



## Prescribed burns can trigger *Diplodia* shoot blight in pine forests

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### ABSTRACT

Climate change has increased the risk of wildfires, making fuel reduction a key objective in forest management. Prescribed burning is a widely used forest management practice to reduce fuel loads and wildfire risk. In NE Spain, prescribed burns were conducted in a *Pinus nigra* stand in autumn 2023 and winter 2024, after which extensive crown dieback resembling shoot blight symptoms was observed. *Diplodia* shoot blight is a disease that affects conifers around the world, particularly pine species. *Diplodia* shoot blight is caused by the fungus *Diplodia sapinea*, which shifts from an endophytic to a pathogenic state when the host is under physiological stress such as drought. To determine whether prescribed fire can trigger *Diplodia* shoot blight, we compared the severity of *Diplodia* shoot blight in areas subjected to prescribed burns with that of neighbouring control areas. Ground disease assessments were combined with satellite and drone-based multispectral and LiDAR measures. Shoot blight symptoms in burned areas were more than twice as severe as those in unburned areas. *Diplodia sapinea* was isolated from approximately 70% of pines showing shoot blight symptoms in burned areas. Temporal reconstruction of the outbreak using satellite-based normalised difference vegetation index values showed that the disease appeared after prescribed burning. Drone multispectral imagery combined with a random forest model was a reliable method for large-scale assessment of disease symptoms. When planning prescribed burns in pine forests, managers need to take *Diplodia* shoot blight into consideration to mitigate the risks of an outbreak.

### 1. Introduction

Forest management operations can cause damage or predispose trees to suffer from pests and diseases (Oliva et al., 2013). Although the effects of thinning, final felling operations and pruning are well documented (Jactel et al., 2012; Roberts et al., 2020; Moreau et al., 2022), less is known about whether prescribed burns predispose trees to disease or incite pest attacks. Forest managers widely use prescribed fire as part of their fire prevention strategy, reducing the amount of available fuel. This is crucial at a time when climate change has led to an increase in the frequency of wildfires globally.

Fire, including prescribed burns, can damage the roots, the stem and the crown of trees. Depending on its intensity and timing, fire can reduce tree growth (Valor et al., 2015), modify eco-physiological functions (Bär et al., 2019) and, in the worst cases, cause mortality (Stephens and

Finney, 2002; Vega et al., 2011). Beyond its direct impact on trees, little is known about the interaction between prescribed fire and biotic agents. Most of the available evidence relates to crown fires. Nevertheless, fire may also benefit pests and pathogens. For instance, fire can stimulate the germination of certain root pathogen spores, including those of *Rhizina undulata* (Gremmen, 1971). Although fires have been shown to shift the foliar fungal endophytic community (Huang et al., 2016), no effects of fire on foliar pathogens have been studied. Some studies have even shown that fire can have a beneficial impact by reducing pathogen attacks. For example, Freeman et al. (2019), reported that fire was associated with a reduction in intraspecific tree competition for water and, hence, there was a lower risk of trees being affected by drought-dependent pathogens such as *Biscogniauxia mediterranea*.

In spring 2024, Austrian pine (*Pinus nigra*) trees growing in an area that had been subjected to a prescribed burn began to show disease

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crown symptoms that were consistent with those caused by *Diplodia sapinea*. *Diplodia sapinea* is a fungal endophyte that can persist latently in multiple *Pinus* species tissues without causing symptoms (Stanosz et al., 1997). It is considered an opportunistic pathogen because it only damages hosts that are under stress (Slippers and Wingfield, 2007). Known stressors are heat and drought (Stanosz et al., 2001; Chhin and O'Brien, 2015), as well as mechanical wounding, such as that inflicted by hail during hailstorms (Zwolinski et al., 1990; Oliva et al., 2021). When *D. sapinea* shifts from a latent to a pathogenic state, it causes Diplodia shoot blight, which is a major disease of pines globally (reviewed in Wingfield et al., 2024). Over the past years, the range of *D. sapinea* and the occurrence of Diplodia shoot blight have expanded towards higher latitudes, indicating that climate warming and drought are favouring its emergence and spread (Fabre et al., 2011; Brodde et al., 2019). Understanding whether prescribed fire could also trigger Diplodia shoot blight is crucial for maintaining forest health.

A post-hoc assignment of causality between a fire and a disease outbreak requires the reconstruction of the epidemic after it has happened, as well as fine-scale mapping of the attacked areas. Remote sensing is becoming a popular way of studying forest diseases based on changes in canopy reflectance and structure across multiple spatial and temporal scales (reviewed in Cotrozzi, 2022). Multispectral imagery is increasingly being applied for this purpose, with the use of spectral vegetation indices as the most commonly used approach for estimating forest biophysical properties (Huete, 2012). Much of this work relies on publicly available satellite imagery, such as that from the Landsat, MODIS, and Sentinel missions (Torres et al., 2021), which allow temporal comparisons. By contrast, drone-based assessments can be used to assess forest health measures at fine spatial scales (Dash et al., 2017). They are also more cost-efficient, flexible and able to revisit an area more frequently than satellites and crewed platforms, provided the area of interest is relatively small (Pádua et al., 2017). Remote sensing has been successfully used for detecting Diplodia shoot blight outbreaks in *Pinus radiata* plantations (Coops et al., 2004; Sims et al., 2007; Schratz et al., 2021); however, drone-based approaches have not been used to assess this disease.

The aim of this study was to determine whether prescribed burns can trigger Diplodia shoot blight outbreaks in pine forests. We assessed forest stand health using a ground systematic sampling method within and outside the burned area. We confirmed *D. sapinea* as the causal agent of the outbreak by carrying out isolations from symptomatic shoots within the prescribed burn area. Ground disease assessments were complemented with aerial assessments using drones. To assign the origin of the outbreak to prescribed burns and to discount alternative triggering factors, such as hailstorms, we reconstructed the temporal development of the disease using satellite imagery.

## 2. Material and methods

### 2.1. Study area and field measurements

The studied forest is a *Pinus nigra* stand located in the Catalan Pyrenees in NE Spain (42°13'58.728"N 0°54'9.900"E, 857 m a.s.l.). Four separate prescribed burns were conducted in the stand between September 2023 and March 2024 (i.e., 15/09/2023, 21/09/2023, 15/02/2024 and 21/03/2024) with no overlapping areas. These prescribed burns were carried out to reduce competition from the understory, which mainly comprised the shrub species *Buxus sempervirens*. Soon after the burns, partial to complete browning of the upper crown with symptoms compatible with Diplodia shoot blight was observed.

We evaluated forest health condition in 28 plots inside the burned areas and 20 plots in the unburned area (which were used as control plots). These plots were distributed systematically across the studied area. Field work was undertaken in June 2024 and repeated in October 2024. In each plot, we evaluated the six dominant mature trees closest to the plot centre. We collected the GPS coordinates of these trees using a

sub-meter precision global navigation satellite system receiver. Bark char height was measured and used as a proxy for the relative fire intensity in prescribed burn plots (Wade and Johansen, 1986; Stephens and Finney, 2002). Bark char height was measured with a height pole and rounded to the nearest 10 cm. Moreover, we assessed Diplodia shoot blight severity by visually evaluating the proportion of dieback in the canopy using binoculars. This dieback corresponds to shoot tip necrosis, the most characteristic symptom of Diplodia shoot blight, and may extend towards the interior of the crown. In some cases, symptoms were restricted to the previous year's growth, whereas in more severe cases they extended beyond one whorl, killing the entire branch. Finally, to isolate the causal agent, we collected a total of 25 symptomatic shoots across all burned areas. The shoots were sampled randomly within the burned areas and were not part of the 28 plots, as branches were not always available for sampling due to their height.

### 2.2. Molecular identification of the causal agent

Fungal isolates obtained from the margins of the necrotic tissue of symptomatic shoots were identified using molecular tools. This was achieved by first surface-sterilising symptomatic shoots with 70% EtOH and removing the bark to expose the necrotic tissue. We then excised 5-mm pieces of necrotic tissue from the lesion front and plated them onto 2% potato dextrose agar (PDA) amended with chloramphenicol (200 mg l<sup>-1</sup>). Any mycelial growth was transferred onto PDA medium to obtain pure cultures. DNA from pure isolates was extracted using the NaOH extraction procedure (Wang et al., 1993). The internal transcribed spacer (ITS) region was amplified using the ITS1 (Gardes and Bruns, 1993) and ITS4 (White et al., 1989) primers and sequenced by Macrogen Spain (Madrid, Spain). Isolates were identified by performing a BLAST search against GenBank.

### 2.3. Drone data acquisition and preprocessing

Imagery from the drone was acquired on July 11th, 2024, using a DJI Mavic 3 M multispectral platform during planned flights executed with DJI Pilot 2. The aircraft integrates a multispectral sensor comprising four bands: green (560 ± 16 nm), red (650 ± 16 nm), red-edge (730 ± 16 nm) and near-infrared (860 ± 26 nm), which were each captured at 5 MP resolution. The system also includes a 20 MP RGB camera (4/3" CMOS sensor) providing high-resolution optical imagery. The drone was equipped with a global navigation satellite system (GNSS) and real-time kinematic (RTK) capabilities to ensure accurate positioning during flight operations. All missions were flown at a constant altitude of 80 m above ground level with 80% forward and side overlap. The drone surveyed 70.3 ha in total, including 10 ha of the prescribed burned area, at a spatial resolution of < 3 cm. The surveyed area included 37 of the 48 plots studied during fieldwork: the 28 burned plots in the burned area and nine of the 20 unburned plots in the unburned area. Pix4D proprietary software was used to preprocess the drone imagery to generate radiometrically calibrated mosaics for both the RGB and multispectral (infrared) datasets. We subsequently calculated 18 vegetation indices as potential predictor variables to analyse disease symptoms using a random forest model. These indices were computed using their specific formulas (Table S1) using R software (v.4.4.1) (R Core Team, 2024).

Light detection and ranging (LiDAR) data were acquired during a single flight conducted on July 11th, 2024, using a DJI Matrice 300 RTK equipped with a DJI Zenmuse L1 sensor. The L1 is a discrete-return LiDAR operating at 905 nm, integrating an inertial measurement unit (IMU) to ensure precise georeferencing, and supporting up to three returns per pulse with an average root mean square error (RMSE) in the z-dimension of 0.05 m. The Matrice 300 platform, which was equipped with GNSS and real-time kinematic (RTK) capabilities, provided high-accuracy positioning throughout the mission. Flight planning and real-time monitoring were performed using DJI Pilot 2. The survey was

performed at a constant altitude of 100 m above ground level with 80% forward and side overlap, yielding a nominal point density exceeding 500 points  $\text{m}^{-2}$ . LiDAR data were processed using DJI Terra (v.3.6.6), retaining all returns within 250 m and exporting them in EPSG:32630 with EGM2008-based orthometric heights. Quality control involved removing spurious and duplicate points. Ground and vegetation were classified using an enhanced Axelsson (2000) TIN-based filter implemented in LAStools (Isenburg, 2017), and a 0.10 m digital elevation model was generated through weighted linear least-squares interpolation (McGaughey, 2014).

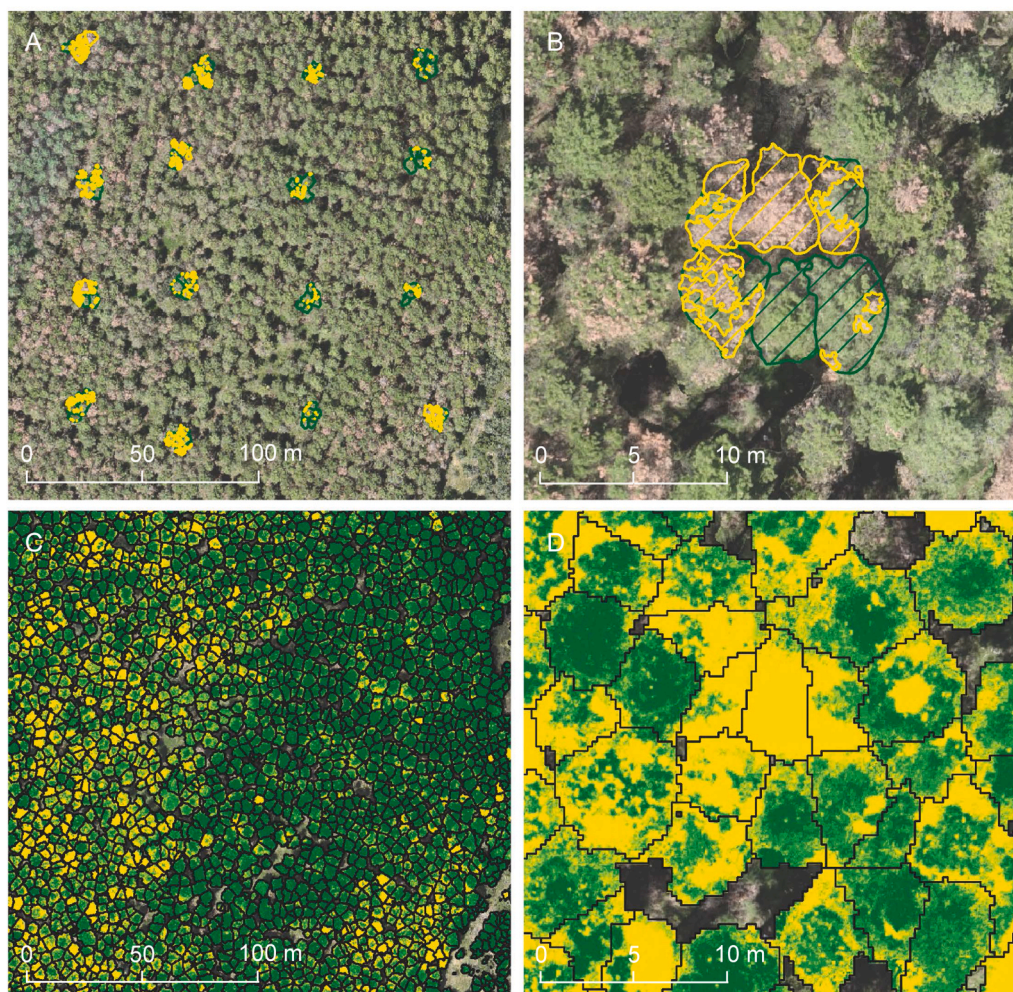
#### 2.4. Individual crown delineation and determination of *Diplodia* shoot blight severity

A total of 219 tree crowns corresponding to field-measured individuals were first manually delineated from the high-resolution RGB orthomosaics generated by the DJI Mavic 3 M. Three field-measured trees could not be incorporated because their canopies could not be reliably located. We quantified the disease severity of each delineated crown as the percentage of canopy area exhibiting symptoms consistent with *Diplodia* shoot blight (Fig. 1A). This information was later used for model training. Afterwards, a full set of individual tree crowns across the study area was automatically delineated from the LiDAR point cloud.

The LiDAR-based delineation automated the identification of tree-tops and crown boundaries following the methodology described by Domingo et al. (2024). Individual tree detection was carried out in R using the *ForestTools* package, applying an iterative parameter-tuning procedure for the variable window filter and marker-controlled watershed segmentation. Intercept values (0.5–1.0) and slope values (0–0.4) were systematically varied to generate alternative treetop and crown delineations, which were visually assessed against the drone RGB orthomosaics to select the most accurate configuration. Small interior voids within the resulting crown polygons were removed using the QGIS *delete holes* function. Based on this assessment, final crown delineation was performed using an intercept of 0.5 and a slope of 0.05.

#### 2.5. Outbreak reconstruction using satellite imagery

To reconstruct the development of the shoot blight outbreak in the study area, we used satellite imagery obtained between June 29th, 2023, when a hailstorm occurred in the vicinity of the study area, and November 6th, 2024 (i.e., the study period began before the first prescribed burn). We obtained Sentinel-2 Level-2A images (satellites 2A and 2B) through the Google Earth Engine, with a revisit frequency of 3–5 days. Only images with < 20% cloud cover over the entire tile were considered, and additional scenes were removed when visually affected



**Fig. 1.** Images of a *Pinus nigra* stand in which a prescribed burn was conducted on September 21st, 2023. (A, B) Canopies from studied plots are delineated. Parts of the canopies have been classified depending on the presence (yellow) or absence (green) of *Diplodia* shoot blight symptoms. (C, D) Manually classified canopies were used to train a random forest model, which was then applied to assess the entire stand. Model predictions were extracted for each canopy using the shapefile derived from drone LiDAR data, outlined in black. Images B and D show a zoomed-in view of the stand shown in images A and C, respectively. Images A and B show the RGB composition, whereas images C and D show the model assessment results.

by clouds or shadows. To compare disease progression in burned areas with that in unburned areas, polygons were manually delineated on the RGB composite image obtained from the drone flight, based solely on visual homogeneity criteria (Fig. S1). Ten polygons were selected for each category: symptomatic pines within the burned area, symptomatic pines outside the burned area, and asymptomatic pines outside the burned area. Each polygon had a mean size of 15 m<sup>2</sup>. The polygons were not associated with field-measured trees but were defined visually using drone imagery to represent homogeneous crown conditions. For each polygon, all pixels within its boundaries were extracted and mean pixel values were calculated and used in subsequent analyses. We quantified temporal changes using every valid image obtained between each time interval by quantifying the normalised difference vegetation index (NDVI) (Table S1), computed at 10-m spatial resolution as an estimate of canopy greenness. This approach allowed greenness to be tracked over time as an indicator of outbreak progression.

## 2.6. Statistical analysis

Shoot blight symptomatology within and outside burned areas was also assessed using a random forest model (Breiman, 2001) that was trained with multispectral data captured by a drone. The canopies of 219 trees, which had been delineated using drone imagery, were used to identify the vegetation index that best represented shoot blight severity: for each tree we evaluated the relationship between the proportion of the canopy affected by *Diplodia* shoot blight and the mean value of each index calculated for the corresponding canopy. For that, we performed linear regressions using the *lm* function of the base R system. This step was used only as an exploratory analysis to select the most informative indices for use in subsequent analyses.

Random forest classifier was used to assess the entire survey area covered by the drone. This ensemble learning algorithm constructs multiple decision trees using random subsets of data and predictor variables. The model aimed to assess the percentage of *Diplodia* shoot blight severity for each pixel, using the multispectral indices that performed best. Before starting to model using the *randomForest* package (Liaw and Wiener, 2002) in R, we removed missing values from the dataset, which was then randomly split into a training set of 164 trees (75%) and a test set of 55 trees (25%). The random forest model was trained using 500 trees (*ntree* = 500) and two randomly selected variables at each split (*mtry* = 2). We checked variable importance using the importance function within the *randomForest* package. To evaluate model performance, we calculated the *r*<sup>2</sup> using base R and the RMSE using the *Metrics* package (Hammer and Frasco, 2018). The validated model was spatially transferred to the drone flight survey area to predict individual tree shoot blight severity for 17,669 trees (5104 in the burned area and 12,565 in the unburned area).

We analysed differences in *Diplodia* shoot blight severity assessed from the ground and by the random forest model from drone data, including both burned and unburned areas. Comparisons between burned and unburned areas were carried out in JMP Pro v.18.0.2 (SAS Institute Inc.) using a Tukey's test to identify significant differences. We also performed linear regressions to evaluate the relationship between *Diplodia* shoot blight severity and bark char height. This analysis enabled us to assess whether symptom severity was associated with fire damage detected in the field and through drone imagery. A significant correlation between these variables would suggest a direct effect of fire on the canopy, whereas a weak or absent relationship would support the interpretation that canopy browning was caused primarily by *Diplodia* shoot blight rather than by fire injury. This analysis was conducted using both field data and drone-based assessments.

## 3. Results

Based on ground assessments, the severity of *Diplodia* shoot blight in areas subjected to prescribed burns was more than double that of

unburned areas (50.9% vs 20.7%, *p* < 0.0001) (Fig. 2). Within burned areas, there was no correlation between bark char height and the mean severity of *Diplodia* shoot blight assessed in the field (*r*<sup>2</sup> = 0.024) (Fig. S2).

The temporal reconstruction of the outbreak using satellite imagery showed that before the prescribed burn, NDVI values for burned and unburned areas did not differ (Fig. 3).

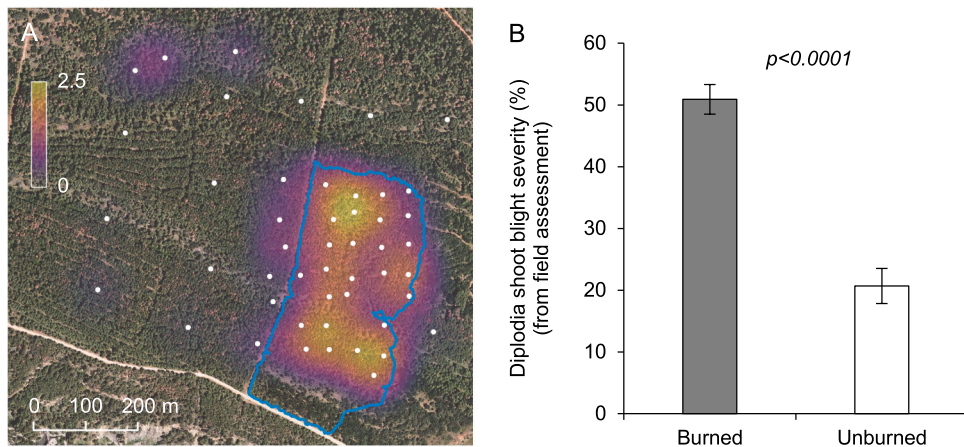
Among the vegetation indices evaluated to predict the *Diplodia* shoot blight severity (Table S2), NDVI values showed the strongest correlation with *Diplodia* shoot blight severity (*r*<sup>2</sup> = 0.843, Fig. 4), closely followed by the redness index (RI) (*r*<sup>2</sup> = 0.841, Fig. S3). A random forest model combining the NDVI and RI as predictor variables achieved an *r*<sup>2</sup> of 0.93 and an RMSE of 0.11. As with ground assessments, the random forest model predicted greater shoot blight severity in burned areas than in unburned areas (Fig. 5). The areas with the highest mean severity of *Diplodia* shoot blight were those burned on September 21st, 2023, (25.3%) and September 15th, 2023, (23.8%) (Fig. 5B), whereas areas burned on March 21st, 2024, (21.4%) and on February 8th, 2024, (12.8%) showed lower mean severity levels (Fig. 5B). *Diplodia* shoot blight severity was lowest in the unburned area (9.5%) (Fig. 5B). As with ground assessments, linear regression showed no significant relationship between bark char height and shoot blight severity predicted by the random forest model (Fig. 6).

*Diplodia sapinea* was isolated from approximately 70% of the symptomatic shoots collected in burned areas. The other identified fungal isolates belonged to non-pathogenic genera such as *Microsphaeropsis*, *Epicoccum* and *Alternaria*.

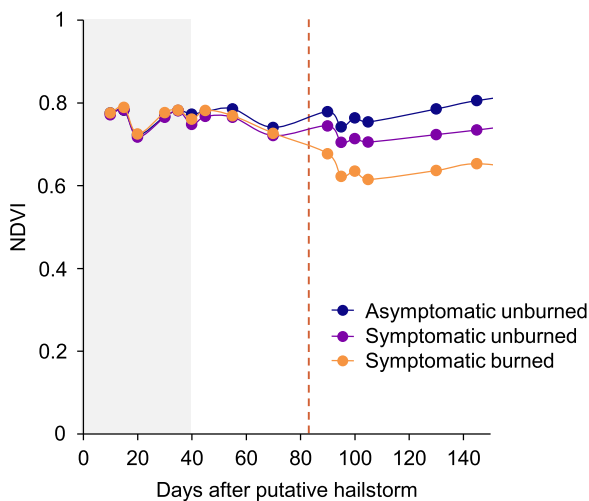
## 4. Discussion

Prescribed burns are regularly used to reduce fuel loads but may also induce stress in trees, potentially favouring facultative pathogens. *Diplodia* shoot blight, caused by *D. sapinea*, is known to be triggered by stressors such as heat, drought (Stanosz et al., 2001; Chhin and O'Brien, 2015) or hail (Zwolinski et al., 1990; Oliva et al., 2021). However, to the best of our knowledge, evidence linking fire with *Diplodia* shoot blight has not been reported. In this study, our analyses showed that fire can trigger *Diplodia* shoot blight outbreaks, likely by stressing pines. *Diplodia* shoot blight severity in the burned area was twice as high as that in the unburned area. No alternative explanations, such as the occurrence of hailstorms or any other stressing event, could explain the observed association. Also, within burned areas, no correlation was found between bark char height and *Diplodia* shoot blight severity, therefore, we can discount the possibility that the observed damage was a direct effect of fire rather than of the pathogen (Fig. S2). *Diplodia sapinea* was isolated from symptomatic tissues and, therefore, was considered the most plausible causal agent of the observed shoot blight. The prescribed burns were carried out to eliminate *Buxus sempervirens*. Prescribed burns for *B. sempervirens* require extremely dry conditions. These burns were conducted immediately following the summer season and, therefore, the overstory pines could have been under significant water stress, which may have also contributed to disease development. Further studies are needed to understand the mechanism of the interaction between prescribed fire and *D. sapinea* and to identify the most appropriate conditions for performing prescribed burns to enable forest managers to manage this threat.

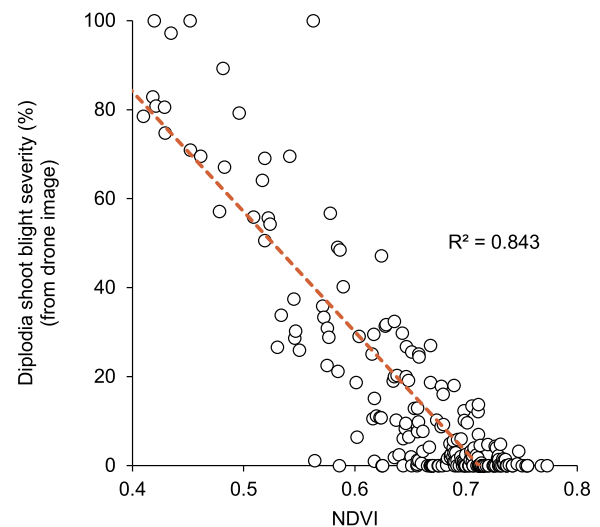
The random forest model achieved an *R*<sup>2</sup> of 0.93, demonstrating its high predictive accuracy for *Diplodia* shoot blight at the individual tree level. The model was based on two drone-derived vegetation indices: NDVI and RI. These indices proved to be reliable predictors of shoot blight severity. The high-resolution multispectral imagery (< 3 cm per ground pixel side) obtained by the drone survey successfully discriminated dead shoots within a healthy crown, which is a typical symptom of shoot blight disease. Remote-sensing technologies have been established as reliable alternatives to traditional *in situ* ground visual surveys, which rely heavily on observer expertise. As a result, remote-sensing



**Fig. 2.** Diplodia shoot blight severity assessed by field observations across burned and unburned areas. (A) Heatmap representing the spatial intensity of Diplodia shoot blight severity, based on the mean of two field assessments conducted in June and October 2024. The heatmap was generated using kernel density estimation (KDE) with a bandwidth of 100 m, using plot-level mean severity as the weighting variable. The colour scale (purple to yellow) represents increasing intensity of disease severity, rather than raw severity values. Assessed plots are represented by white points. The light-blue line delimits the area in which prescribed burns were conducted. (B) Comparison of mean Diplodia shoot blight severity between burned and unburned areas.



**Fig. 3.** Evolution over time of the canopy greenness in burned and unburned areas. Normalised difference vegetation index (NDVI) values, extracted from Sentinel-2, are shown for the first 140 days following the hailstorm event on June 29th, 2023. The grey area indicates the first 40 days after the hailstorm. The dashed vertical red line indicates the prescribed burn conducted in the study area on September 21st, 2023.

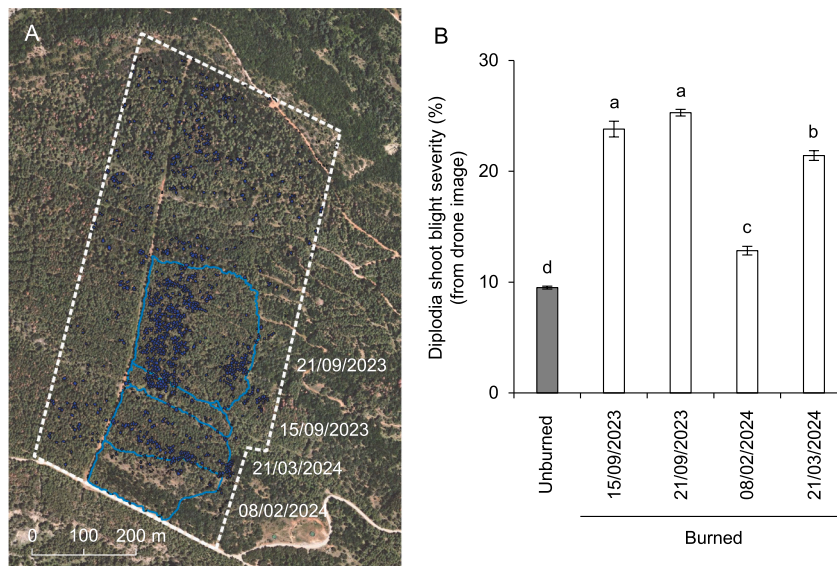


**Fig. 4.** Correlation between the mean severity of Diplodia shoot blight for each sampled tree, as assessed manually using RGB images from a drone, and the mean normalised difference vegetation index (NDVI) values obtained for its canopy.

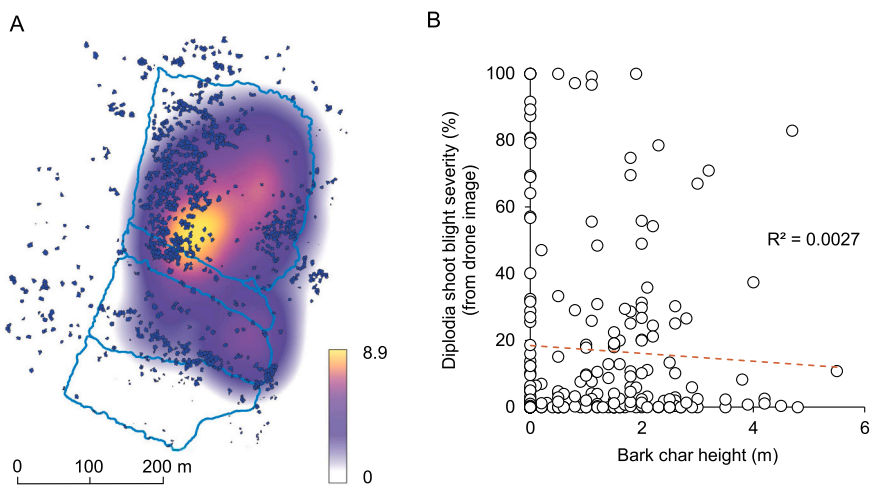
technologies are increasingly being integrated into drone-based forest health assessments, and are often preferred to high-resolution satellite imagery because of their flexibility and their ease of use (Guimarães et al., 2020). Similar drone-based workflows combining vegetation indices with random forest classifiers have been reported in previous studies of forest health. For instance, the detection of pine wilt disease using a support vector machine had an accuracy of 94% (Syifa et al., 2020). In simulation studies, clusters of affected trees have been successfully detected from unmanned aerial vehicle (UAV) imagery using the NDVI as the most effective vegetation index (Dash et al., 2017). In the case of Diplodia shoot blight, the aerial perspective brings some additional advantages, enabling the crown to be observed from above, where symptoms are more prevalent, and ensuring that symptoms observed were not confounded by the presence of scorched branches below the canopy. Furthermore, by using a multispectral-based machine-learning approach based on random forest, we were able to compare 5104 trees in burned areas with 12,565 trees in unburned areas, which

was far more trees than were assessed from the ground. Such an approach is more robust and incomparably more efficient in financial terms than traditional *in situ* ground visual surveys or the use of high-resolution satellite imagery. Furthermore, *D. sapinea* can produce large outbreaks of Diplodia shoot blight, with tree survival mainly determined by the severity of the symptoms (Caballol et al., 2022). The same drone-based approach used in this study to compare the disease severity of burned and unburned areas could be used to map the most severely affected areas within an outbreak. Such mapping could then be used to quantify the amount of damage and to locate with precision those areas where higher mortality is expected.

In conclusion, our analyses show that prescribed burns can trigger Diplodia shoot blight outbreaks in pine forests. These findings have implications for forest health and the use of prescribed burns as a fire-prevention measure. Forest managers therefore need to consider how to mitigate the risk of Diplodia shoot blight outbreaks when planning prescribed burns in pine forests. This study also demonstrates that high-resolution drone multispectral imagery, combined with a random forest



**Fig. 5.** Diplodia shoot blight severity across burned and unburned areas of a *Pinus nigra* stand. (A) Satellite image with prescribed burn areas delineated in light blue. Canopies assessed by a random forest model as showing > 40% shoot blight severity are coloured dark blue. White dashed lines indicate the limits of drone images used for model assessments. The date of the prescribed burn is shown for each zone. (B) Mean severity of Diplodia shoot blight in the canopies of each zone assessed by a random forest model. Burned or unburned areas with the same letters do not differ significantly (Tukey,  $p < 0.05$ ).



**Fig. 6.** Diplodia shoot blight severity and bark char height across a *Pinus nigra* stand. (A) Canopies with > 40% Diplodia shoot blight severity, as predicted by a random forest model, are shown in dark blue. The background heatmap, generated using kernel density estimation (KDE) with a bandwidth of 100 m, represents the spatial intensity of mean bark char height across plots, where colours from purple to yellow indicate increasing intensity rather than raw values. Prescribed burn areas are delineated in light blue. (B) Correlation between the Diplodia shoot blight severity of each tree, as predicted by the random forest model, and its bark char height.

classifier, can be reliably used to detect and quantify the severity of Diplodia shoot blight outbreaks in forest stands.

**CRedit authorship contribution statement**

**Juan de la Riva:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Dario Domingo:** Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Oriol Vendrell:** Investigation. **Jonàs Oliva:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Maria Caballol:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Francesc Serradó:** Writing – review & editing, Writing – original draft, Methodology, Investigation,

Formal analysis, Data curation.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.foreco.2026.123779](https://doi.org/10.1016/j.foreco.2026.123779).

## Data availability

Data are available from figshare: <https://doi.org/10.6084/m9.figshare.31933935> (Serradó et al., 2026).

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