A. (1995). Recapture of dispersing bark beetle *Ips typographus* L.  
752 (Col., Scolytidae) in pheromone-baited traps : Regression models. *Journal of Applied*  
753 *Entomology*, 119(1-5), 285-289.

754

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756