Rendiconti Lincei. Scienze Fisiche e Naturali
https://doi.org/10.1007/s12210-025-01387-5

Remote sensing across scales and platforms: monitoring Castelporziano nature reserve forest insect outbreaks

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Received: 28 May 2025 / Accepted: 20 November 2025

Abstract
Stone pines (*Pinus pinea*) are a dominant species in Mediterranean coastal forests, playing a crucial ecological and landscape role. However, these ecosystems are experiencing increasing pressure from rising temperatures, prolonged droughts, and other stressors, which weaken trees and make them more susceptible to natural disturbances, such as insect infestations, leading to significant forest decline. This study presents a multi-platform, temporal, and spatial resolution remote sensing approach to detect and monitor insect outbreaks. The study area is Castelporziano Presidential Estate (Rome, Italy), a pine-dominated periurban forest of high ecological value and severely affected by *Tomicus destruens* (Coleoptera: Curculionidae) and *Toumeyella parvicornis* (Hemiptera: Coccidae). Very high-resolution Pléiades and DigitalGlobe images were used to map forest disturbances accurately and to assess the accuracy of the yearly forest disturbance maps obtained through Sentinel-2 data. Sentinel-2 data enabled the production of yearly disturbance maps in near real time (NRT), improving the Three Indices Three Dimensions (3I3D) unsupervised forest disturbance algorithm. Lastly, PlanetScope data were used to calculate the Mean Time Lag (MTL) between disturbance occurrence and detection in Sentinel-2 NRT images, revealing an average detection delay of 8.5 days. Additionally, the unsupervised model's performance was evaluated, yielding an overall accuracy of 85%. The accuracy of the Sentinel-2 forest disturbance map was assessed against the map derived from Pléiades/DigitalGlobe, achieving an overall accuracy of 92%. These findings confirm that integrating multi-source remote sensing data enhances the timeliness and reliability of insect outbreak monitoring, offering valuable tools for managing Mediterranean forests threatened by climate change and biotic agents.

This special issue gathers peer-reviewed articles promoted by the Scientific Council of Castelporziano Presidential Estate and supported by the Segretariato Generale della Presidenza della Repubblica as part of the Presidential Decree n. 69/N/2020 and subsequent amendments and supplements.

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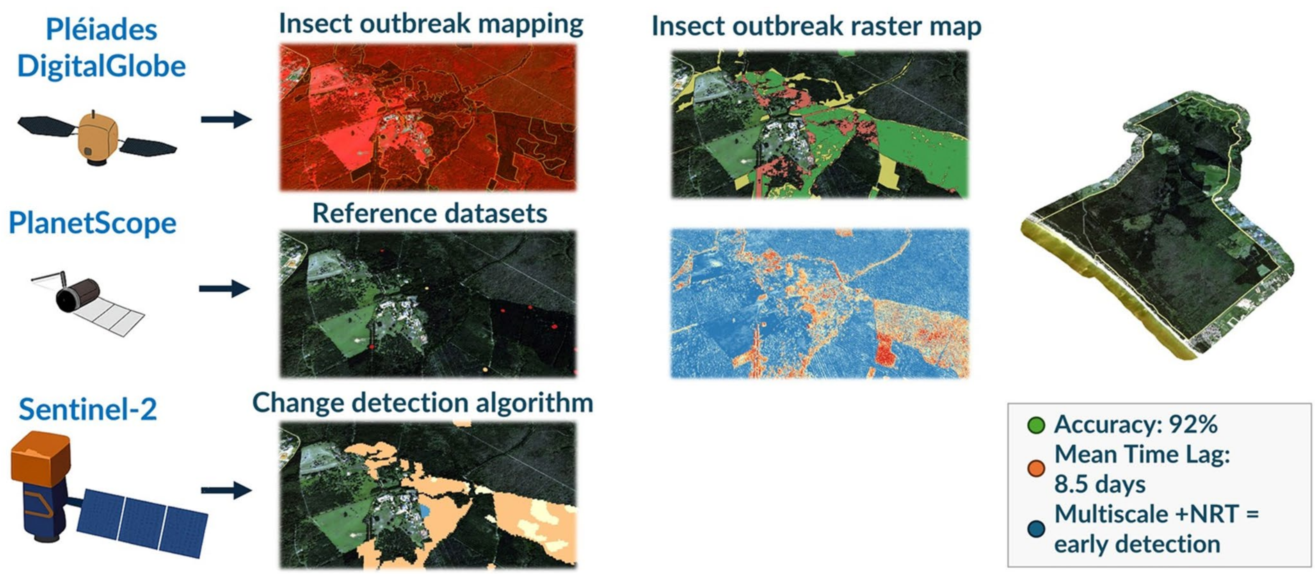
Published online: 20 February 2026

Graphical Abstract



Keywords Climate change · Forest disturbance · Insect outbreak · Remote sensing · Tree health

1 Introduction

Forests provide essential ecosystem services, including carbon sequestration, protection from soil erosion, habitat for many species, and timber production (Thom and Seidl 2016). Beyond their ecological role, they also contribute to human well-being, both physically and mentally (Plieninger et al. 2015; Capotorti et al. 2019). However, forests are increasingly exposed to natural disturbances such as wildfires, insect epidemics, and windthrow events, which have intensified worldwide over the past decades (Chapin et al. 2000; Schelhaas et al. 2003; Balshi et al. 2007; Gardiner et al. 2010). Such disturbances are expected to increase further in the future, primarily due to changes in land use and climate (Seidl et al. 2011, 2014; Reichstein et al. 2013; Temperli et al. 2013; Li et al. 2013; Sommerfeld et al. 2018; Lindenmayer and Taylor 2020; Collins et al. 2021).

Insect outbreaks, in particular, have become more frequent and severe in Mediterranean forests (Azcárate et al. 2023; Domingo et al. 2024; Parisi et al. 2025), where climate warming directly affects the development, abundance, range, and survival of defoliators, causing negative effects on forest growth and vigour (Bale et al. 2002). In addition to this, rising temperatures intensify drought stress in forests, worsening the quality of plant tissues and altering trees' susceptibility to pests (Park Williams et al. 2013) and resistance (Gely et al. 2020). Notably, globalization and the increased transportation of goods heighten the risk of introducing new invasive alien species. As a result of these compounding stressors, forests are becoming increasingly vulnerable to insect infestations, making early detection crucial for applying targeted control strategies to curb the spread of invasions and reduce the resulting damage (Hlásny et al. 2021).

Traditional monitoring methods, such as ground surveys and manual photo interpretation, have historically been used to track forest disturbances. However, these approaches often present limitations. Ground surveys are costly, time-consuming, and have limited temporal and spatial coverage (Liang et al. 2018; Wittke et al. 2019; Gessler et al. 2024), which hinders the rapid detection of such disturbances. On the other hand, visual photointerpretation is highly influenced by the viewpoint of the photo interpreter and lacks objectivity. Furthermore, it is still not straightforward to obtain the homogeneous, quantitative, ground-collected data necessary for calibrating and validating models (Senf et al. 2018). Remote sensing has become an efficient tool for high-resolution and large-scale mapping (Chirici et al. 2020; Senf and Seidl 2020; Forzieri et al. 2021; Francini et al. 2022) and to enable forest disturbance early detection (Senf et al. 2017; Francini et al. 2020; Huo et al. 2021; Falanga et al. 2024; Jamali et al. 2024). However, identifying the causes of these disturbances remains challenging (Palahí et al. 2021; Sebald et al. 2021).

This study focuses on pine-dominated forest of the Castelporziano Presidential Estate (CPE) (Metropolitan Area of Rome, Italy). In particular, the periurban forest is threatened by two insect pests: *Tomicus destruens* (Coleoptera: Curculionidae) and *Toumeyella parvicornis* (Hemiptera: Coccidae). These invasive insect species have significantly contributed to forest decline in the region over the past decade (Garonna et al. 2015; Lieutier et al. 2015; Frigerio et al. 2023; Falanga et al. 2024). *Tomicus destruens* is a bark beetle that infests coniferous trees, tunnelling through the bark and disrupting vascular tissues, ultimately leading to tree mortality (Lieutier et al. 2016). In urban and periurban areas, its activity weakens tree canopies and reduces essential ecosystem services such as pollutant absorption, temperature regulation, noise reduction, and ornamental value (Dobbs et al. 2014; Livesley et al. 2016). Similarly, *Toumeyella parvicornis* (or pine tortoise scale) feeds on tree sap, causing stress and making trees more vulnerable to other pests and diseases. Its presence exacerbates environmental degradation, contributing to biodiversity loss and increasing the need for intensive forest management. The combined impact of these species threatens the health and stability of urban and periurban green spaces, undermining forestry efforts and ecosystem resilience.

In this study, Pléiades and DigitalGlobe very high-resolution (VHR) spatial satellite imagery were used to accurately map forest disturbances caused by insect outbreaks through visual photointerpretation, despite their poor temporal resolution. These datasets provide sub-meter to meter-scale resolution, allowing detailed mapping of affected areas. Complementarily, Sentinel-2, part of the European Copernicus program, with its 10-meter resolution and 3–5 day revisit time, has proven effective for tracking forest disturbances through the detection of subtle changes in vegetation health and has been widely employed for monitoring insect outbreaks in European forests (Stone and Mohammed 2017; Lastovicka et al. 2020; Bárta et al. 2021; Dalponte et al. 2022a, b; Francini et al. 2022; D'Amico et al. 2023). Herein, Sentinel-2 data were used to monitor the spread of the insect infestations, producing yearly maps in near real time (NRT) by adapting and improving the Three Indices Three Dimensions (3I3D) unsupervised forest disturbance algorithm (Francini et al. 2021). The outputs obtained from Pléiades and DigitalGlobe imagery were also used to assess the accuracy of Sentinel-2 yearly forest disturbance maps. In addition, PlanetScope imagery was employed to assess the Mean Time Lag (MTL) of Sentinel-2 NRT maps, which quantifies the delay between the actual occurrence of disturbances and their detection, as well as to evaluate the accuracy of the unsupervised model's performance. PlanetScope offers daily imagery at 3-meter spatial resolution, allowing for near real-time tracking of forest health changes (Falanga et al. 2024). Integrating these multi-platform satellite data enhances the ability to effectively detect, monitor, and respond to forest disturbances. By combining VHR spatial imagery for disturbance detection with high-temporal-frequency satellite data for monitoring, this study aims to improve early warning systems for insect outbreaks and contribute to more effective management strategies.

2 Study area

The study area is the pinewood forest of CPE, located in a periurban area of the Municipality of Rome, in Latium (Fig. 1). The pinewood, situated within the CPE, is a state-owned forest designated for the President of the Republic as a venue for representation and recreation for himself and his guests. However, it is also open for research and educational purposes. CPE is a State Nature Reserve of 6,000 ha; its main species are broadleaf oaks (4,000 ha) and pinewood (900 ha). The pinewood is particularly relevant with numerous trees aged over 100 years and is probably the last remaining example of a mature pinewood forest along the Latium Tyrrhenian coast after the 2017 forest fires (Recanatesi et al. 2019). The study area presents the typical climatic characteristics of the Mediterranean coastal area, with altitudes ranging from sea level to a maximum of 50 m and gentle morphology resulting from the sandy and clayey substrate. Annual rainfall is 700 mm, mainly concentrated in the late autumn season, the average annual temperature is 16.5° C, and the three-month dry period extends from June to August (Di Giuseppe et al. 2025).

3 Data

To effectively map and monitor insect outbreaks on the CPE, various remotely sensed data sources at multiple scales were integrated.

3.1 Pléiades

Pléiades-1 A and 1B, launched in 2011 and 2012 respectively, are VHR satellites operated by Airbus Defence and Space. They provide 0.5 m panchromatic and 2.0 m multispectral resolution imagery across five bands (panchromatic and four multispectral RGB + NIR). Their 20 km swath width and rapid tasking capabilities enable stereo and tri-stereo imaging, making them highly suitable for mapping and monitoring applications (Piermattei et al. 2019). The Pléiades constellation provides high geolocation accuracy (~3 m CE90) and fast response times, ensuring timely and detailed satellite images.

3.2 DigitalGlobe

GeoEye-1, launched in 2008 and operated by Maxar Technologies (formerly DigitalGlobe), provides VHR satellite

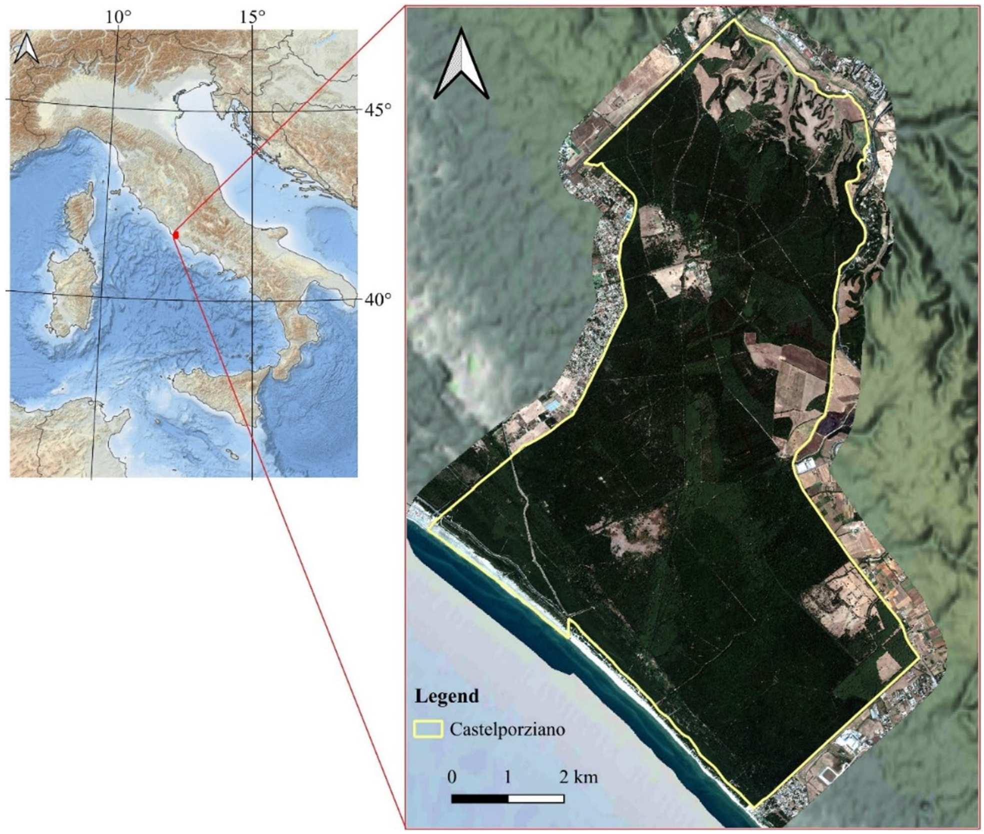


Fig. 1 Location of the study area; in the right 2015 Pleiades image of the Castelporziano Presidential Estate in the state before disturbances

imagery with a panchromatic resolution of 0.5 m and 2 m for multispectral data. With a swath width of 15.2 km and a geolocation accuracy of ~3 m (CE90) without ground control, GeoEye-1 captures five spectral bands (panchromatic and four multispectral RGB+NIR), offering detailed, valuable imagery for environmental mapping and monitoring (Schepaschenko et al. 2019).

3.3 Sentinel-2

The Sentinel-2 mission samples images at resolutions ranging from 10 to 60 m, with a global revisit time of 2.9 days, covering a wide swath of 290 km using both Sentinel Level-2 A and Level-2B satellites (J. Li and Roy 2017). We accessed and processed the harmonized Sentinel-2 MSI Level-2 A images from the Google Earth Engine cloud computing platform (Gorelick et al. 2017). Each Sentinel-2 image is consisting of 13 bands with 10 m (B2, B3, B4 and B8), 20 m (B5, B6, B7, B8A, B11 and B12), and 60 m (B1, B9, B10) spatial resolution, and the pixel-based bitmasks (QA60) band. All harmonized Sentinel-2 images were accessed by filtering out pixels with more than 70% cloud coverage. We also masked out the clouds, edges, and snow of the remaining Sentinel-2 images (Francini et al. 2021, 2023a, b, c; Alvites et al. 2025). The output of this section will be a collection of properly pre-processed Sentinel-2 images.

3.4 PlanetScope

PlanetScope images are provided by Planet Labs' Dove satellite constellation, which provides high-resolution images of the Earth's surface, very useful for many purposes, such as natural disturbances. One of the strengths of PlanetScope images is their high spatial resolution, which is 3 m for Dove-C and Dove-R, and 3.7 m for SuperDove. They also benefit from daily acquisition due to the presence of more than 130 satellites in orbit. PlanetScope images are characterized by eight bands: Coastal Blue: 431–452 nm, Blue: 465–515 nm, Green I: 513–549 nm, Green: 547–583 nm, Yellow: 600–620 nm, Red: 650–680 nm, RedEdge: 697–713 nm and NIR: 845–885 nm (Francini et al. 2020). The images used in this study refer to the period from March 11 to September 18. The images were selected according to their quality and to avoid those with high cloud coverage.

4 Methods

This study combines different remote sensing data and techniques to accurately map insect outbreaks with very high spatial detail and to monitor them with very high frequency. In summary, Pléiades and DigitalGlobe yearly maps were used to accurately identify the infestation through photointerpretation, while Sentinel-2 data were used to implement an automatic method to monitor in near real-time the spread of the infestation. Pléiades and DigitalGlobe outputs were also used to assess the accuracy of Sentinel-2 yearly forest disturbance maps, while PlanetScope imagery were used to assess the accuracy of the unsupervised model's performance; PlanetScope imagery was also used to calculate the MTL of Sentinel-2 NRT maps (Francini et al. 2021; Reiche et al. 2018), i.e., the average number of days between the occurrence and detection of the forest disturbances due to the insect outbreak.

4.1 Very high resolution infestation detection

Stone pine degradation over the years was monitored through video photointerpretation using VHR Pleiades and DigitalGlobe images acquired in the summers between 2015 and 2020 (Table 1, Annex 1).

The images from 2015 to 2017 enabled the evaluation of the CPE's pre-disturbance condition. Since 2018, the infested areas have been mapped each year within a GIS environment. False-color imagery proved particularly effective in highlighting stress conditions (Annex 1). As photosynthetic activity decreased and canopy browning occurred, the false-color image appeared progressively darker, making it easier to identify the infestation's progression (Annex 1).

4.2 Sentinel-2 mapping

To map insect outbreaks, we used a revised version of the Three Indices Three Dimensions (3I3D) algorithm. 3I3D is an unsupervised algorithm originally designed to produce a new map every year and to detect forest disturbances characterized by a very rapid photosynthetic activity decrease, such as harvesting or fires (Francini et al. 2021). To capture both the decline during the disturbance and the recovery in the subsequent year, by default, 3I3D processes cloud-free composite imagery over three consecutive years. 3I3D evaluates three-year trends using three vegetation indices (3I) in a three-dimensional framework (3D), and it produces five multitemporal photosynthetic activity indices (PMI) that can be averaged to quantify the overall change during this period (magnitude). The three indices used by 3I3D were identified in previous research as the most useful for monitoring forest disturbances (Kennedy et al. 2018; Hermosilla et al. 2019; Francini et al. 2022).

The first three PMIs refer to the change between the previous year and the current year of analysis, correspond to the decrease in spectral activity, and can be calculated using just two images instead of three. Since beetle infestations result in a progressive reduction of photosynthetic activity in the forest, early identification of the disturbance is essential. In this study, the magnitude of the change was calculated by averaging only those three PMIs (D'Amico et al. 2023) using data from just two images.

To produce a yearly forest disturbance map, we constructed a cloud-free composite for 2019 using images acquired between June 1, 2019, and August 31, 2019, and a cloud-free composite for 2020 using images acquired between June 1, 2020, and August 31, 2020. In 2019, the insect infestation had not yet started in the study area, while in 2020, most of the trees were already damaged. To construct these two composites, we used the Medoid algorithm, a state of the art pixel compositing approach (Kennedy et al. 2018) where the pixel of the final composite image is populated with surface reflectance values that are as similar as possible to the median calculated considering the entire image collection, excluding clouds and shadows (Francini et al. 2024a 2024b). For each composite, band's pixel values are compared to the median of all available images using Euclidean distance, and the spectral values from the pixel with the smallest Euclidean distance to the median are selected (Fassnacht et al. 2016; Kennedy et al. 2018; Francini et al. 2023a, b, c). Using these two composites and implementing 3I3D, we produced a single forest disturbance map that identified all infested trees between the summers of 2019 and 2020.

Differently, to produce forest disturbance maps in NRT, we applied 3I3D each time a new image was acquired by comparing it to the "initial condition". To construct a composite of the "initial condition," we used the Medoid algorithm over Sentinel-2 images acquired between February 15, 2020, and March 15, 2020. Then, we applied 3I3D to all images acquired between March 15, 2020, and September 1, 2020.

Table 1 Acquisition dates of VHR satellite images by sensor

Data	Satellite
May 31 st 2015	DigitalGlobe
August 6th 2015	Pleiades
August 14th 2017	DigitalGlobe
August 11th 2018	Pleiades
August 11th 2019	DigitalGlobe
August 16th 2019	Pleiades
August 6th 2020	Pleiades
August 19th 2020	DigitalGlobe

4.3 Accuracy assessment

4.3.1 Sentinel-2 VS Pléiades/DigitalGlobe

To assess the overall accuracy of the Sentinel-2-derived yearly forest disturbance map, we compared it with the disturbances identified through photointerpretation using VHR images from Pléiades and DigitalGlobe. Considering the photointerpretation as the truth dataset, we compared the maps within the CPE. To maintain the effectiveness of photointerpretation at the edges of disturbances, the comparison was conducted by intersecting two vector maps. The accuracy assessment was conducted at the intersection of the two layers using a confusion matrix and three accuracy indices: overall accuracy (OA), producer accuracy (PA), and user accuracy (UA).

$$\mathrm{OA} = \frac{(\mathrm{TP} + \mathrm{TN})}{(\mathrm{TP} + \mathrm{TN} + \mathrm{FP} + \mathrm{FN})} \tag{1}$$

$$\mathrm{PA} = \frac{\mathrm{TP}}{(\mathrm{TP} + \mathrm{FP})} \tag{2}$$

$$\mathrm{UA} = \frac{\mathrm{TP}}{(\mathrm{TP} + \mathrm{FN})} \tag{3}$$

This assessment identifies the areas correctly classified as disturbed (True Positives, TP), the areas incorrectly classified as disturbed (False Positives, FP), the areas mistakenly labeled as not disturbed (False Negatives, FN), and the areas correctly classified as not disturbed (True Negatives, TN).

4.3.2 Sentinel-2 VS planetscope

Sentinel-2 unsupervised model's performance was assessed in terms of OA, PA, and UA by using PlanetScope images and photointerpretation. A sample of 60 random points was selected to be photointerpreted for analysis from the forest disturbance map, with 30 points allocated to "Undisturbed" and 30 to "Disturbed" cover statuses. The photointerpretation process considered trees within a 20 m buffer area around each point. For example, buffer areas where all trees exhibited the lowest greenness tonality of vegetation were classified as "Disturbed". In contrast, buffer areas where at least half of the trees displayed the highest greenness tonality were classified as "Undisturbed". The Pinus disturbance status was assigned to points using downloaded PlanetScope images (those from 2–5-12 July 2020). To evaluate the forest disturbance map, a confusion matrix was constructed using the Planet reference data, and the accuracy indices OA, PA, and UA (presented in Sect. 4.3.1) were calculated.

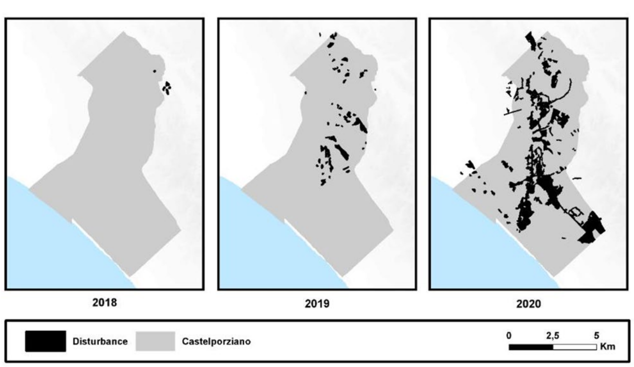


Fig. 2 Disturbance maps of 2018, 2019, and 2020

4.3.3 Near real time Sentinel-2 assessment

To evaluate the performance of the NRT Sentinel-2 product, the MTL methodology was also applied. MTL provides an estimate of the promptness (measured in days) with which forest disturbances can be detected (Reiche et al. 2018). To assess the MTL, we constructed reference data using PlanetScope imagery. A new sample of 30 points, distinct from those used for the confusion matrix, was extracted from the "Disturbed" cover status and selected for analysis based on the forest disturbance map. The photointerpretation of these points allowed to report the first day the disturbance was visible in the PlanetScope images and compare it to the first day the forest disturbance map detected it.

5 Results

The annual maps, derived from Pléiades and DigitalGlobe imagery, facilitated the precise identification of infestation areas. Meanwhile, the Sentinel-2-based automatic monitoring method effectively tracked the outbreak's spread in near real-time. Performance assessments of the model using PlanetScope imagery underscored the method's effectiveness, which was further validated by comparisons between Pléiades/DigitalGlobe and Sentinel-2 maps. Lastly, the MTL calculated from PlanetScope images offered insights into the delay between the occurrence of disturbances and their detection. Results follow below.

5.1 Very high-resolution pine degradation map

The monitoring activity, based on the visual photointerpretation of VHR Pléiades and DigitalGlobe summer images, revealed the progression of the infestation over time (Fig. 2). The decrease in photosynthetic activity and the gradual browning of the canopy were particularly evident in the false-color images (Annex 1). Indeed, the images darkened as forest stress increased, effectively highlighting the ongoing degradation.

Integrating the disturbance dataset with the CPE's forest species map results in 762 hectares of pine forest and approximately 100 hectares of other forest types (Table 2).

5.2 Sentinel-2 accuracy assessment

5.2.1 Sentinel-2 VS Pléiades/DigitalGlobe

Comparing the forest disturbance map generated through photointerpretation of Pléiades and DigitalGlobe images with the forest disturbance map automatically obtained from Sentinel-2 images within the CPE boundary yields an overall accuracy of 92% (Table 3). Figure 3 shows the distribution of areas in the different classes of the confusion matrix. A total of 600 hectares have been correctly identified as disturbed, with a PA of 68% and a UA of 73%. While the undisturbed areas show a PA of 96% and a UA of 95%.

5.2.2 Sentinel-2 VS planetscope

The photointerpretation of the 60 random points extracted from the forest disturbance map using PlanetScope images (Fig. 4) highlighted an overall accuracy of 85% for the unsupervised Sentinel-2 model's performance (Table 4). Of the 30 points, 22 were correctly classified as undisturbed, with a PA of 73% and a UA of 96%. Meanwhile, 29 out of 30 points were correctly classified as disturbed, achieving a PA of 97% and a UA of 78%.

5.2.3 Near real time Sentinel-2 assessment

Photointerpretation of daily PlanetScope images enabled the calculation of the MTL for the first appearance of the insect outbreak in 2020. The 30-points analysis (Fig. 5) yielded an average MTL of 8.5 days, with a median of 7 days. In half of the analysed points, Sentinel-2 time series detected the first signs of insect outbreak several days before they became visible in PlanetScope images through photointerpretation, likely due to Sentinel-2 superior spectral and radiometric resolution (Annex 2).

6 Discussion

This study focuses on the multi-platform remote sensing monitoring of the progressive decline of stone pine (*Pinus pinea*) stands within the CPE, started in 2018 and caused by an infestation of the pine tortoise scale (*Toumeyella parvicornis*) and later exacerbated by secondary degradative events. Relying on Very High Resolution (VHR) data,

Table 2 Degraded areas by year and type for the years 2018–2020

Forest category	2018 (ha)	2019 (ha)	2020 (ha)	Total (ha)
Other broadleaves	0,0	0,0	1,1	**11**
Holm oak	0,0	0,0	4,0	**4,0**
Plantations	0,0	2,1	6,0	**8,1**
Pinewoods	0,2	134,1	627,9	**762,2**
Deciduous oaks	0,0	2,4	74,2	**76,6**
Cork oaks	0,0	1,1	23,3	**24,4**
Total	**0,2**	**139,7**	**736,5**	**876,4**

Table 3 Confusion matrix between the photointerpreted forest disturbance map and the automatic forest disturbance map within Castelporziano presidential estate boundaries (values in hectares)

		Predicted			
		Undisturbed	Disturbed	Total points	PA
Observed	**Undisturbed**	4823.6.7	223.4	5047.1	0.96
	Disturbed	276.7	600.0	876.7	0.68
Total points	5100.4	823.4			
UA	0.95	0.73		**OA** = 0.92	

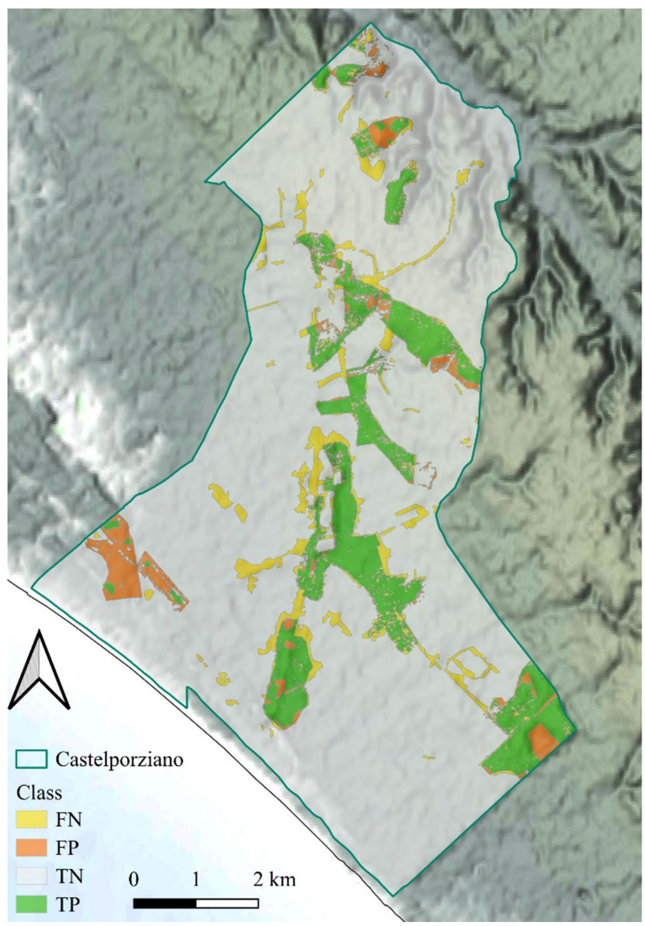


Fig. 3 Class distribution from the confusion matrix (Table 3) comparing Sentinel-2 with Pléiades/DigitalGlobe

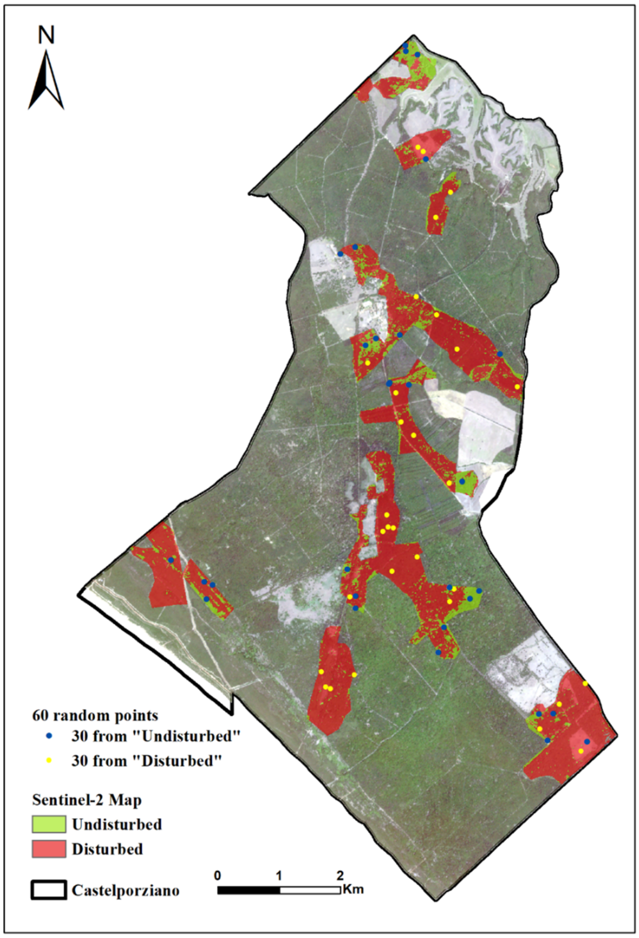


Fig. 4 60 random points, 30 "Undisturbed" and 30 "Disturbed", extracted from Sentinel-2 forest disturbance map and photointerpreted with PlanetScope images

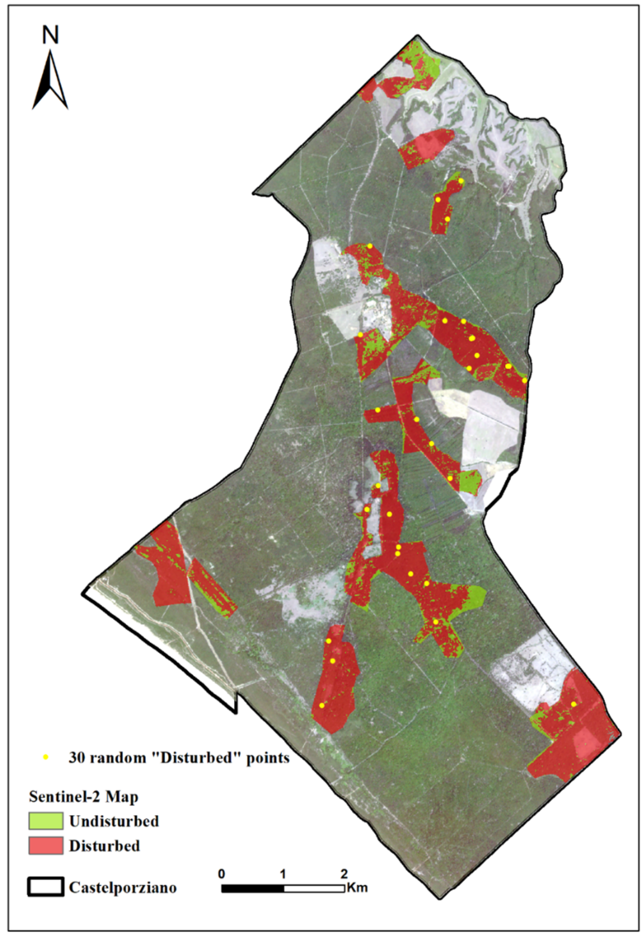


Fig. 5 30 random "Disturbed" points used to calculate the MTL

Table 4 Confusion matrix for a sample of 60 random points extracted from the forest disturbance map: 30 "Undisturbed" and 30 "Disturbed," verified through planetscope images

		Predicted			
		Undisturbed	Disturbed	Total points	PA
Observed	**Undisturbed**	22	8	30	0.73
	Disturbed	1	29	30	0.97
Total points	23	37	60		
UA	0.96	0.78		**OA** = 0.85	

pre-disturbance conditions were studied using images acquired in 2015 and 2017, highlighting clear-cutting areas totalling approximately 49 hectares. The first cluster of infested stone pines appeared in a summer 2018 VHR image near the northeast boundary, with canopy browning progressively intensifying over time. Throughout 2019, the infestation expanded significantly, affecting approximately 140 hectares, and by 2020, it had spread across the entire CPE, impacting more than 762 hectares. The areas near the coastline remained relatively unaffected until 2021, when an additional 25 hectares of degradation were detected in VHR images (Annex 1), which were not included in this study.

Given the rapid spread of these disturbances, continuous monitoring is essential for understanding their dynamics and implementing timely mitigation strategies. This study leverages multi-platform remote sensing data to map, monitor, and assess the progression of insect outbreaks with very high spatial and temporal resolution.

The reliability of the Sentinel-2 forest disturbance map was assessed through PlanetScope and Pléiades/DigitalGlobe imagery. On one hand, samples distributed equally in disturbed and undisturbed areas were photointerpreted using PlanetScope images to assess the performance of the Sentinel-2 forest disturbance map. Indeed, several studies highlight the significance of measuring model performance with appropriately balanced samples (Francini et al. 2023a, b, c, 2024). The derived confusion matrix showed an OA of 85%, with a PA of 97% for disturbed areas and 73% for undisturbed ones. These values are consistent with previous studies that have used Sentinel-2 for forest health monitoring. For instance, Dalponte et al. 2022a, b) studied the detection of bark beetle (*Ips typographus*) outbreaks at the level of individual tree crowns in a Norway spruce forest in the Italian Alps using Sentinel-2 multispectral imagery, achieving an 83.4% OA in distinguishing between early and late infestation stages, although faced with significant imbalance classes. Similarly, Bárta et al. (2021) achieved a 78% OA in detecting *Ips typographus* infestations in Norway spruce forests in the Czech Republic, distinguishing between healthy trees and those in the green-attack stage. Bozzini et al. (2023) compared Sentinel-2 derived bark beetle infestation maps with ground surveys, focusing on very small spots (groups between 5 and 50 infested trees), still reaching an OA up to 72%.

On the other hand, Pléiades/DigitalGlobe images allowed the assessment of the accuracy of the Sentinel-2 yearly forest disturbance maps; the confusion matrix showed an OA of 92%, suggesting that the use of VHR images enhances validation capabilities. Additionally, the comparison between the disturbed areas highlighted by Sentinel-2 images (9,208,900 m^2) and those photointerpreted with Pléiades/DigitalGlobe ones (8,764,000 m^2) showed that Sentinel-2 overestimates the areas by only 5%.

The ability of Sentinel-2 to detect disturbances promptly was evaluated through the MTL assessment, using PlanetScope imagery as a reference. The analysis, based on 30 disturbed points, resulted in an average detection time of 8.5 days (with a median of 7 days). In approximately half of the analyzed cases, Sentinel-2 identified the disturbances earlier than PlanetScope, despite its lower spatial resolution and revisit time (Annex 2). This outcome is likely due to Sentinel-2's superior spectral and radiometric sensitivity, particularly in detecting subtle variations in vegetation reflectance. While PlanetScope enables daily monitoring, reducing the risk of missing rapid changes, Sentinel-2's spectral capabilities allow for earlier detection of vegetation stress, reinforcing the importance of multi-sensor approaches for effective early detection and monitoring of forest disturbances. Other studies have found similar results, such as Abdollahnejad et al. (2021), who demonstrated that spectral resolution is crucial for early *I. typographus* detection. Their study showed that Sentinel-2 and WorldView-2 bands could predict tree health up to two years before visible signs of decline appeared. This underscores the importance of combining spectral sensitivity with high spatial resolution for effective forest monitoring.

A critical aspect in evaluating classification performance is the distribution of omission and commission errors. When compared with Pléiades/DigitalGlobe imagery, the Sentinel-2 forest disturbance map showed lower PA for disturbed areas compared to undisturbed ones, suggesting that some disturbed zones may not have been promptly detected. This imbalance could result from differences in infestation severity, spectral response variations, or the timing of photointerpretation used for validation.D'Amico et al. (2021) highlighted that, in such scenarios, focusing on omission and commission errors can provide more valuable insights than relying solely on OA. Addressing this issue may require refining classification thresholds and incorporating additional spectral indices to enhance detection sensitivity.

Importantly, the use of the forest mask in the 3I3D model introduced some limitations in classification accuracy. Although the mask helped delineate forested areas, its resolution and classification errors may have led to the misclassification of some pixels. The accuracy of forest classification is strongly influenced by the type of mask used, as variations in resolution and data sources can lead to discrepancies in the mapped forest areas (Vangi et al. 2021). Areas mistakenly excluded or included in the analysis could have influenced the accuracy of the Sentinel-2 forest disturbance map. Improving the segmentation of forest classes and refining input data could help mitigate these errors, enhancing the model's ability to distinguish between disturbed and undisturbed vegetation more effectively.

The rapid spread of *T. parvicornis* and the subsequent secondary infestations by *T. destruens* underline the need for continuous forest monitoring (Lieutier et al. 2015). The study demonstrates how remote sensing can provide critical insights into the spatial and temporal progression of infestations, supporting early detection and management strategies. The results emphasize the importance of integrating multi-platform satellite data, combining high-frequency observations with high-resolution imagery to optimize detection and response efforts. Given the increasing threats posed by climate change and invasive species, developing robust monitoring frameworks is essential for ensuring the resilience of Mediterranean forest ecosystems. The combined use of Sentinel-2, PlanetScope, and Pléiades/DigitalGlobe imagery allowed for a comprehensive monitoring process, demonstrating the effectiveness of remote sensing in combatting insect outbreaks.

7 Conclusion

This study highlights the importance of combining multi-platform remote sensing data to improve insect outbreak detection. While Pléiades and DigitalGlobe provide high spatial resolution images that are useful to precisely delineate disturbances, Sentinel-2's higher spectral and radiometric sensitivities permit detection of vegetation stress more promptly, as highlighted by the MTL. These findings demonstrate how crucial it is to use multiplatform data to improve the timeliness and accuracy of disturbance detection.

PlanetScope data were used to evaluate the performance of the unsupervised Sentinel-2 model, while Pléiades/DigitalGlobe data were employed to assess the accuracy of annual Sentinel-2 forest disturbance maps; both produced very positive results, confirming the effectiveness of the Sentinel-2 automatic method for identifying insect outbreaks. However, accuracy is significantly influenced by the choice of mask and classification criteria, which can lead to potential misclassification. To further refine detection sensitivity and reduce mistakes, future works could explore improved segmentation algorithms and use additional spectral indices.

Ultimately, due to the rapid spread of *T. parvicornis* infestation followed by *T. destruens* outbreak this study underlines the importance of combining advanced spectral analysis with VHR temporal data to enhance early detection and monitoring of insect outbreaks in urban and periurban areas.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12210-025-01387-5.

Acknowledgements This study was partially supported via the following projects: (1) "National Biodiversity Future Center—NBFC", funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4—Call for tender No. 3138 of 16 December 2021, rectified by Decree n.3175 of 18 December 2021 of Italian Ministry of University and Research funded by the European Union—NextGenerationEU; Project code CN_00000033, Concession Decree No. 1034 of 17 June 2022 adopted by the Italian Ministry of University and Research, CUP H73C22000300001. (2) FORWARDS "The ForestWard Observatory to Secure Resilience of European Forests", HORIZON project funded by the European Commission, number 101084481 call HORIZON-CL6-2022-CLIMATE-01. (3) MONIFUN. H2020 project funded by the European Commission, number 101134991 call HORIZON-CL6-2023-CircBio-01-14. (4) NextGenCarbon. H2020 project funded by the European Commission, number 101184989 call HORIZON-CL5-2024-D1-01-07. (5) Space It Up. Project funded by the Italian Space Agency and the Ministry of University and Research - Contract No. 2024-5-E.0 - CUP No. I53D24000060005. (6) SUPERB "Systemic solutions for upscaling of urgent ecosystem restoration for forest related biodiversity and ecosystem services" H2020 project funded by the European Commission, number 101036849 call LC-GD-7-1-2020. We would like to thank the Castelporziano Presidential Estate for supporting our research.

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Funding This study was partially supported via the following projects: (1) "National Biodiversity Future Center—NBFC", funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4—Call for tender No. 3138 of 16 December 2021, rectified by Decree n.3175 of 18 December 2021 of Italian Ministry of University and Research funded by the European Union—NextGenerationEU; Project code CN_00000033, Concession Decree No. 1034 of 17 June 2022 adopted by the Italian Ministry of University and Research, CUP H73C22000300001. (2) FORWARDS "The ForestWard Observatory to Secure Resilience of European Forests", HORIZON project funded by the European Commission, number 101084481 call HORIZON-CL6-2022-CLIMATE-01. (3) MONIFUN. H2020 project funded by the European Commission, number 101134991 call HORIZON-CL6-2023-CircBio-01-14. (4) NextGenCarbon. H2020 project funded by the European Commission, number 101184989 call HORIZON-CL5-2024-D1-01-07. (5) Space It Up. Project funded by the Italian Space Agency and the Ministry of University and Research - Contract No. 2024-5-E.0 - CUP No. I53D24000060005. (6) SUPERB "Systemic solutions for upscaling of urgent ecosystem restoration for forest related biodiversity and ecosystem services" H2020 project funded by the European Commission, number 101036849 call LC-GD-7-1-2020.

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Ethics approval Not applicable.

Consent to participate Not applicable.

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