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Participatory ground data are complementary to satellite bark beetle detection

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Abstract

Key message During pest outbreaks, mapping tools play an important role. Participatory projects can provide useful ground data, which have a high accuracy in detecting early-stage infestations and small spots of the European spruce bark beetle *Ips typographus*. However, satellite approaches are fundamental to clearly estimate infestation occurrence because ground data are spatially biased. Here, we show how a participatory approach involving nonspecialized staff and based on GIS-based app may contribute ground truth data that are fully complementary to satellite data.

Context In Europe, bark beetle outbreaks were recently triggered by windstorms and heat waves, with the European spruce bark beetle *Ips typographus*. as the most important pest species. Huge efforts are needed for continuous mapping and monitoring of affected areas, especially during an incipient large-scale infestation. This is particularly difficult in mountain landscapes because of the rugged topography.

Aims In addition to the use of remote sensing techniques, ground surveys are still an important source of data, providing detailed information on the symptoms of the affected trees and the stage of the attacks. Unfortunately, these surveys are extremely time demanding and require intensive field work. We wanted to assess how a participatory approach based on nonspecialized staff may contribute to data collection.

Methods Georeferenced outbreak data were collected in the field in the Southern Alps (Italy) using a smartphone application based on ArcGIS platform. The survey was based on a participatory approach on a voluntary basis, involving citizens aware of forest practices. Visual analysis of satellite images was performed monthly to assess the visibility of reported infestations. Using a binomial model, we tested how the type of report (i.e., on-site/off-site), size of spot, stage of infestation, and their interactions affect detectability. In addition, spot occurrences within a study area were mapped for comparison with ground surveillance. Closeness to roads was tested between reported and unreported spots.

Results WebGIS platform allowed us to retrieve near real-time information on bark beetle outbreaks and to compare the results with satellite imagery. Using visual analysis of satellite images, we detected only ~ 50% of the spots

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observed in the field, and detectability decreased dramatically for smaller and early-stage spots. Field observations were mostly concentrated near roads and covered only ~ 10% of the spots detected on satellite images.

Conclusion The participatory approach is particularly helpful in mapping early-stage and small infestations, while satellite images are better suited at covering large areas and detect large and advanced-stage spots. The integration of those approaches is promising, and it can greatly improve the overall understanding of bark beetle outbreaks under emergency situations. A greater effort in developing smart applications for ground detection will benefit future monitoring of forest pests.

Keywords Bark beetle, Citizen science, Digital technology, GIS, Smartphone application

1 Introduction

In the last decades, bark beetles have severely threatened temperate coniferous forests worldwide (Bentz and Jönsson 2015). In Central Europe, large infestations of the European spruce bark beetle, *Ips typographus* (L.), were triggered by windstorms, drought, and other large-scale disturbances (Hlásny et al. 2021b, 2021a; Netherer et al. 2021, 2019). Huge efforts are needed for mapping and constantly updating the epidemic situation of bark beetles. Infestations can be mapped by detecting symptomatic trees using high-resolution satellite images, or by foresters' field visual surveys (Nardi et al. 2022a). Remote sensing has been largely used for assessing bark beetle damage (Zimmermann and Hoffmann 2020). However, the broad spectral, spatial, and temporal resolutions of the most commonly used satellites still pose limitations for detecting early asymptomatic stages (i.e., green stages) or small infestation spots (Luo et al. 2023). Moreover, ground-truth data are still needed for calibrating machine learning algorithms (Huo et al. 2021). For that reason, ground-truthing is required and this is usually carried out by field workers visually checking tree stands. During these field surveys, the use of mobile apps might serve as a smarter and more standardized way to collect data than paper forms (Tahri et al. 2022).

Citizen science approaches consist of involving non-professional scientists asked to follow simple and clear tasks with the aim of reporting scientific observations (Bonney et al. 2009; Dickinson et al. 2012, 2010). Furthermore, digital tools, such as cloud-based GIS systems and smartphone apps, can improve the accessibility and sharing of collected georeferenced data, increasing citizen contributions (Kearns et al. 2003; Van Vliet and Moore 2016). In pest monitoring projects, a mutualistic relationship exists between scientists and citizens: scientists have the opportunity to gather more data from the field covering larger study area and easily detect new infestations or harmful organisms at the early stages, while citizens become more aware of the scientific methodology and can improve their awareness of the target organisms (de Groot et al. 2023). Citizen science approaches are promising, and they have been extensively used in entomology and forest health projects in the last years leading to fruitful results (Crocker et al. 2020; de Groot et al. 2023; Hulbert et al. 2023).

Significant tree mortality due to bark beetles and the resulting management have attracted the attention of citizens and the media worldwide, contributing to the debate on intervention versus conservation measures (Kortmann et al. 2021; Müller 2011). Since large infestations can even lead to socioeconomic issues (Grégoire et al. 2015), providing scientific knowledge and updated information on the ongoing infestation to citizens is of primary importance. In particular, those people already working in forest management and involved in such projects might act as deliverers of science-based knowledge by themselves, especially in small communities.

Here, we discuss the use of a participatory approach using WebGIS systems aimed at mapping bark beetle outbreaks and based on a collection of data from volunteers. Volunteers collected data in the field without predetermined areas of interest. The approach is slightly different from a canonical citizen science project, since we involved a specific target group: people already working in forest environments, such as plant-health inspectors, self-employed foresters, and forest officers. They already have a minimum knowledge of the target organism, but no specific competence in field surveying. The ground observations were compared with high-resolution satellite imagery to assess survey data, and finally we investigated the trade-offs of the two approaches and their possible integration in a comprehensive framework of real-time forest health assessment. The latter could be applied over a large range of conditions of temperate and boreal forests. We would like to address two questions: (I) Can participatory-based ground data contribute to bark beetle monitoring with useful information? (II) Given an area, are participatory-based ground data a good proxy for estimating the bark beetle infested area?

2 Materials and methods

2.1 Ground survey with participatory approach

In the southern Alps, a windstorm called Vaia occurred in October 2018 and uprooted almost 40,000 hectares of forest, mainly Norway spruce (*Picea abies* (L.) H. Karst) (Giannetti et al. 2021). The storm-felled trees provided the initial conditions for the largest bark beetle outbreak ever recorded in the area. The study was conducted in the Veneto region, Italy, using a participatory approach involving people already working in the forest sector, but not specifically in plant health survey. The survey aimed to report spots of infested trees from ground observations, with a spot being formed from few trees to hundreds of trees (Fig. 1). The participatory project was active from June 15th to September 20th, 2022, and it was based on volunteers providing random observations during the entire season for the whole region.

Before starting the survey, a recruitment campaign was launched on the local networks of professionals related to forestry and more generally to local citizens interested in forestry. Two information workshops were offered, one in person and one remotely, aiming at training the operators in the recognition of bark beetle outbreaks. The workshop was divided into three parts: a first part was dedicated to the biology of *I. typographus* and how to recognize infested trees in the field; a second part explained how the project works and how to fill the reporting form using a mobile app; and finally, the last session was a field test. The last part was particularly useful to calibrate answers among different field operators. During the workshop, scientific terminology was duly explained to make the data collection done by the operators consistent with the aims of the research.

To facilitate ground-truth data collection by users on smartphones, we used a custom module within the Survey123 app (ESRI Inc., Redlands, CA). Survey123 is a mobile app belonging to the ArcGIS suite and it is designed for standardized collection of georeferenced data in the field. When a user submits a report, the geographic location (latitude and longitude) of the device from which they are working is attached. Two types of reports are considered: on-site reports (the field operator is within the infestation spot, providing the exact location) and off-site reports (the operator is at some distance from the spot, generally lower than 2 km). In the case of off-site reports, additional fields are added to better locate the spot, such as the compass direction and the estimated distance. In both cases, a photograph of the spot taken by the smartphone can be attached. The operator is also asked to fill out a form with information on visible symptoms and spot size. A list of the variables is provided in Table 1. The mobile app is coupled with the ArcGIS Online platform, so users could can field data using mobile devices and then populate a shared WebGIS project. All the questions in the form are indeed associated with specific fields in a shapefile. Survey123 can temporarily work even without an Internet connection and then, when connection is available, report data are directly submitted to the WebGIS project hosted in ArcGIS Online, which is continuously updated (Appendix` Fig. 6).

After the ground data was received, a manual curation was carried out by two independent experts to validate each entry using a simple consistency criterion (Fig. 2). First, few records with incomplete documentation were excluded. Second, those records without attached photos or in which photos were not consistent with the submitted information (e.g., declared symptomatic stage different from what shown) were classified as "invalid" or "to be validated by an expert." Furthermore, if a difference in the observed stage of infestation was found between what was declared by the operator and what was visible

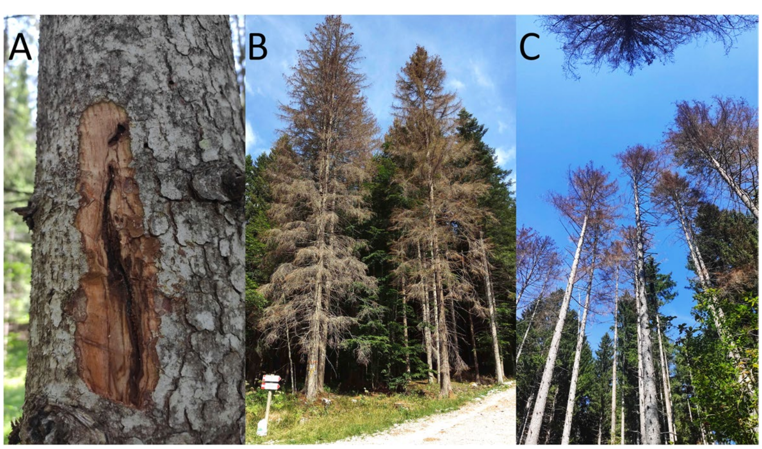

Fig. 1 Infestation stages of *Ips typographus* on Norway spruce. **A** An apparently healthy tree at the early/green stage characterized by green needles (not visible in the picture) shows entering holes and frass on the bark. After removing the bark, maternal galleries are visible. **B** Intermediate infestation symptoms with red needles (red stage). **C** Advanced infestation characterized by needle and bark loss (grey stage)

Table 1 Variables used in the form for the ground survey

Name of variable	Type of data	Multiple choice	Notes
Geographic position	Geopoint		
Report type	Multiple choice	Off-site	Operator away from the spot
		On-site	Operator inside the spot
Orientation	Multiple choice	Compass quarters	Only for off-site
Estimated distance	Integer		Only for off-site
Other	Free text		Only for off-site
Infestation stage	Multiple choice	Early (green)	Green needles still present
		Intermediate (red)	Yellow-orange needles
		Advanced (gray)	Trees without needles
Spot size	Multiple choice	Diffuse infestation	Sparsely occurring infested spruce trees, often interspersed with other tree species
		Small (< 10 trees)	
		Medium (10–50 trees)	
		Large (50–200 trees)	
		Very large (> 200 trees)	
Other notes	Free text		
Photo	Attachment		
Operator name	Free text		
Date	dd/mm/yyyy		

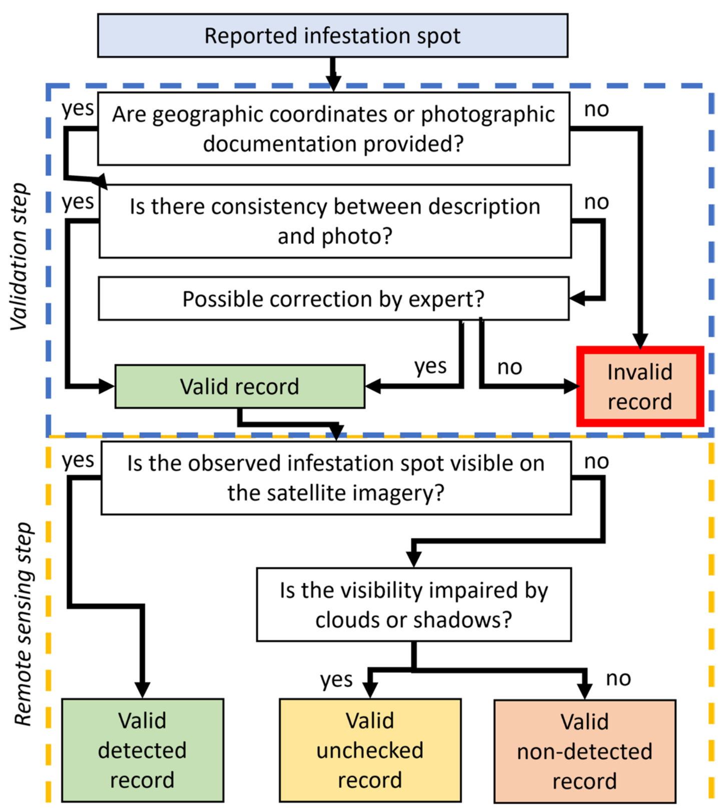

Fig. 2 Decisional scheme of the procedure for the report validation and for the comparison with satellite imagery. Invalid records are shown in red; valid records in green; non-detectable valid records in orange

in the photograph, priority was given to the latter. Data of the validated records are available in Nardi et al. (2023).

2.2 Checking spot visibility from remote using satellite images

The ground collected data were compared with high-resolution multispectral imagery (3 m resolution) of Planet Dove constellation to estimate how ground detections match with remotely damage assessment. Satellite images covered all the alpine territory of the northern part of the Veneto region, where all the operators' reports were collected. The images were acquired monthly from June to September 2022, with clear sky and good illumination of north-facing slopes. For each report, we selected the relative satellite image considering the nearest available satellite date (about 2 weeks range) since the reporting date. Because we considered only new infestations starting in 2022, satellite images from 2021 (on September 9th and 24th) were also selected to separate the 2022 damage from the 2021 one. The final validation of reports was conducted using the open-source software QGIS (QGIS.org 2023), by overlaying the positions of the field observations over satellite imageries. A first operator checked and corrected the size and stage of infestation by looking at the photo submitted with the report, assigned a satellite image depending on the date of the report, and, if possible, direction and distance were used to identify the spot. A second operator performed a visual detection by photointerpretation of the satellite images, without information about the distance, direction of the spots, and type of report from the observation point. Operatively, all the recognizable spots were mapped surrounding each reporting position at a 1:5000 scale. Satellite data were displayed in true colors and false colors (near-infrared, red, green) to maximize spot detection by photointerpretation. Then, mapped spots were compared with the reporting information to validate the match between the ground reports and satellite imagery. The reports were classified as "detected" if the reported infestation spot was detected by the second operator, and as "undetected" if it was not possible to recognize the infestation spot on satellite imagery. In the latter case, additional information was added to distinguish the reports that could not be validated due to visibility obstacles, such as cloud cover or shade. A summary of the procedure is shown in Fig. 2.

We performed a binomial regression model using detection (binary) as the response variable, and reporting type, spot size, and infestation stage as explanatory variables. Before the analyses, 35 reports were removed because spots were not visible due to clouds and shade, or because logging activities were carried out during the reporting month. Spot size was ordered by size from diffuse spots to very large spots. We also tested interactions among predictors, but only significant interactions were included in the final model. Multicollinearity and residuals were checked using VIF (VIF < 1.5) and diagnostic tools in car (Fox and Weisberg 2019) and DHARMa (Harting 2021) packages. Analyses were performed in R 4.2.2 (R Core Team 2022).

2.3 Comparing completeness of remote approach vs. field observations

Furthermore, to understand how complete the ground dataset is compared to what is visible from the satellite, we polygonized all the visible spots within a study area. We selected an area of 8090 ha in the municipality of Canale d'Agordo (Belluno province), because it has a high frequency of ground reports and high-quality satellite imagery. The thorough analysis of satellite images allowed the location and polygonization of every infestation spot that occurred in that area in 2022. Infestation spots that included the 2022 expansion of old spots from 2021 were also considered. We used only images taken in September for mapping infestation spots within the study area, because they represent the situation at the end of the season. For each polygon, we computed the area (in ha) and the distance from the nearest road. Additionally, we indicated whether a spot was reported by the ground survey. The layer of the driveway roads was extracted by OpenStreetMaps (www.openstreetmap.org, accessed on 15/09/2023). A nonparametric Mann–Whitney-Wilcoxon test was used to test the hypothesis that reported infestations are closer to roads than unreported infestations.

3 Results

A total of 841 ground reports were retrieved from June 15th to September 20th, 2022, by 34 operators, with an average of 35 reports per operator (SE = 13.8). After the first step of curation and validation, a total of 740 reports (88%) were considered eligible for comparison with satellite imagery. Of these, 402 reports (54.3%) were recorded off-site and 338 reports (46.7%) on-site. Most of the reports (410, 55.4%) concerned an intermediate stage of infestation (i.e., red stage), 218 (29.4%) were in the grey stage and 112 (15.1%) were in the early stage. Regarding the infestation spot size, 99 records (13.4%) were diffuse spots, meaning that infested trees were few in numbers and were interspersed with other trees, 132 (17.8%) were small (less than 10 trees), 308 (41.6%) were medium (10–50 trees), 175 (23.7%) were large (50–200 trees), and 26 (3.5%) were very large (more than 200 trees). Afterward, we checked the visibility of validated records with high-resolution satellite images. Some validated records were excluded from the analyses because of satellite impediments, such as clouds or shade (35 records, 5% of all validated records). Of the remaining records, 350 records (49.6%) were successfully double-checked with satellite imagery, of which 98 (28%) were on-site and 252 (72%) were off-site. A total of 355 records (50.4%) were detected only from the ground.

Our results suggest that all the three variables are important factors affecting the detectability of bark beetle spots (Fig. 3, Table 2). Overall, we found that larger spots were more detectable than smaller spots; however, this effect depended on the type of spot (LR = 9.35, *P* value = 0.002) and infestation stage (LR = 8.17, *P* value = 0.017). On-site reports had a low detectability (approximately zero), especially for the smaller ones. In contrast, off-site reports held a good detectability (approximately 40%) even in the case of small spots. Moreover, infestation spots at the early stage are difficult to detect regardless of size.

In the area considered for polygonation (Fig. 4), a total of 717 infestations occurring in 2022 were identified by photointerpretation and thus polygonized, for a total of 190.5 ha. In the same area, 54 polygons corresponded to the operators' reports, 8 of which were observed more than once (76 reports were validated), for a total damaged surface of 25.9 ha. Overall, only 10% of detected spots were reported by ground operators, corresponding to 13.6% of the total infested area assessed by satellite. Moreover, we found a bias in reporting infestations during the ground survey because reported spots are closer to roads than unreported ones (Mann–Whitney test, $W = 9712$, P value = < 0.0001) (Fig. 5).

4 Discussion

4.1 The use of WebGIS, mobile devices and participatory approaches

The increasing risk of bark beetle outbreaks due to the occurrence of windstorms and drought imposes the need for a multi-approach effort aimed at depicting near real-time outbreak situations. Within this general need, ground-truth data play an important role as early-warning bells and for supporting automated remote approaches. Here, we presented the opportunity to use a GIS mobile app and a participatory approach to specifically address the need for data collection under a large-scale outbreak scenario.

Although similar mobile apps have already been used in the ground-collection of target pest infestations in forestry, users are generally researchers or technical staff with previous competence in forest entomology and geographic digitizing (Hamdi et al. 2019; Tahri et al. 2022). Conversely, we used a participatory approach here, similar to a citizen science framework, in which forest service workers and self-employed foresters were directly involved in the data collection from the field. Although we could upscale the study area because of the higher number of involved people, we needed to simplify the field tasks. Indeed, we decreased data resolution and

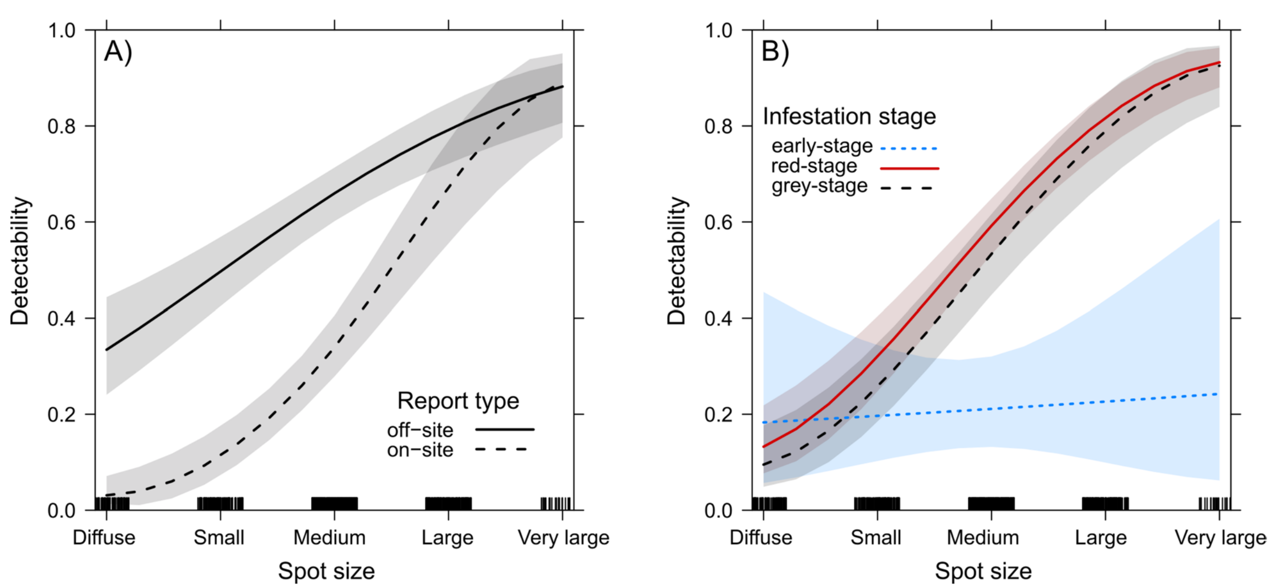

Fig. 3 The detectability of ground reported spots using satellite images depends on the interaction between type of report and spot size (**A**), and the interaction between infestation stage and spot size (**B**). In Fig. 3A, detectability of small spots is lower for on-site reports (dashed line) than off-site reports (solid line). In Fig. 3B, the detectability of red-stage (solid red line) and grey stage (dashed black line) increases with spot size, while the detectability of early-stage (dotted blue line) remains low regardless of size class

Table 2 Deviance table of binomial regression model shows significant factors

Variables	Likelihood ratio	Degree of freedom	*P* values
Report type	25.65	1	< 0.0001 ***
Spot size	0.42	1	0.516
Infestation stage	2.63	2	0.268
Report type: spot size	9.35	1	0.002 **
Infestation stage: spot size	8.17	2	0.017 *

Significance levels: *** *P* value < 0.001, ** *P* value < 0.01, * *P* value < 0.05

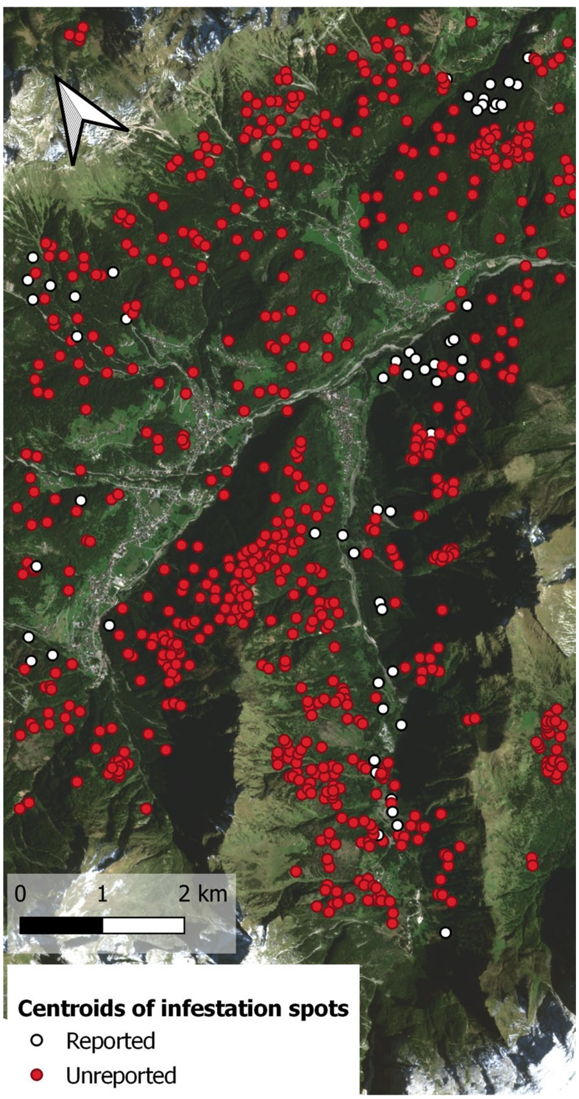

Fig. 4 Area considered for the polygonation of the 2022 infestation spots. Centroids of visible spots are shown: in red those without ground correspondence (unreported), in white those with confirmed records from the ground (reported). Basemap: Dove satellite (real colors) by Planet Labs

precision by using points instead of polygons, but this is a common trade-off in participatory approaches (MacPhail and Colla 2020). On the one hand, our expeditious approach allowed us to cover large areas and was useful when there were only a few expert operators working full-time on infestation detection activity. On the other hand, involvement of people already working on similar topics might increase awareness of such plant health problems, thus increasing interest and science-driven knowledge in society. Moreover, presenting to all participants the results of the project should be important since they have feedback on their work and increase their awareness and engagement (de Groot et al. 2023). Therefore, we suggest that participatory methods in plant health are a win–win approach, especially in studies targeting specific and easy-to-detect pests or symptoms.

Furthermore, our study is based on a WebGIS system, which provides tools for user-friendly graphic visualization. We designed a web page using the dashboard tool by the ArcGIS Online platform for visualizing raw data (Appendix Fig. 6). A great advantage of using visual elements in WebGIS systems is the possibility of having an immediate overview of the observed data in real time. The dashboard could be interrogated by project managers and allows a day-by-day monitoring and the possibility of visualizing the full reports directly on a map. Additionally, simple statistics (e.g., pie charts and count indicators) and filtering tools were added to the web page for customized queries. All these tools help scientists to directly share data and information with forest offices and decision makers (Grainger et al. 2016; Keenan and Jankowski 2019). Finally, the platform allows us to restrict access to specific users whenever needed.

4.2 Coverage vs. accuracy: a trade-off in forest health surveys

The concept of accuracy is one of the most important in disease detection in plant health and it represents how a detection system is able to correctly identify a target (Sankaran et al. 2010). However, when dealing with pest outbreaks, such as bark beetles, another important factor to take into account is the spatial coverage of the detection method (Bárta et al. 2022; Hicke et al. 2020; Nardi et al. 2023). Here, we compared a ground survey with a visual inspection with satellite data, and we discussed trade-offs in accuracy and coverage.

Overall, we detected 50% of the spots identified on the field by using visual inspection of satellite images; however, three factors strongly affected the detectability of bark beetle spots: type of ground report, size, and infestation stage. Our findings highlighted that detectability dramatically increased with the size of the spot. Smaller spots were more difficult to detect compared to larger

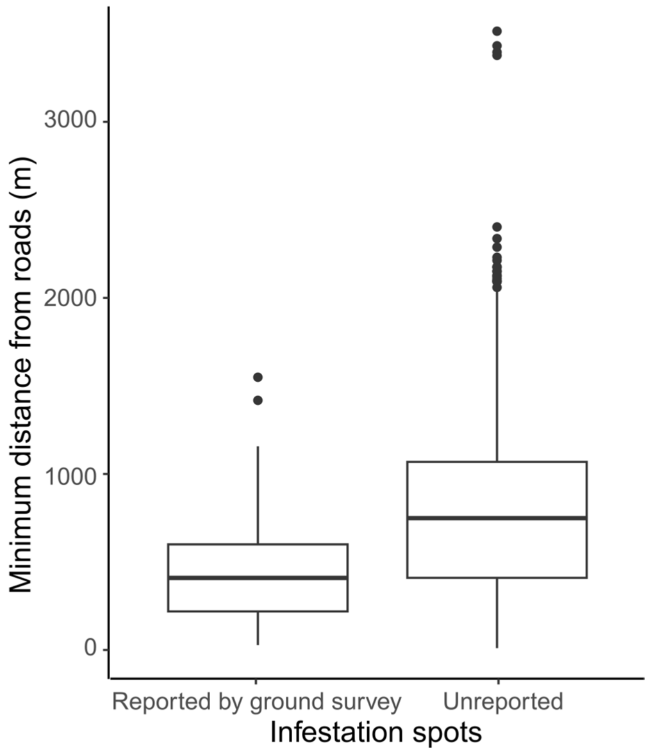

Fig. 5 Boxplot showing different distance-from-road distributions for spots confirmed by ground survey (i.e., "reported") and spots detected only by photointerpretation of satellite imageries (i.e., "unreported")

spots, especially those composed of less than 10 trees or showing a diffuse shape. This expected result is probably due to the spatial resolution of the satellite data, which fails to detect small spots, and due to the noise in certain cases, such as sparsely affected trees, which are usually interspersed with other tree species (Zabihi et al. 2021). However, the size effect depends on the type of the report and the infestation stage: on-site reports were less detectable than off-site reports, and this difference was even greater for the small spots. We argue that on-site reports were usually closer to roads or logged areas, and they are often referred to infestations occurring at the margin of the forest, where the satellite data suffer higher noise. Nonetheless, off-site reports achieved approximately 40% of detectability even in the case of small spots. Moreover, early stages are difficult to detect, regardless of their size. Instead, infestations at the red or grey stages are easily mapped, which is expected since photointerpretation is mainly based on the color change of the crown. Using advanced remote sensing analyses might help in the early detection of newly infested trees; however, previous studies integrating ground data and remote sensing estimated a delay of 3 weeks, which is in line with our observations (Bárta et al. 2022). However, comparing the ground reports with the satellite data taken at the end of September, we achieved approximately 72% detectability. Most of the green stages surveyed during the activity might become visible at the end of the season (September), and they might be no longer in the green stage. This process might be even more exacerbated by the occurrence of an intensive drought event during the study campaign. Indeed, the entire region experienced an extreme drought during summer 2022 (Faranda et al. 2023), which might speed up symptom appearance and increase the number of susceptible trees.

In the second part of our study, we selected a study area, mapped all the visible spots by visual photointerpretation using satellite data, and noted those spots also reported by the ground survey. The remote approach gives a better estimation of the area affected by bark beetles, providing a better representation of the damage. For instance, in a few cases, satellite images were used to correct the actual size of the spots, which were misinterpreted from the ground (Appendix Fig. 7). Moreover, reported spots are closer to roads, given a biased representation of the current infestation occurrence. This is a common bias in citizen science approaches (Dickinson et al. 2010; Sicacha-Parada et al. 2021) and the efficacy of ground detection quickly decreases far away from the main roadways. The remote sensing approach is very useful in damage quantification, as it can be used for large area surveys (Fernandez-Carrillo et al. 2020). In addition to visual photointerpretation, other advanced approaches for tree decline detection, such as machine learning, have been proven to be helpful in forest health as they might discover hidden signals or small changes in the spectral signature of infested trees (Bárta et al. 2021; Dalponte et al. 2023; Migas-Mazur et al. 2021).

On the one hand, satellite data can suffer from missing detection due to high noise in mixed forests and different lighting in complex topography, and a delayed detectability of early stage attacks. Moreover, remote sensing approaches usually require a large amount of ground-truth data. Therefore, even in the era of Earth Observation (EO), ground-truth data are still needed (Bárta et al. 2022), and field surveys are quite useful to provide such data, even if they are time demanding. On the other hand, the use of only ground observations will generally lead to biased interpretation as infestation spots can be missed or reported spots are biased depending on their closeness to roads. We argue that integrating near real-time ground observations with remote sensing approaches potentially allows us to achieve a greater degree of completeness of the outbreak delimitation. The comparison between damage retrieved by remote and ground can inform on the error rate in the overall estimations, and it can be done monthly or annually depending on the objective of the study. Unfortunately, because in our study ground data are "presence only," it is not possible to estimate "false positive" remote detections, instead one can estimate "false negative" remote detections. If the aim is to assess the total area affected by bark beetle attacks, comparison with ground-driven estimation is less important because larger spots were efficiently mapped even by satellite. However, it is much more relevant if the aim is to identify small spots of new infestations, which are extremely important in predicting intra- and interannual future scenarios and are more difficult to detect remotely.

4.3 Costs and other opportunities

The major costs associated with the ground survey were due to the ArcGIS license, which was paid by the University of Padua under an institutional subscription (i.e., no direct costs were associated with this project). Although these subscriptions are usually expensive, cheaper opportunities also exist. An alternative would be using open-source WebGIS, such as QField, which offer a cloud-based platform and the user can buy storage space. However, property software provides several ready-to-use applications that can be easily customizable without coding knowledge. In contrast, open source software requires great efforts in customization and specific computer engineering skills. Regarding the field operators, we used a participatory approach involving people already working in the sector. In such a way, they can contribute to the survey during field operations without additional costs. However, an important aspect of the project is the strong collaboration between the institutions to improve the motivation and coordination of all the contributors. The training has been provided as a presence meeting (1 day) for the core team (i.e., regional phytosanitary service), as a recorded online meeting for all the others, and as a short electronic guideline. These training should be repeated annually to ensure a high-quality level in the participatory approach.

Regarding remote sensing, costs are associated with the collection of satellite data and their analyses. The resolution of satellite data makes the difference in terms of results and costs: medium-resolution images (i.e., Sentinel and Landsat) are usually freely available but the spatial resolution is often too broad for detecting small spots or infestations in heterogeneous forests; on the other hand, commercial satellite images have a better resolution, but they are expensive. We used PlanetScope imagery, which is provided for free for educational and research purposes and are acquired with a 3.7 m resolution. Second, we performed a visual photointerpretation which is time-consuming (2 weeks*operator) but it does not require specific skills. Automatic detection using machine learning algorithms could automate the process, but they require specific skills, training data, and validation steps, and they are beyond the purposes of this work.

5 Conclusion

The mapping of plant health agents in forestry and the management of forest stands for production and conservation aims is a priority task for forest managers under the changing climate worldwide (Forzieri et al. 2023). The recent large-scale outbreaks of *Ips typographus* in Europe require smart and effective tools for rapid infestation detection and mapping. Participatory-based ground surveys are still important because they might provide complementary data to remote sensing. Ground data can be used for training machine learning algorithms or for mapping small early infestation spots and estimate missing detection of remote sensing methods. For instance, the detectability of early stages and small spots is difficult and delayed using satellite data. Mobile apps and WebGIS platforms can support the field activities by enhancing the user experience and facilitating data sharing. However, participatory-based ground observations are biased and have a low coverage compared with remote approaches. We suggest that remote sensing systems should be coupled with a greater effort in developing and deploying of smart applications for ground detection for bark beetle outbreaks occurring with a spot dynamic in several forest ecosystems of temperate and boreal regions. Such an integration of the methods would benefit efforts needed for surveillance at large scale, as needed, for example, by international initiatives of forest surveillance.

Appendix

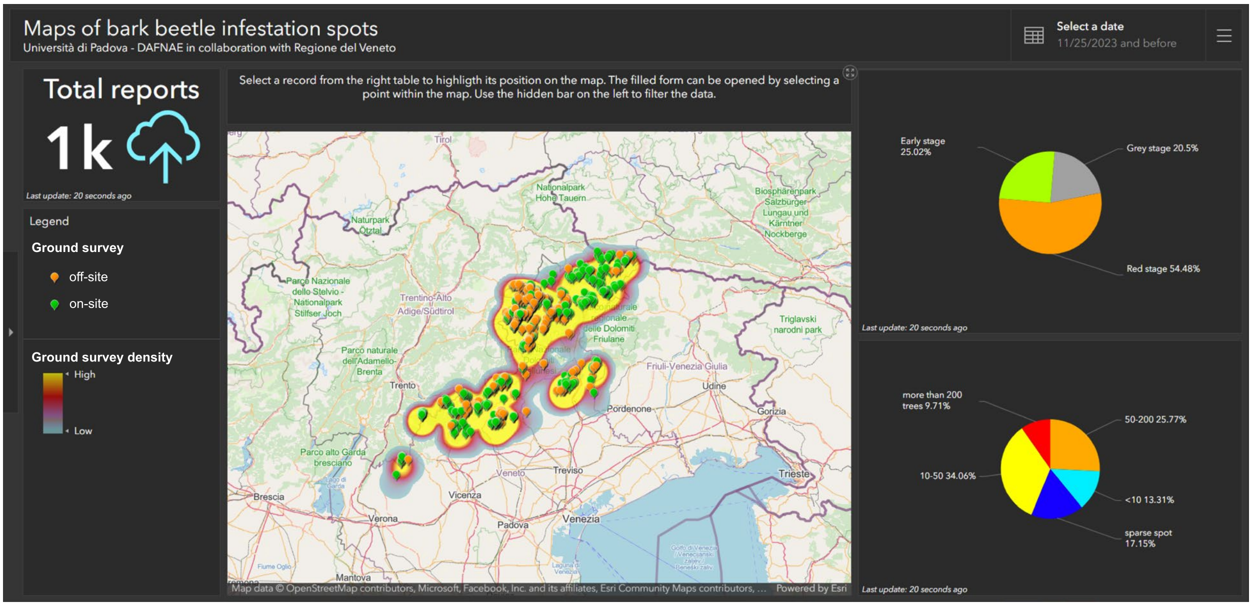

Fig. 6 Project dashboard on ArcGIS Online. The dashboard can be accessed by a restricted number of accounts since reports from volunteers are collected directly, without quality check. The map is navigable and single reports (points on the map) can be interrogated to visualize filled form and attached photo. Simple chart plots can be settable

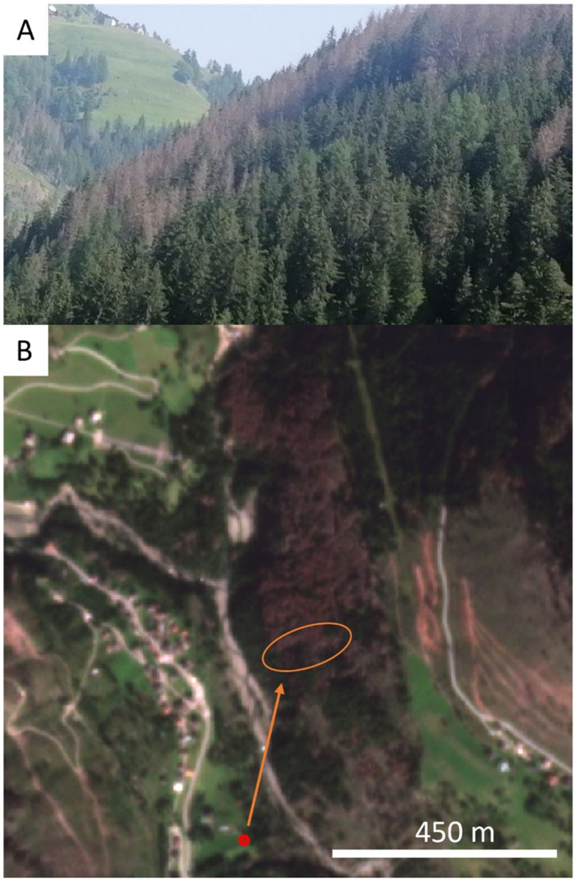

Fig. 7 **A** shows the attached photo from the mobile app and reflects what is visible from the ground. **B** shows the real size of the spot from remote sensing. The red dot represents the position of ground observation, orange arrow the direction of seeing, and orange ellipse the area shown in Fig. 7A

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Authors' contributions
Conceptualization: Davide Nardi, Valerio Finozzi, Andrea Battisti; methodology: Davide Nardi, Andrea Battisti; formal analysis: Davide Nardi; investigation: Aurora Bozzini, Giuseppe Morgante, Angelo Gaccione; writing—original draft preparation: Davide Nardi; writing—review and editing: Davide Nardi, Aurora Bozzini, Andrea Battisti; funding acquisition: Valerio Finozzi, Andrea Battisti; resources: Davide Nardi; supervision: Andrea Battisti. The authors read and approved the final manuscript.

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The dataset of the records validated within this study is available at https://researchdata.cab.unipd.it/id/eprint/1078.

Code availability
Not applicable.

Declarations

Ethics approval and consent to participate
Not applicable.

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All authors gave their informed consent to this publication and its content.

Competing interests
The authors declare no competing interests.

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