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Massive windfalls boost an ongoing spruce bark beetle outbreak in the Southern Alps

Danni da vento amplificano un attacco incipiente di bostrico dell'abete rosso nelle Alpi Meridionali

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Abstract: European coniferous forests are currently threatened by bark beetles (e.g. *Ips typographus*) because of an increasing incidence of triggering factors, such as drought and windstorms. Furthermore, such natural disturbances are expected to increase in terms of magnitude and frequency due to climate change, and thus interacting with each other. Here, we present a particular case study in the Southern Italian Alps (Gares, Canale d'Agordo, Belluno), in which wind disturbance interacts with an ongoing outbreak of *I. typographus*, probably associated with an extended drought in the previous three years. By combining remote sensing and field surveys, we spatially reconstructed the bark beetle attack in the period 2015-2021, which includes the Vaia windstorm in October 2018. Although the windstorm occurred in an expanding phase of the bark beetle outbreak, attacks on standing trees did not occur during the first year after the windstorm but were observed two years later. Our findings suggest that an overlap of a large availability of wind felled trees with an incipient outbreak of *I. typographus* resulted in an immediate decrease of standing trees mortality in the year following the storm. However, the fallen trees worked as a hidden sink for the beetle population, which in the following years massively attacked the standing trees that survived the storm.

Key words: wind damage; tree mortality; *Ips typographus*; Norway spruce; *Picea abies*.

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1. Introduction

Bark beetle disturbance is increasing in Europe affecting mostly coniferous forests (Marini *et al.*, 2017; Stadelmann *et al.*, 2014). In the last decades, severe bark beetle outbreaks occurred and caused large forest loss in Europe (Havašová *et al.*, 2017; Hlásny *et al.*, 2021b). Unfortunately, these biotic disturbances are expected to increase in terms of magnitude and frequency under climate change (Bentz *et al.*, 2019; Jakoby *et al.*, 2019; Romashkin *et al.*, 2020; Seidl *et al.*, 2017; Temperli *et al.*, 2013). In particular, the European spruce bark beetle (*Ips typographus* L.; Coleoptera: Curculionidae) is the most important pest in European coniferous forests, mainly affecting and killing Norway spruce (*Picea abies* [L.] H. Karst.) (Biedermann *et al.*, 2019; Økland *et al.*, 2015). At stand scale, the insect may kill the host tree through a combination of high attack density and impaired tree defenses, as it is typically observed in weakened or stressed trees (Matthews *et al.*, 2018; Netherer *et al.*, 2015, 2019). At landscape scale, bark beetle populations are characterized by endemic phases (low population size, low spruce mortality) and epidemic phases (high population size, high spruce mortality) (Kautz *et al.*, 2014). Epidemic phases are triggered by external factors, such as heat waves or windfalls, which promote a rapid increase in population densities on local level. Increased numbers of offspring from breeding systems in weakened trees can lead to successful mass attack of healthy trees (Mezei *et al.*, 2017; Senf and Seidl, 2018).

Windfalls are well-known triggering factors for *I. typographus* outbreaks because uprooted and broken trees are heavily stressed, badly defended and thus easily colonized by spruce bark beetles (Hroššo *et al.*, 2020; Louis *et al.*, 2016; Mezei *et al.*, 2014). After large windfalls, fallen trees act as sink for local populations of bark beetles, and allow for multiplied offspring development. Indeed, from the population dynamics perspective, a high amount of fallen trees means surplus of food and more space for brood development, while intra-specific competition is reduced (Faccoli and Bernardinelli, 2010; Holuša and Lukášová, 2017).

Traditionally, outbreak spots are detected during field surveys, since infested trees show visible symptoms. However, the detection of very early stage symptoms, such as boring dust, boring holes and resin flow, needs a deep visual inspection of the trunks and so it is hard to carry out over large areas. On the contrary, late symptoms, such as discoloration and debarking, are easily recognizable. Although late symptoms occur when offspring has already emerged, they are commonly used by foresters to detect and map infestation spots during bark beetle outbreaks. Also, these late symptoms are associated with a different spectral signature detectable by optical sensors (i.e., remote sensing detection). Recently, the combination of free remote sensing data collections, such as Sentinel 2 (https://scihub.copernicus.eu) and Landsat (https://earthexplorer.usgs.gov), and server computational platforms, such as GEE (https://earthengine.google.com), allow foresters to easily use remote sensing data for detecting forest health changes (Jahromi *et al.*, 2021). Once a tree was successfully attacked by bark beetle, three different stages can be generally distinguished by visual inspection (Wulder *et al.*, 2006). "Green attack" stage occurs at the very beginning of the infestation and is characterized by no change in crown color; "red attack" stage is characterized by chromatic shifting to yellow or reddish, depending on host species and climatic conditions, and indicates recent attacks; "grey attack" stage is mainly referred to old attacks and is characterized by the gradual loss of needles. Despite some studies showed a moderate detectability of green attacks (Abdullah *et al.*, 2019), free satellite images have still a broad spectral resolution to reach a good accuracy of these early stages of tree decay (Huo *et al.*, 2021). However, free and multispectral optical images from satellites, such as Sentinel 2, are good enough to map visible changes in forest, i.e., red and grey stages, at large spatial scale with acceptable resolution and accuracy, though spatial resolution of images does not allow the detection of spots constituted by only few trees (Fernandez-Carrillo *et al.*, 2020). Among the plethora of vegetation indices used in forestry, the Normalized Difference Vegetation Index (NDVI) has been successfully used for post disturbance detection of bark beetle damage, as a proxy for photosynthetic activity and thus suitable for discoloration detection (Fernandez-Carrillo *et al.*, 2020; Lastovicka *et al.*, 2020; Meddens *et al.*, 2013; Senf *et al.*, 2017).

Despite the multiplication effect of wind disturbances on bark beetle populations is well-known, most of the studies were focused on wind damage as initial triggering cause (observational studies: e.g. Havašová *et al.*, 2017; Kärvemo *et al.*, 2014; Økland *et al.*, 2016; Stadelmann *et al.*, 2014; simulations: e.g. Honkaniemi *et al.*, 2018; Jönsson *et al.*, 2012; Potterf and Bone, 2017). Instead, the occurrence of wind disturbance in areas already affected by bark beetle outbreaks has been rarely investigated. However, due to climate change, both abiotic and biotic disturbances, are expected to intensify in the coming years (Hlásny *et al.*, 2021a; Seidl and Rammer, 2017), thus increasing spruce forest susceptibility and probability of co-occurring damage events (i.e., windstorm occurrence during a bark beetle outbreak). Here, we present a case study in the Southern Italian Alps where the windstorm Vaia, occurring at the end of October 2018, interacted with an ongoing spruce bark beetle outbreak. In particular, we aimed to investigate the effects of the windstorm on a pre-existent local outbreak of *I. typographus*, focusing on attack patterns and population dynamics, and considering the climatic conditions in the years preceding and following the storm event.

2. Materials and Methods

Our study area is a mountain slope located near Gares (Canale d'Agordo, Belluno, Italy), facing south-east. The study area extends over 5 km^2, with an altitude ranging from 1200 to 2000 m (46.307° N 11.866° E - 46.330° N 11.890° E). The stands are mainly composed of Norway spruce (*Picea abies*), interspersed with European beech (*Fagus sylvatica* L.) and European larch (*Larix decidua* Mill.). The age of the trees ranges between 70 and 120 years and the stands are generally even-aged, resulting from both natural and artificial afforestation of previously grazed areas. The main function of the forest is protection from erosion and avalanches, due to the steep slopes and high peaks above timberline, although timber was occasionally exploited especially from the lower elevation stands. In the winter period 2013-2014, heavy snowfalls and winds caused local tree breaking and uprooting that triggered a small outbreak of the spruce bark beetle *I. typographus*. Infested trees were removed and pheromone traps were activated by the forest service in 2015 for monitoring bark beetle populations. Trapping activity was resumed in 2017 because of increasing infestation and then again in 2019 and 2020 after the windstorm.

We used an image differencing method to investigate the forest loss from 2015 to 2021 using Sentinel 2 data. All available images taken in June of each year were firstly processed in GEE (Google Earth Engine). We used data collected in June to assess bark beetle disturbances because of good lighting and cloud-free images, and because all trees infested by bark beetle in the previous year(s) were clearly detectable. For each pixel, we retrieved the cloud probability value from Cloud Probability collection on GEE. Pixels with cloud probability higher than 0.1 were discarded. Finally, outputs were computed by using the median value of NDVI for each pixel in June in the same year.

In order to make images comparable along time-series, we performed a relative radiometric normalisation based on linear regression of each band, by using 51 pseudo invariant points from a field survey comprehending both intact evergreen forest and buildings. After computing NDVI index, we computed differences between years to detect forest cover changes. Since thresholding is a crucial choice in differencing approach (Rogerson, 2002), we used 12 verified points of bark beetle spots and 18 verified points of windfall spots to estimate the magnitude of NDVI difference within disturbance area. Ground-truth points were assessed by visual inspection during field survey. Threshold for forest change detection was set as the mean NDVI difference in bark beetle spots — 2 * standard deviation (Sohl, 1999). Besides the simplicity of this method, we found that threshold (value = -0.12) did not overlap with values in no-change areas. To remove no-forest areas, we used a forest cover map retrieved by photointerpretation of Google Earth high resolution images. Then, to remove noise, we applied a minimum size of 500 m^2 and smaller patches were discarded. Data analysis was done in R (R Core Team, 2020) by using RASTER (Hijmans, 2020) and SF (Pebesma, 2018) packages. Outputs were visualised and printed in QGIS 3.16 (QGIS.org, 2021).

Field surveys were carried out in August 2020 and March 2021 to confirm remote sensing observations and to assign the disturbance categories, i.e., bark beetle or wind, for each patch of disturbance. Patches of dead trees based on remotely sensed data were printed on technical maps for each year. Then, visual surveys and photographic reports were carried out from the opposite slope. Old and recent infestations of bark beetles and windfelled trees were clearly visible since no salvage logging was carried out in the study area after 2016. The final map was compiled by integrating remotely sensed forest changes and visual survey data, including the disturbance category of forest loss (Fig. 2).

We retrieved temperature and precipitation data since 1994 from a weather station located in the study area (11.8837° E - 46.3131° N) and solar radiation data since 2015 from a near weather station (Falcade, 11.87° E - 46.35 °N, distance from study area ~ 4 km). Data were validated and provided by ARPAV agency (available on www.arpa.veneto.it). To assess the conditions for host trees (i.e., water stress), we computed annual SPEI index using monthly data of precipitation and mean temperature. SPEI index is based on time series of water balance (i.e., difference between precipitation and evapotranspiration) and it is widely used for estimating drought (Vicente-Serrano *et al.*, 2010). Computations were performed in R using SPEI package (Beguería and Vicente-Serrano, 2017). Since phenological pattern of bark beetle population cannot be fully retrieved from trap catches (because of missing data or unavailability of weekly catches), to assess the potential development of *I. typographus* we ran the phenological model PHENIPS (Baier *et al.*, 2007) using daily temperature, solar radiation data, and default parameters. Model computation was performed in SAGA GIS (Conrad *et al.*, 2015).

3. Results

Climatic conditions of the study period are presented in Fig. 1. The period 2015-2017 was characterized by water stress with negative anomalies of water balance compared with the long-term trend. On the contrary, the pe-

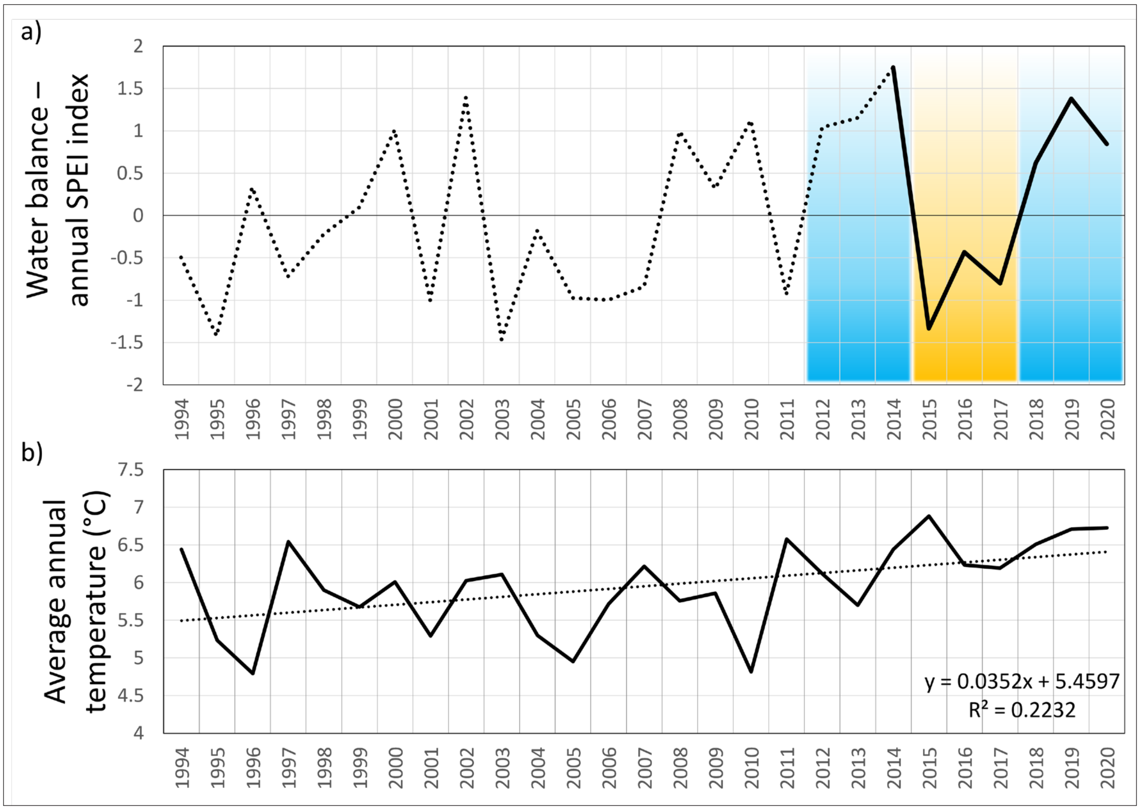

Figure 1 - SPEI index (Fig. 1a) and average annual air temperature (Fig. 1b) for 1994-2020 time series. In Fig. 1a, the dotted line indicates overall time series, while the solid line indicates the last period (2015-2020), concerning the studied bark beetle outbreak. Wet periods were highlighted in blue, water stress periods in orange. In Fig. 1b, the solid line indicates average temperature, the dotted line the linear regression, showing increasing temperatures. Climatic data were retrieved from a local weather station within the study area.

riod 2018-2020 was characterized by wetter climate. Regarding temperature, we did not observe annual anomalies in our study period (2015-2020), however, we found a weak trend of increasing average temperatures from 1994 onwards.

A total of 47.5 ha of forest (~ 20% of coniferous forest included in our study area) were damaged, of which 13.5 ha by bark beetles and 34 ha by windstorm from June 2015 to June 2021 (Fig. 2). Bark beetle spots occurring before Vaia started to be detectable by remote sensing in 2016 (two spots) and extended over about 3.5 hectares by 2018 (10 spots). Our findings by remote sensing were consistent with those resulting from surveillance activities by the forest service, which detected few single infested trees in 2015 and several infestation spots in 2017.

We found an increasing number of new bark beetle spots from 2016 to 2021, considering both completely new spots and new infestation expanding within neighbourhoods of previous spots (Fig. 3). We did not find, however, new damaged areas by bark beetles during 2019 (first summer after wind disturbance). Instead, a massive spruce mortality due to bark beetle occurred during 2020 and early 2021, damaging more than 10 ha of spruce forest in a total of 71 new spots.

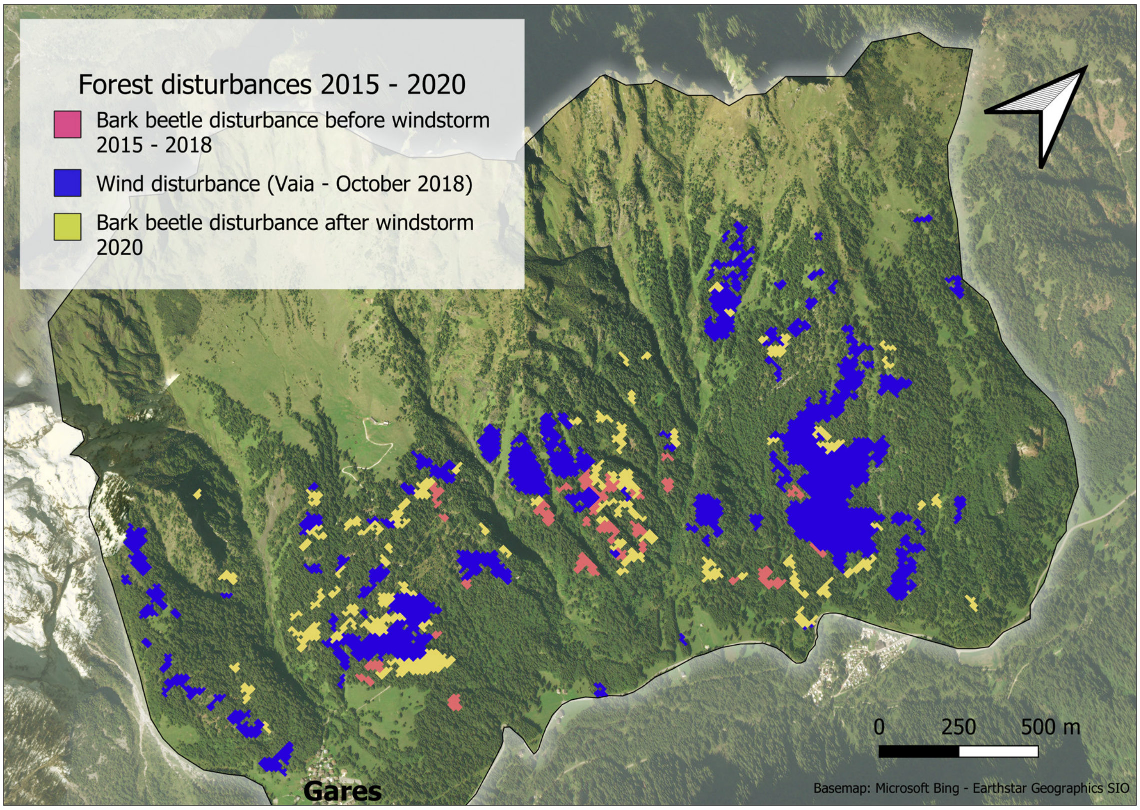

Figure 2 - Map of forest disturbances occurring in our study area between June 2015 and June 2021. In the base map forest is clearly visible in dark green, compared to pastures in light green. Bark beetle spots before and after the wind damage were depicted in pink and yellow, respectively. Wind disturbance was reported in blue.

Pheromone traps collected 5,800 beetles/trap (SD = 5,157, N = 27) in 2015 and 12,765 beetles/trap (SD = 15,694, N = 20) in 2017. After the windstorm, the catches decreased to 4,853 beetles/trap (SD = 3,502, N = 5) in 2019 and increased to 33,200 beetles/trap (SD = 24,742, N = 8) in 2020.

PHENIPS model indicated the occurrence of two generations per year, with swarming of 1st generation, 2nd generation (despite 2016 showed a late swarming of the 2nd generation), and sister brood generally regular among years (Table 1). The swarming of overwintering adults varied among years, probably depending on fluctuating conditions during spring. A comparison with field trapping curves was possible only for 2020 catches (see Supplementary Materials) and it confirmed the number of generations, with small deviations in the peak timing.

4. Discussion

Here, we show a case-study in which wind disturbance boosted a pre-existent local outbreak of the European spruce bark beetle, *I. typographus*, despite of favourable climatic conditions for Norway spruce due to a wetter period after the windstorm, and steady bark beetle generation development. Besides the well-known role of wind disturbance in bark beetle population dynamics, there is a lack of knowledge and observational studies dealing

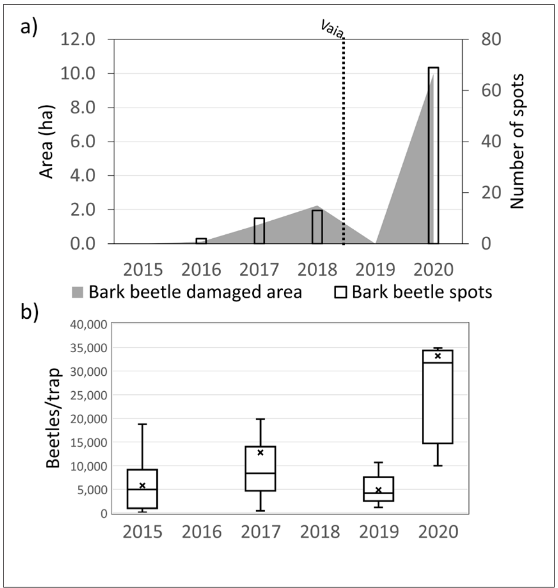

Figure 3 - Summary of bark beetle damage at Gares (BL) from 2015 to 2020. For each year, the total amount of newly damaged area and the number of new infestation spots were reported in Fig. 3a. In 2015, no bark beetle spots were detected by remote sensing. The vertical dotted line indicates the end of October 2018, when the Vaia windstorm severely hit the area, causing large windfalls. In Fig. 3b, we summarized pheromone trap data. Within each box plot, the central line represents the median and the cross represents the mean value of beetles/trap. Outliers were not displayed.

with natural disturbances affecting ongoing bark beetle infestation areas. By combining field surveys and remote sensing, we were able to follow a local spruce bark beetle outbreak four years before and two years after the massive wind disturbance event Vaia, which occurred in October 2018 (Chirici *et al.*, 2019).

Small windthrow events, which occurred in 2013-2014 on the north facing slope near our study area, were probably the triggering factors of an epidemic phase in spruce bark beetle population dynamics in 2016. We found increasing damage by bark beetles between 2016 and 2018, indicating that an outbreak was building up. Our spatial estimates were confirmed by increasing numbers of bark beetles caught in pheromone traps in 2017. Probably, water stress contributed to an expansion of infestation spots during this period. Indeed, many studies showed that water deficiency and drought can negatively affect spruce defenses against biotic agents such as bark beetles and associated blue-stain fungi (Netherer *et al.*, 2021). On the other hand, warmer temperatures can accelerate bark beetle development, potentially resulting in more generations per year (Mezei *et al.*, 2017; Wermelinger and Seifert, 1998; 1999). The phenological model PHENIPS was confirmed by trap catch data in terms of number

Table 1 - Developmental phases of the life history of *Ips typographus* at Gares as predicted by the PHENIPS model based on daily temperature and solar radiation data.

Development phase	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*
Potential fully developed generations (sister broods)	2 (1)	2 (1)	2 (1)	2 (1)	2 (1)	2 (1)
Total thermal sum (degree days)	1240	1114	1212	1287	1208	1192
Spring swarming	5th May	20th May	13th May	26th Apr	31st May	25th Apr
1st filial gen. - swarming	18th Jul	28th Jul	16th Jul	20th Jul	26th Jul	22nd Jul
1st sister brood gen. - swarming	13th Aug	29th Aug	11th Aug	16th Aug	21st Aug	19th Aug
2nd filial gen. - swarming	17th Sep	29th Oct	29th Sep	18th Sep	28th Sep	20th Sep

of developed generations, with small differences in peak timing. Moreover, we found similar thermal sums and bark beetle maximum generations among studied years. Overall, temperature anomalies appeared negligible and did not affect bark beetle phenology during our study period. However, increasing temperature trend over the last thirty years suggested that *I. typographus* populations might increase in the future leading to increasing risk of infestation (Seidl and Rammer, 2017). In conclusion, a high number of weakened and stressed trees susceptible to bark beetle attacks, probably favored the spreading of infestation areas, especially during the drier climate occurring before the windstorm Vaia (2018).

In October 2018, storm Vaia severely hit north-eastern Italy and large windfalls occurred also in our study area. During 2019, standing trees were not attacked by bark beetles, however we recorded a huge increase in infested area and number of infestation spots in intact forest during 2020. According to literature, effects of wind damage on bark beetle population densities are usually observed from the second year after the storm (Grodzki, 2008; Meier *et al.*, 2003; Stadelmann *et al.*, 2014). The mechanism underpinning this response depends on the high availability of breeding material after the windstorm. Indeed, during the first year fallen trees were massively colonized, thereby acting as sink for the local bark beetle population. Moreover, the surplus of breeding material might result in a low intraspecific competition for the substrate and thus a low colonization density and a higher reproductive success (Komonen *et al.*, 2011). However, in spite of an ongoing outbreak, it seemed remarkable that no infestation spots were newly detected on standing trees in 2019. Moreover, since living standing trees were not attacked during the first summer after the windstorm, attacks were supposedly concentrated on fallen trees.

The continued infestation of standing trees in 2020 occurred in spite of more favorable climatic conditions for host trees (i.e. increased precipitation) and similar seasonal development of bark beetle populations. Indeed, we found a large increment of infestation spots in 2020, confirming that the local population of bark beetles was still present and active during the 2019. Our findings are consistent with other studies highlighting the importance of the number of infested fallen trees as predictive variable for outbreak risks after windstorm damage (Kärvemo *et al.*, 2014). Moreover, we cannot exclude that some fallen trees were still infested in 2020 since they cannot be detected by remote sensing methods and previous studies showed that fallen trees can be attacked during the second summer after the windstorm depending on desiccation conditions (Eriksson *et al.*, 2005; Hroššo *et al.*, 2020). Furthermore, although natural enemies may already be present due to the previous outbreak phase before the storm, previous studies showed that natural enemies play a weak role during the epidemic phase (Marini *et al.*, 2013).

Our results (i.e., damaged area estimates) should be considered as conservative, and probably bark beetle disturbance was slightly undervalued for two main reasons. First, we used 10 m resolution images and the mapping of forest disturbances at very high resolution could not be achieved (i.e., single infested trees or very small spots). Second, since some infestation spots in 2018 may include uprooted trees, and some fallen trees might still be infested in 2020, overlapping of bark beetle and windstorm damage might have occurred. Finally, we showed that remote sensing data may have a great potential for rapid assessments at large spatial scale and for giving a good estimate of damaged surface areas and locations.

4. Conclusions

We showed how wind disturbance may boost an ongoing bark beetle outbreak and provoke huge infestations in the following years, even under favorable climatic conditions for Norway spruce and comparable beetle voltinism. Moreover, since most of the attacks may have remained undetected by remote sensing in the first year after the wind disturbance because of colonization of fallen trees, an underestimation cannot be excluded. Furthermore, we found that phenological models can successfully estimate bark beetle population development and pressure on host trees. However, the PHENIPS model needs to be accurately assessed by using robust climatological data, bark temperatures and comparison with field observations in the Southern Alps. On the application side, the measures to prevent or reduce bark beetle damage following abiotic disturbance events should be prioritized where bark beetle outbreaks are ongoing, irrespective of the climatic conditions. The time lag between the windfall and the attack on the standing trees allows to deploy the sanitation measures.

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RIASSUNTO

Le foreste di conifere in Europa sono attualmente minacciate da infestazioni di scolitidi (come *Ips typographus* L.) a causa di crescenti fattori scatenanti quali siccità e danni da vento, verosimilmente associati al cambiamento climatico. Le interazioni tra questi fattori sono un interessante argomento di studio e il presente lavoro propone un caso studio nelle Alpi Meridionali (Gares, Canale d'Agordo, Belluno), dove un danno da vento si è sovrapposto a un'infestazione da scolitidi (bostrico dell'abete rosso, *Ips typographus*) in atto e probabilmente legata a una serie di tre anni siccitosi. Attraverso la combinazione di osservazioni da remoto e rilievi in campo, è stato riscostruito l'attacco dell'insetto dal 2015 al 2021, periodo che comprende i danni da vento della tempesta Vaia nell'ottobre 2018. Nonostante l'attacco del bostrico fosse in fase di espansione al momento della tempesta, gli attacchi su alberi in piedi non sono stati osservati nell'anno successivo, ma a partire dal secondo anno dopo l'evento. Le osservazioni suggeriscono che la grande disponibilità di materiale a terra, altamente suscettibile di colonizzazione da parte del bostrico, abbia catalizzato la popolazione locale, creando le condizioni per un consistente aumento dell'attacco agli alberi sopravvissuti alla tempesta.

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