



Canopy volume mitigates hail damage on grapevine berries: insights on the use of ground-based LiDAR and Bayesian probabilistic analysis

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Abstract

Purpose Hailstorms are a relevant hazard for viticulture in Europe, with the northern regions of Italy being particularly vulnerable. The unpredictability of hailstorm events limits the possibility of extensive studies; therefore, hail damage on crops remains poorly investigated by the scientific community.

Methods An experiment with four canopy management practices was established in North-eastern Italy, and a hailstorm event occurred on 24/07/2023. Through the LiDAR monitoring of the vineyard using a mobile robotic platform a few hours before the hailstorm event we were able to map the canopy structure and relate it to the berry damage.

Results The vineyard showed an average of 32% of berries damaged per bunch. We found that the basal part of the canopy provided shielding for the grape bunches, resulting in reduced damage. Plants with basal damage also exhibited greater canopy contraction in the basal section, confirming the protective role of the canopy. The results were analyzed with a Bayesian approach to produce robust probabilistic inference.

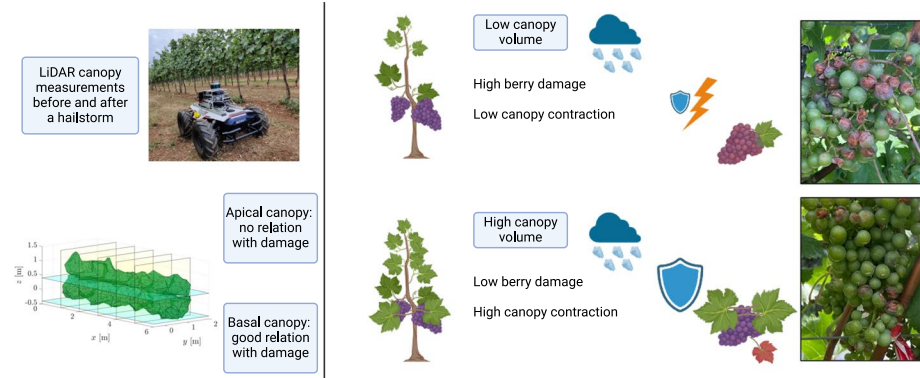
Conclusion Our study contributes to a better understanding of the dynamics of hail damage in viticulture and can be a valuable tool to better assess the risk of hail damage in vineyards.

Highlights Hailstorm damage on berries and canopy was monitored with LiDAR sensor 12 h before and after the event.

The volume and projected area in the basal part of the canopy were associated with lower damage.

Grapevines with high canopy contraction after the hail showed less damage.

Graphical abstract



Keywords *Vitis vinifera* L. · LiDAR sensor · Remote sensing · Hierarchical model · Climate change

Introduction

Hailstorms are a major hazard, resulting in billions of dollars in economic losses worldwide (Changnon, 2009), with agriculture being one of the most impacted sectors (Botzen et al., 2010). In recent years, climate change has intensified this problem by increasing the frequency and intensity of hailstorms across the European continent (Raupach et al., 2021). The records from 1950 to 2021 indicate an increase in the frequency and severity of hail events in Europe, with the northern regions of Italy being the most exposed area in the European continent (Battaglioli et al., 2023). Moreover, in the record of hail precipitation between 1988 and 2016 for northeastern Italy, hailstone mean size increased over the 29 years analyzed (Manzato et al., 2022).

Considering the diffusion of European viticulture, hail represents a major challenge for grapevine farmers in Europe. Despite the considerable challenges posed by hailstorms, research into their effects on viticulture remains limited, possibly due to the unpredictable nature of hail events (Kim et al., 2023). To overcome the casualty of these events, in many works available in literature the hail damage was simulated by reducing leaf area or canopy structure with mechanical tools such as gun drill (Wang et al., 2021), or a garden rake (Zhou et al., 2016). However, these studies approximate the real conditions in the field, making it difficult to apply the results to real scenarios.

The damage caused by hail on crops can vary in intensity depending on factors such as hailstone dimensions, kinetic energy, and obviously the crop considered (Yue et al., 2019). Given the scarcity of data available on hail damage and the wide spectrum of factors influencing the damage to crops, understanding environmental conditions is essential for future generalizations of studies. The study of Petoumenou et al. (2019) report the effect of natural hail with diameters of 2.5–3 cm and a wind of 78 km/h on table grapevine, assessing the hail impact on: photosynthesis, production, and berries phenolic compounds, showing the implication for grape yield and quality. Natural hailstorm has also been reported to affect the

grapevine canopy, resulting in alteration of vegetative development in the cultivars Chardonnay, Pinot Noir (Baniță et al., 2020), and Storgozia (Simeonov et al., 2021).

A precise assessment of defoliation resulting from natural hail was demonstrated in the study of Vescovo et al. (2016) conducted on corn (*Zea mays* L.). The researchers used an airborne light detection and ranging (LiDAR) sensor to map the canopy of a hail damaged cornfield, finding a good estimation of the defoliation measured on field (Vescovo et al., 2016). Extending this approach to understand the effects of hail on grapevine canopies and the relationship between canopy and economic damage would be important even for the grapevine industry. This data could be helpful for insurance companies or farmers to better estimate the damage and to assess the risk. However, to the best of the authors' knowledge, a precise evaluation of canopy structure using techniques such as LiDAR sensors has never been applied to grapevines after a hail event.

Mobile robotic platforms are becoming widespread for mapping and monitoring purposes in agriculture, especially to provide LiDAR measurements of the canopy under investigation (Ammoniaci et al., 2021; Bietresato et al., 2016; Ristorio et al., 2017; Tiozzo Fasiolo et al., 2023a). Unlike traditional remote sensing methods that rely on satellites, aircraft, or UAVs and mainly offer a top-down perspective, ground robots can collect high-resolution data from close range and multiple viewpoints (Tiozzo Fasiolo et al., 2023a). They also acquire information more consistently and accurately than handheld LiDAR systems, as their autonomous navigation ensures uniform scanning and reduced operator-induced variability (Maset et al., 2022). This capability allows them to capture detailed structural parameters of crops and plants, such as height, volume, and canopy density. Moreover, mobile robots are less affected by weather conditions, are not subject to the same strict regulations as aerial platforms and can carry heavier payloads for advanced sensing equipment (Tiozzo Fasiolo et al., 2023a). The data acquired enable precision farming practices, including variable-rate application of water and pesticides, reducing resource waste. For example, LiDAR-based 3D point clouds can assess the effects of different irrigation treatments in vineyards (Tiozzo Fasiolo et al., 2023b). Such detailed mapping contributes to improved crop health, better decision-making, and represents a promising tool to traditional remote sensing in modern agriculture.

In the night of 24/07/2023 a severe hailstorm was registered in Northeast of Italy, with intense hail drop and winds up to 80 km/h (OsmerFVG, July 2023). In that event the new European record for the largest hailstone was broken in Azzano Decimo (Pordenone, Italy), with 19 cm of diameter (Eisenbach, 2023). In this single event 4800 ha cultivated with grapevine were damaged. This hailstorm also impacted a vineyard located at the University of Udine, where an experiment on different canopy management techniques was being conducted. In this vineyard, different canopy management techniques were monitored using a mobile robotic platform equipped with LiDAR technology 12 h before the hailstorm, providing an invaluable opportunity to have data about hail dynamics. The aim of this paper was to assess canopy contraction, and to understand the role of the canopy in the damage of grape bunches due to hail. The assessment of an environmental hazard affecting grapevines, resulting in economic losses, such as a hailstorm, highlights the advantages of using probability distributions to represent uncertainty related to grapevine damage. A Bayesian approach was employed to analyze the data, yielding a probability distribution of the estimates. The Bayesian approach proves particularly valuable when dealing with limited or uncommon data, as it enables the integration of prior information to refine model estimates.

Using probability distributions makes estimates easier to interpret and facilitates decision-making (Sondhi et al., 2021; Addy et al., 2024).

Our work contributes to expanding the knowledge about the hail effect in vineyards, bringing significant innovations such as: (i) monitoring the damage of a natural hail event on grapevines, (ii) a more precise analysis of the hail effect on the vineyard using LiDAR sensor data acquired by means of a mobile robotic platform, and (iii) estimating the hail effect with Bayesian regressions.

Material and methods

Experimental field

The trial was carried out in 2023 at the experimental farm “Antonio Servadei” belonging to the University of Udine, located in Northeastern Italy (46°01'53.0" N, 13°13'29.0" E, 90 m a.s.l.). In this area, the soil is rich in gravel (composed of coarse and permeable fluvial deposits), subalkaline, and excessively drained. The climate in this area is temperate humid, with average annual temperatures of 13.5–14.5 °C. The experiment was set up on two rows of a Merlot Kanthus vineyard, approximately 90 m long, cultivated with single Guyot with a planting spacing of 2.6 m between rows and 1 m within the row.

Canopy management

A completely randomized block design was set up with four treatments in comparison, and four replicates for each treatment, for a total of 16 plots. Every experimental plot accounted for six plants, with a length of 5.4 m. Before the hailstorm, the main aim of the trial was to compare canopy management techniques, with and without shoot trimming, together with the presence or absence of laterals. With this trial we wanted to ascertain how the modification of the canopy structure could modulate the grape maturation and what the contribution of the laterals was. Thus, the treatments in comparison were assigned as follows: trimmed canopy (TR), wrapped canopy (WR), trimmed canopy without laterals (TR–L) and wrapped canopy without laterals (WR–L). Trimming was applied on TR and TR–L treatments on 14/06/2023, by cutting the shoots when they overcame the last wire by approximately 30 cm; the trimming was repeated on to allow maintaining the vertical position of the canopy. As for the wrapping treatments WR and WR–L, the shoots were wrapped on the last trellis wire; this operation was repeated to follow the elongation of the shoots. The lateral removal on the TR–L and WR–L treatments was performed at the time of trimming and reiterated in the following weeks to remove the laterals that appeared on the main shoots.

Hailstorm characterization and bunch damage measurements

On the night of 24–25/07/2023, a two-round hailstorm struck large areas of the Friuli Venezia Giulia plain. The first occurred at 8 pm on 24/07/2023, followed by the second at 6 am on 25/07/2023. The wind reached a maximum speed of 80 km/h as shown in Table 1.

Table 1 Meteorological data collected on the night of 24–25/07/2023 during the hailstorm

Date	Hour	Rainfall (mm)	Atmospheric temperature (°C)	Relative humidity (%)	Average wind speed (km/h)	Maximum wind speed (km/h)	Average size of hailstones (cm)
24-07-23	20:00	14,7	19,3	90	15	69	1–3
25-07-23	6:00	25,4	18,6	92	21	80	1–3

The data were acquired by the weather station located at the “Antonio Servadei” farm (Sant’Osvaldo, Udine, Italy)



Fig. 1 Styrofoam hail pad after the hailstorm of 24-25/07/2023 in Basiliano (Udine, Italy). The hail diameters range between 1 and 3 cm

Figure 1 shows the size of the hailstones detected in Basiliano on a styrofoam hail panel, which is about 5 km from Sant’Osvaldo, where the vineyard under test is located. The visible size of the hailstones reached values ranging from 1 to 3 cm in diameter.

Following the hailstorm on 24/07/2023, an assessment of the damage was carried out on bunches on 31/07/2023. Eight bunches were randomly selected and analyzed for each replicate.

The severity of damage was assessed on the bunches by rating the berries damaged by the impact of the hail (counted in each bunch), over the total number of berries (estimating by rating the bunch weight and the average berry weight) thus, hail damaged was expressed in a scale of 0 to 100%.

LiDAR canopy measurements and data processing

In this work, the mobile robotic platform Scout 2.0 by AgileX (AgileX Robotics, Shenzhen, China) was used to collect the data related to the surface, the area projected on the ground, and the volume of the plants in the vineyard. The Scout 2.0, shown in Fig. 2, is a skid-steered mobile robot equipped with four electric motors, a Velodyne VLP-16 (Velodyne, Santa Clara, USA) LiDAR sensor, a 9-axis Xsens MTi-630 (Xsens Technologies B.V., Henderson, Nevada, USA) Inertial Measurement Unit (IMU), and a NVIDIA Jetson AGX Xavier (NVIDIA, Santa Clara, USA) onboard computer (Octal-core NVIDIA Carmel ARMv8.2 CPU @ 2.26GHz; 512-core Volta GPU with 64 Tensor Cores; 32 GB 256-bit LPDDR4x @ 2133 MHz) with Ubuntu 18.04 and ROS Melodic.

The robot was remotely controlled along the vineyard rows to scan both sides of the plants at the same time. The data from the LiDAR sensor, the IMU, and the wheel encoders was stored in the standardized ROS bag files. Then, the bag files were processed in a workstation (Intel® Core i5-10600 K CPU @ 4.10 GHz × 12, Intel® UHD Graphics 630, 32 GB RAM, 64-bit) to reconstruct the 3D point cloud of the vineyard, using the LIO-SAM SLAM algorithm (Shan et al., 2020). LIO-SAM integrates LiDAR and IMU measurements in a factor graph for accurate path estimation. This SLAM algorithm was employed since it provides a good trade-off between density and accuracy of the point cloud when also IMU data are integrated (Tiozzo Fasiolo et al., 2023c), eliminating the need to use filters to discard the outliers.

The point cloud of the vineyard obtained by means of LIO-SAM was processed with the open-source CloudCompare software to discard the points belonging to the ground using a Cloth Simulation Filter. The cloth resolution (the grid size of cloth used to cover the terrain) was set to 0.5 m, the maximum number of iterations to 1000, and the classification threshold to 0.5. A point cloud for each of the four rows analyzed was extracted from the entire 3D reconstruction of the vineyard.



Fig. 2 The Scout 2.0 mobile robot by AgileX

These four sets of points were then imported in Matlab® (version R2022b; The Math-Works Inc.®, Natick, MA, USA) for further processing. The point clouds were initially expressed in the ENU reference frame, i.e., a reference frame with the origin in correspondence to the position of the robot at the beginning of the acquisition, and with its axis pointing to the magnetic East, North, and Up, respectively. Principal Component Analysis (PCA) was used (on the point cloud composed of the four analyzed rows) to find the directions of a new reference frame, such that the first principal axis corresponds to the direction of progression along the vineyard row, the second principal axis corresponds to the direction of the height of the plants with respect to the ground, and the third principal axis is chosen accordingly to complete the right-handed system of vectors. This new reference frame is centered in the barycenter of the point cloud comprising all four vineyard rows not considering the points belonging to the ground.

LiDAR canopy measurements split

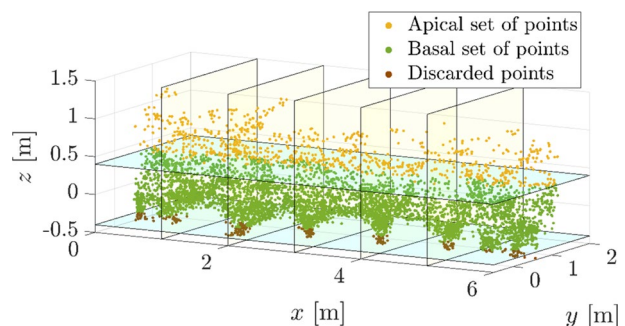
Two canopy management practices, i.e., wrapping and trimming, were tested both with and without laterals. To accurately assess the effects of these practices, LiDAR measurements were divided into two sets of points: basal and apical. The apical set captured the effects of trimming and wrapping practices, whereas the basal set contained information on lateral management. Moreover, the basal part of the canopy was selected to contain all the grapevine bunches. This division allowed to discriminate a section of the canopy containing the fruits (basal) and a part of canopy non containing the fruits (apical), both subjected to different canopy management.

An offset $h = 4$ m from the barycenter was chosen so that the basal set comprised the points whose z coordinate is included in $[-h, h]$, omitting points attributed to trunks, whereas the apical set comprised the points with $z > h$. Moreover, to obtain a set of points for each single plant, the apical and basal sets of points were subdivided by means of vertical sections distant one meter to each other along the first principal axis.

An example of the result of this operation on a set of points containing six plants is shown in Fig. 3, where the points of the basal section are marked in green, the points of the apical section are marked in yellow, and the discarded points (attributed to trunks) are marked in brown. Vertical (yellow) and horizontal (light blue) section planes are also depicted.

The estimates of the volume and surface of the hull bounding each set of points are calculated by using the Alpha Shape algorithm (Edelsbrunner et al., 1983). The algorithm creates a bounding volume enclosing all points through a triangulation (mesh). Then, the total surface is computed as the sum of the area of each triangular element, whereas the total volume

Fig. 3 . Example of apical and basal sets of points



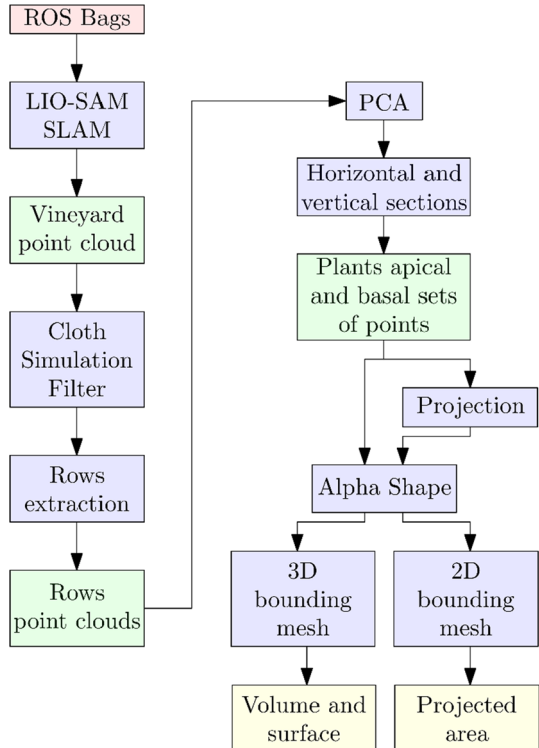
is computed breaking down the alpha shape into tetrahedra and summing their volumes. Similarly, the area of the plants projected on the ground plane is computed using the Alpha Shape algorithm on a 2D set of points obtained by projecting the points along the vertical axis (the second principal axis). The LiDAR data processing is summarized in Fig. 4.

Modeling canopy contraction after hailstorm

The model analysis was performed with the R statistical software (version 4.3.1; R Core-Team, Austria). To identify the variables most influential in determining canopy contraction, we compared several models using the information-theoretic approach to model selection (Anderson & Burnham, 2002). The dependent variable was the canopy LiDAR measurement, recorded at two time points: before and after the hail event. This factor was treated as a categorical variable called “Time,” with each canopy LiDAR measurement associated with a corresponding Time category. A full model including Time, row, and plot as explanatory variables was compared with nested models in which one or more variables were removed, to test whether including Time improved the model’s explanatory power. We compared the models selecting the one with the lowest Bayesian information criterion (BIC). The selected likelihood model (model 1) had a hierarchical structure containing the canopy measurements time (Time), composed by two levels: Pre hail and Post hail, and the random intercept for the measured plots (1|plots):

model 1.

Fig. 4 Overview on the point cloud processing. The input file is marked in red; the operations performed on data in blue; the data resulting from the processed point clouds in green; the obtained LiDAR measurements in yellow



$$Canopy\ measurements \sim Time + (1|plot) + \varepsilon$$

The Bayesian approach was chosen for its ability to incorporate prior information into the model, which can improve parameter estimation, especially when dealing with limited data or when prior knowledge exists. Furthermore, in our case we were particularly interested in the continuous and probabilistic output of the Bayesian approach. The posterior distributions of the Bayesian models estimate a continuous distribution of the uncertainty, which is critical to evaluate hail damage.

Prior information about the intercept and angular coefficient was added to model 1. The intercept, representing canopy measurements the day before the hail, and the angular coefficient, indicating the expected contraction in canopy measurements, were taken from prior studies. The intercept was derived from the work of Tiozzo Fasiolo et al. (2023b), which provided canopy LiDAR measurements for Pinot Gris under various water status conditions during the 2022 vegetative season. The same vineyard location and the similar grapevine age between the two studies allowed us to use their data as informative priors. We adjusted the standard deviation of the well-watered treatments to account for differences between the cultivars used in our study.

For the prior angular coefficient, we selected low-informative priors with slightly negative coefficients and wide standard deviations. This choice was based on the fact that canopy LiDAR measurements taken after a hailstorm would likely show a reduction of leaf area, rather than an increase, as compared to a non-damaged canopy.

To estimate the posterior distributions, we employed the Markov chain Monte Carlo (MCMC) method, using the `brm` function from the `brms` package (Bürkner, 2018), with a warmup period of 1000 iterations. The trace plot of the Markov chains was monitored to ensure convergence. Finally, the credible interval distributions of the intercept and regression coefficients were visualized using the `tidybayes` package (Kay, 2023).

Modeling grape damage as a function of canopy measurements

The effect of the canopy treatments on the grapevine bunch damage was assessed with analysis of variance (ANOVA) of the factor treatment. The residuals distribution was evaluated to ensure normality and homoskedasticity. The analysis was followed by a pairwise multiple comparison test (Tukey HSD), and the significant letters discriminating the levels with a 95% of confidence intervals with an $\alpha=0.05$. The relationship between the hail damage and the canopy LiDAR measurements (model 2) or the difference between the value pre and post hail (model 3) were assessed by linear regression based on ordinary least squared (OLS):

model 2.

$$Damage \sim \beta_0 + \beta_1 Canopy\ measurements + \varepsilon$$

model 3.

$$Damage \sim \Delta Canopy\ measurements + \varepsilon$$

where:

$$\Delta Canopy = Canopy_{Pre\ hail} - Canopy_{Post\ hail}$$

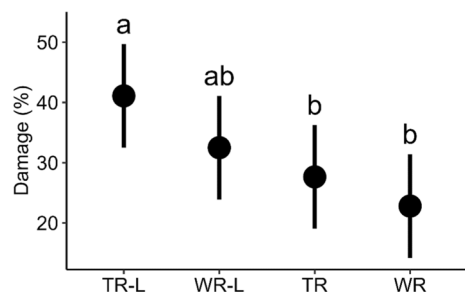
calculating determinant coefficients and regression equations for the apical and basal part of canopy.

Based on the regression results from models 2 and 3 applied to both the basal and apical parts of the canopy, it became evident that the basal canopy exhibited more interesting coefficients. Consequently, we chose to compute and display Bayesian regressions on the basal canopy measurements, to have precise inferences from this specific part of the canopy. Posterior distributions of the regression parameters (for the same model 2 and 3) were sampled with the package *brms*. We selected low informative priors for the two models (Gelman et al., 2008) based on our field knowledge. With weakly informative priors, the posterior distributions concentrate around the maximum likelihood estimates. In our case, the resulting parameter estimates are close to the OLS solution, with the Bayesian framework additionally providing full posterior distributions for both the intercept and the slope. After a severe hailstorm like the one on 24/07/2023, the value of damage is likely to be above 0% but is unlikely to be 100%. This information was included in the models as prior distributions. The sample of MCMC were started after a warmup of 1000 cycle, while the chains longitudinal behaviors were monitored with the trace plot. The credible intervals distributions of the intercept and regression coefficients were plotted with the package “tidybayes” (Kay, 2023), while the R^2 was computed with the method of Gelman et al. (2019), using the *r* packages “performance” (Lüdtke et al., 2021).

Results

After the hailstorm on 24/07/2023, the vineyard analyzed showed an average of $31.9 \pm 9.4\%$ of berries damaged per bunch, with significant differences among the canopy management treatments. Plants with trimmed and lateral removed canopies (TR-L) showed the highest level of berry damage, reaching 41.1% per bunch, statistically higher than TR (27.7%). The treatment with a wrapped canopy with laterals (WR) had the least damage at 22.8% (Fig. 5); the damage on TR-L treatment was 44.5% higher than WR. The different canopy managements did not affect the production in terms of yield, number of bunches per plant and average bunch weight (Figure S1a, S1c, S1e). The production was not correlated with the observed damage of the berries; the R^2 demonstrated a weak association between these two measurements, with values of 0.11 in the yield, 0.052 for bunches number and 0.053 for bunches average weight (Figure S1b, S1d, S1f).

Fig. 5 Severity of damage on bunches by canopy management: trimmed and lateral removed (TR-L), wrapped and lateral removed (WR-L), trimmed with lateral (TR), and wrapped with lateral (WR). The mean damage for each treatment is denoted by the black dot, while the lines represent 95% confidence intervals. Letters indicating significant differences were assigned for each treatment based on a protected Tukey Test



Canopy treatments shaped the canopy structure, which was monitored with the LiDAR measurements. The canopy LiDAR measurements poorly discriminated among the different canopy management treatments (Figure S2), as indicated by the nonsignificant ANOVA (data not shown). However, the TR-L treatment consistently exhibited lower measured values for all LiDAR measurements in the basal canopy (Figure S2a, c, e) and higher values in the apical canopy (Figure S2b, d, f). Conversely, the WR treatment consistently resulted in the highest values in the basal canopy (Figure S2a, c, e) and lower values in the apical canopy (Figure S2b, d, f).

Monitoring the canopy the day before and after the hailstorm allowed us to record differences in the canopy structures (Fig. 6). The hailstorm reduced the apical part of the canopy in terms of volume (Fig. 6a), projected area (Fig. 6b), and surface (Fig. 6c) in the overall vineyard. The basal part of the canopy was also reduced in terms of volume by -11.2% (from 0.331 to 0.293 m³) (Fig. 6d) and projected area by -7.2% (from 0.737 to 0.683 m²) (Fig. 6e), whereas the surface was not affected by the hailstorm (only -0.1%) (Fig. 6f). A Bayesian hierarchical model built on these data, revealed with a 95% probability that the basal part of the canopy was reduced in volume between -0.02 and -0.05 m³ (Fig. 6g, Table S2), the projected area between -0.02 and -0.09 m² (Fig. 6h, Table S2), and the surface value between 0.09 and -0.11 m² (Fig. 6i, Table S2). The R^2 computed on the bayesian model and on the OLS yield similar values (Fig. 6 and Table S3).

Berry damage was not directly influenced by the apical part of the canopy (as revealed by LiDAR measurements, and reported in Fig. 7a, b, and c). The regressions resulted in a near-zero R^2 and angular coefficients. However, a clear relationship was identified between the damage on the berries and all the canopy LiDAR measurements in the basal section of the canopy (Fig. 7d, e, f). The R^2 and angular coefficients were higher compared to the apical part of the canopy, indicating lower error and a stronger relationship between the observations. The posterior analysis of the basal part of the canopy provided a probabilistic view of this relationship (Fig. 7g, h, i). The 95% credible intervals for the angular coefficients indicated that the damage was reduced between -2.07% and -32.60% with an increase of 0.250 m³ of basal canopy volume per grapevine plant (Fig. 7g, Table S2), between -1.02% and -17.01% with an increase of 0.250 m² of basal projected area (Fig. 7h, Table S2), while an increase of 0.250 m² of the basal surface resulted in a damage value between -3.18% and $+0.68\%$ (Fig. 7i, Table S2).

The difference between the canopy LiDAR measurements before and after the hailstorm (Δ canopy) indicated the change in the canopy after the hail. A positive value (Δ canopy > 0) indicated an increase in canopy value with hail, and a negative value (Δ canopy < 0) indicated a decrease after the hail. As observed in Fig. 6, hail promoted a contraction of the canopy in terms of volume and projected area, which was more evident in the basal measures. Berry damage was not related to the Δ canopy in the apical volume and projected area (Fig. 8a, b), while a weak positive relationship was observed in the apical surface (Fig. 8c). In the basal canopy, the value of Δ canopy volume (Fig. 8d) and Δ canopy projected area (Fig. 8e) negatively influenced berry damage. No clear relationship was visible between the berry damage and the basal Δ canopy surface (Fig. 8f). The posterior distributions of the angular coefficient, identified with a 95% probability, that damaged berries decreased between -1.02% and -65.34% when the basal volume decreased by 0.250 m³ because of the hailstorm (Fig. 8g, Table S2). In the basal projected area, this trend was even more evident (Fig. 8h, Table S2) with a decrease between -11.74% and -12.06% with a contraction

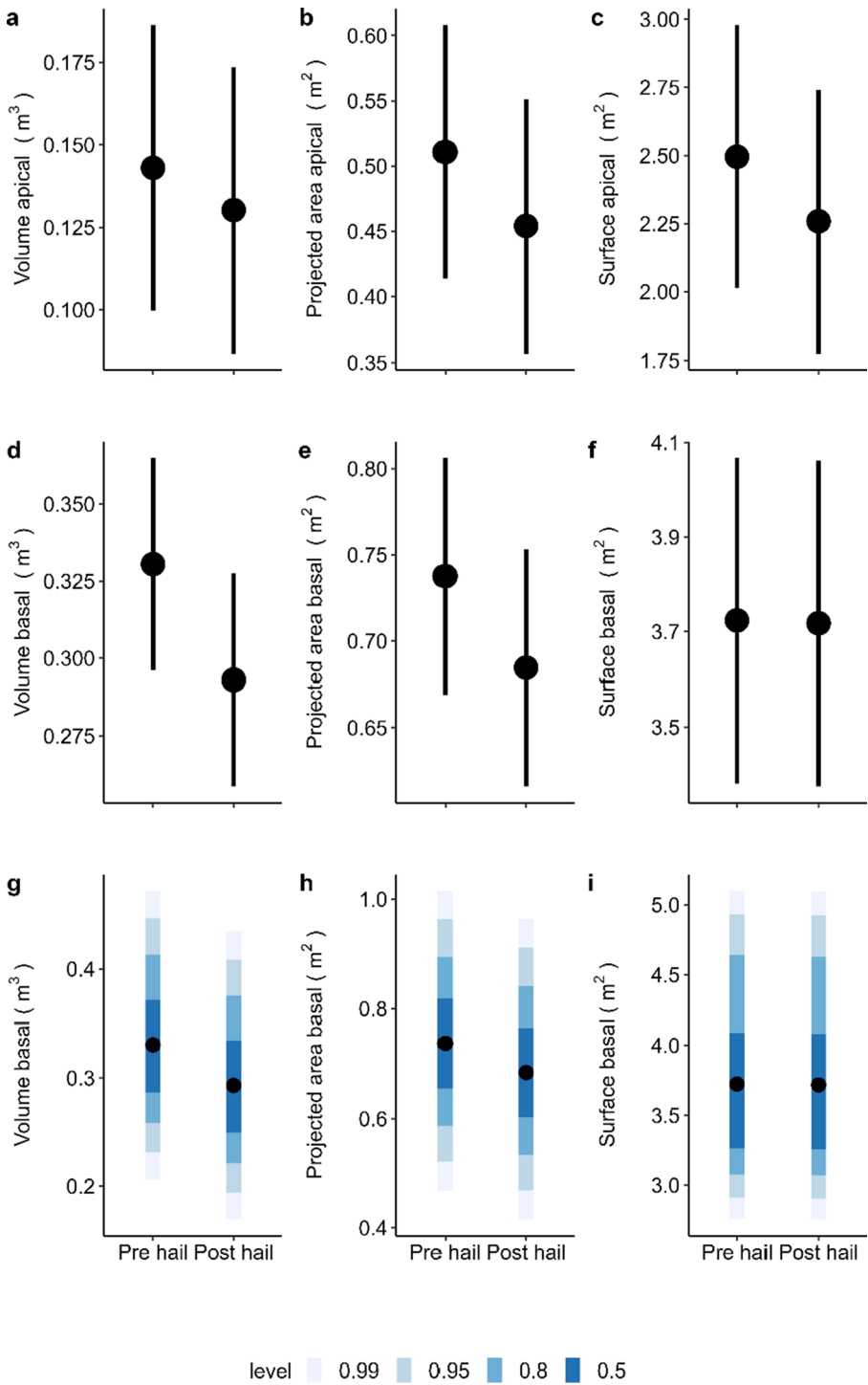


Fig. 6 Canopy LiDAR measurements (volume, projected area and surface) measured the day before and after the hailstorm of 24/07/23 in Udine (Italy) in the apical part of canopy (a, b, c), and basal part of the canopy (d, e, f). The black dot represents the measured mean for the canopy parameters, while the vertical lines indicated the 95% confidence intervals. The bottom row displays the posterior distribution of a hierarchical model for the basal canopy parameters: volume (g) (m³) basal projected area (h) (m²), and basal surface (i) (m²). The black dot represents the measured mean for the canopy parameters while different levels of credible intervals are shown by the color intensity

of 0.250 m², while no visible trend was observed for the basal surface measurement (Fig. 8i, Table S2).

The canopy management did not result in great differences in Δ canopy measurements with LiDAR (Figure S3), as indicated by the nonsignificant ANOVA (data not shown). However, in the basal part of the canopy the treatments TR-L and WR resulted in the wider

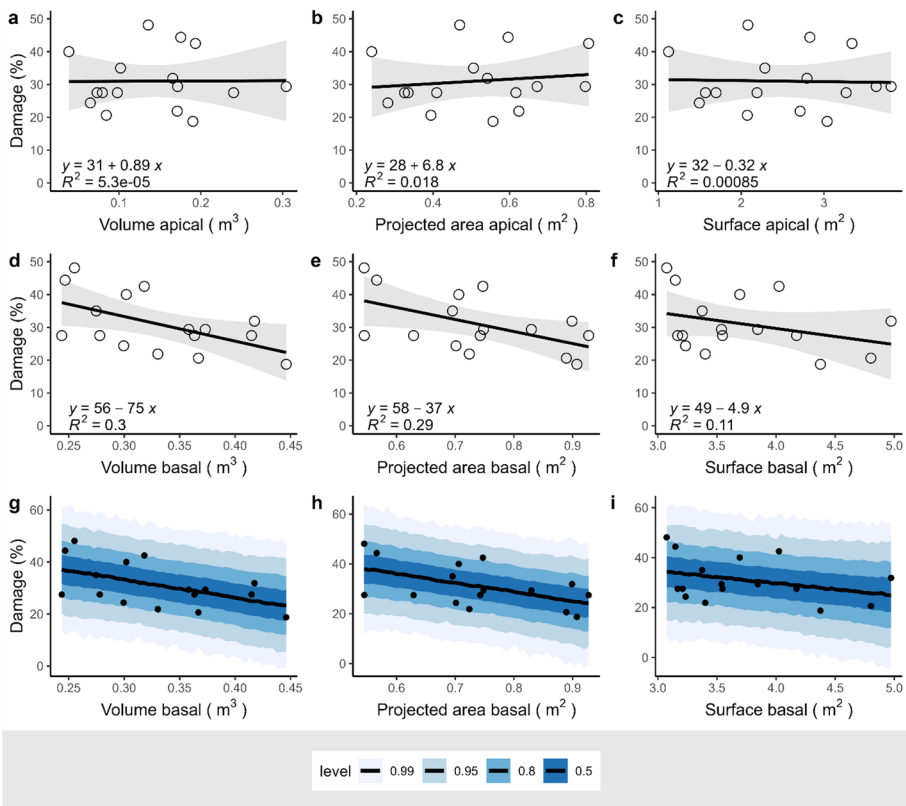


Fig. 7 Ordinary least squared (OLS) regression between the percentage of damaged berries per bunch and Canopy LiDAR measurements: volume (m³), projected area (m²), and surface (m²), measured in the apical (a, b, c), and basal part of the canopy (d, e, f), 12 h before the hailstorm of 24/07/23. The regression line is shown in black with the 95% confidence intervals in gray, the linear equation and the determination coefficient (R²) are presented in the bottom left of the plot. The bottom row displays the posterior distribution of a model for the basal canopy parameters: volume (g) (m³) basal projected area (h) (m²), and basal surface (i) (m²). The black dots represent the measured values for the canopy parameters while different levels of credible intervals are displayed by the color intensity

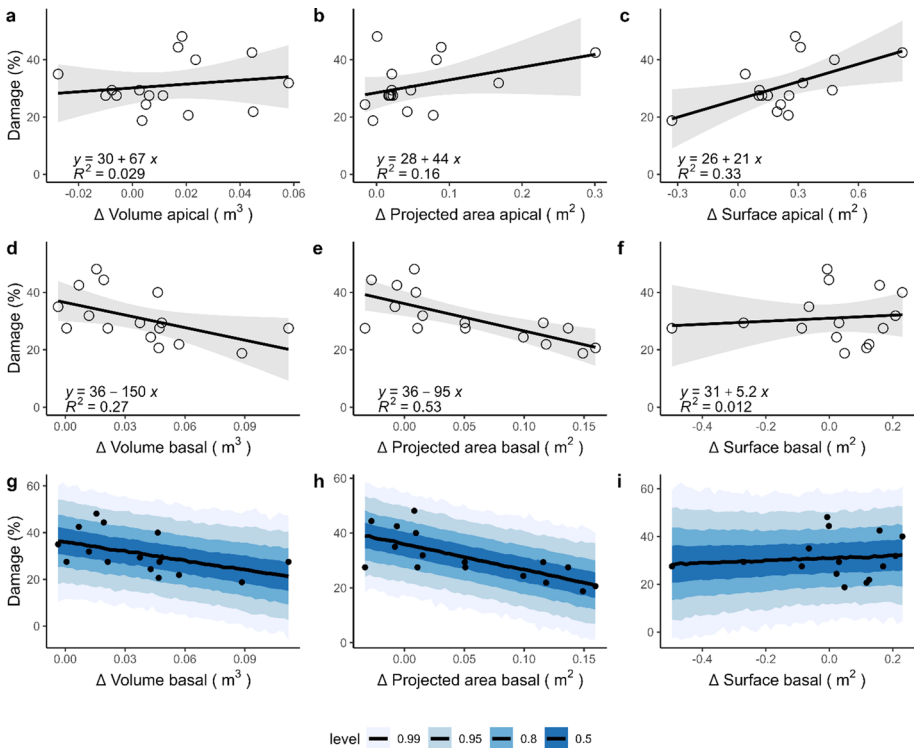


Fig. 8 Ordinary least squared (OLS) between the percentage of damaged berries per bunch and the difference between the Canopy LiDAR measurements (Δ canopy) measured the day before and after the hailstorm of 24/07/23 in Udine (Italy). The measure of volume (m^3), projected area (m^2), and surface (m^2), measured in the apical of the canopy are presented in the first row (**a**, **b**, **c**), while in the second-row basal part of canopy is reported (**d**, **e**, **f**). The regression line is shown in black with the 95% confidence intervals in gray, the linear equation, and the determination coefficient (R^2) are presented in the bottom left of the plot. The bottom row displays the posterior distribution of model for the basal canopy parameters: volume (**g**) (m^3) basal projected area (**h**) (m^2), and basal surface (**i**) (m^2). The black dots represent the measured values for the Δ canopy parameters while different levels of credible intervals are displayed by the color intensity

distance between the group means for the measures Δ canopy volume and projected area (Figure S3a, S3c).

Discussion

Hailstorm and berry damage in viticulture

Hailstorms are a major hazard for viticulture in Europe, particularly in the northern regions of Italy, which are considered the most exposed area in Europe (Battaglioli et al., 2023). Despite the significance of hail-related challenges, research on hail damage in viticulture remains very limited. This need for more studies can be attributed to the difficulties in replicating hailstorm damage and the unpredictable nature of hail events.

The diverse canopy management of our experimental vineyard exhibited different shapes and characteristics depicting scenarios that can be observed in a general productive vineyard. While there was an interest in identifying canopy management practices that could potentially reduce hail damage to the berries, our research aimed to discover and measure which canopy characteristics determined the significant differences observed among treatments or, in other words, what was a reliable hail damage predictor.

The severity of canopy loss in our study was modest ($\approx 11\%$ volume reduction) compared with the simulated extreme defoliation scenario of Stafne and Carroll (2019), where complete removal of lateral leaves and bunches reduced yields by 19–81%. Our smaller impact highlights that moderate hail events may not trigger the same yield penalties, particularly when the crop has structural traits that mitigate losses. This is consistent with our observations of cv. Merlot Kanthus, where moderate leaf and berry loss did not translate into significant yield reduction. Petoumenou et al. (2019) reported high berry damage in a table grape cultivar under similar meteorological conditions, leading to yield and bunch weight reductions. When scaled to average bunch size, our berry damage estimates (31.93%, ≈ 30 –40 berries per bunch) are comparable to their findings in absolute numbers. However, unlike their results, our yields were largely maintained. This difference likely reflects varietal characteristics: Merlot Kanthus berries are smaller and more numerous, allowing partial compensation through increased weight of undamaged berries. This suggests that varietal morphology and resilience should be considered in damage modeling and in developing cultivar-specific thresholds for intervention.

The relationship between canopy structure and the berry damage

Previous studies have shown that LiDAR can be an effective tool for assessing hail damage, but differences in platform, timing, and crop type influence its applications and outputs. For example, Vescovo et al. (2016) used drone-mounted LiDAR to estimate canopy reduction in maize several weeks after hail, demonstrating the technology's potential for monitoring. In our case, ground-based LiDAR measurements taken immediately after the event captured the canopy condition before regrowth, producing a highly detailed lateral model of vineyard rows (Tiozzo Fasiolo et al., 2023b). This earlier timing can deliver a precise damage assessment, which has practical implications for insurance evaluations and post-event management decisions.

The results on the LiDAR canopy measurements revealed how only the basal section of the canopy was associated with berry damage. These findings can be explained since hail precipitations are often associated with strong winds (López et al., 2007), and the hail fall is impacting the object with a certain angle (Mobasher et al., 2022). Consequently, the damage on canopy is often more abundant on the windward side of the crop (Kim et al., 2023). In our condition the wind speed recorded on 24/07/2023 suggests that the hail impact was not vertical, thus the side of the grapevine was exposed to hail damage. The basal part of the canopy contained the grapevine bunches. The canopy structure in proximity of the bunches protected them and was directly related to the damage reduction. On the contrary, the apical part of the canopy was not directly shielding the berries, resulting in a null relationship with the damage. These results are particularly relevant for developing applications that estimate the hail risk for specific vineyards, since the canopy at bunch level plays a predominant role in preventing damage.

The fact that damage reduction was related to the greater contraction of the basal part of the canopy is another consequence of the canopy structure and bunches position. Canopy trimming promotes the growth of the laterals on the apical part of the canopy, because of the removal of apical dominance; as opposite, in case of shoot wrapping, by maintaining shoot tips, the growth of laterals is more abundant on the basal part of shoots, where the hormonal signal of IAA inhibiting prompt buds to sprout is weaker (France et al., 2018; Logan et al., 2021). The four different canopy management techniques had varying effects on the basal part of the canopy, with the TR-L treatment showing the lowest canopy LiDAR measurements and WR exhibiting the highest. Previous research by Poni and Giachino (2000) found that canopy leaf area is significantly reduced in vines pruned with simultaneous lateral removal (TR-L). In contrast, the canopy compensates better for this loss in trimmed plants with laterals (TR) or a wrapped canopy with removed laterals (WR-L).

Vines with a greater structure in the basal canopy had less berry damage but experienced higher canopy contraction (Δ canopy) because this leaf area was damaged by the hailstorm. On the other hand, management strategies with less canopy in the basal part may experience less contraction, potentially exposing the grape bunch to more hail damage. These data may seem counterintuitive, as they show low grape damage even when canopy damage is high. Explaining this dynamic is fundamental for future applications of such models, since a simple assessment of canopy structure before and after a hail event could otherwise lead to misleading conclusions.

Hail damage and berries maturation

It is important to consider the timing of hail damage in this discussion. Even a small amount of hail damage in the late stage of fruit maturity can result in the proliferation of *Botrytis cinerea* disease, leading to potential losses in fruit quality and quantity (Nair et al., 1988), while damages occurring at the beginning of the growing stage may be better recovered by the plants (Gourieroux, 2019). In our observed event, the grapevines were in the pre veraison stage (BBCH 77). At this stage, berry damage can result in low-quality grapes with severe consequences in terms of their commercial value. At this time of the season the berries reach the translucent phase of berry growth, when the berries start to change colour and the sugars begin to accumulate. The reduction of the leaf area at this stage significantly affects the final concentration of sugars in the berries because of the limitation of photosynthesis (Palliotti et al. 2013; Poni et al., 2023). Moreover, in conditions of limited photosynthesis, the vines could spend more carbon for the accumulation of sugar in the berries reducing the production of secondary metabolites, that are particularly important for grape and wine quality (Bobeica et al., 2015). At last, the removal of leaves at this stage increases the cluster exposure to sunlight, resulting in a higher susceptibility to sunburns (Vanderweide et al., 2018).

Probabilistic models to estimate hail damage

Our probabilistic analysis is especially advantageous in this context as it can delineate a continuous distribution of probable damage and, consequently, loss in value. A Bayesian probabilistic model has recently been applied to estimate hail damage to buildings in Switzerland (Miralles & Davison, 2024), showing superior performance in capturing extreme losses compared with the deterministic functions traditionally used by insurance companies.

Such probabilistic approaches provide more realistic estimates of damage and are therefore highly valuable for the insurance sector. In this context, our study highlights how canopy structure can modulate hail impacts. The developed model provides estimates of potential damage based on plant characteristics, which can help calibrate insurance schemes and improve risk assessment. The Bayesian framework is particularly valuable in this context, where data are scarce and difficult to replicate. In addition, allowing the integration of prior knowledge, whether from previous experiments, field experience, or related studies, enables our dataset to serve as informative priors for future studies, thereby improving the predictive power of models applied to similar hail events.

Furthermore, the Bayesian approach facilitates the updating of model estimates as new data become available, making it especially suitable for this type of scenario where events are not reproducible. This cumulative learning process enables our dataset to serve as informative priors for future studies, improving the predictive power and generalizability of models applied to similar hail events.

Conclusions

In this work we assessed the relationship between the hail damage on grape berries and the light detection and ranging (LiDAR) sensor measurements on grapevine canopy contraction after a hailstorm. The LiDAR data were collected shortly before and after a hailstorm event in Udine, Italy, providing precise insight into canopy health before and after the storm. Canopy LiDAR measurements in the basal pre hail were negatively associated with the damage on the bunches, while the apical part of the canopy was not related with the damage. Moreover, the contraction of canopy in the basal part was negatively associated with the bunch damage, with a poor association for the apical part. These results indicate that canopy in proximity of the bunches mitigated hail impact, resulting in reduced damage and increased canopy contraction. Management practices targeting the apical canopy, such as trimming and wrapping, showed limited effectiveness in hail damage prevention.

Compared to the frequentist interpretation, where probability refer to repeated observations of events and parameters are treated as fixed but unknown, the Bayesian approach employed in our study allows results to be expressed as probabilities of the parameters themselves. This leads to a more intuitive and interpretable framework in our context, while also naturally representing uncertainty in a continuous probabilistic form. Our findings suggest that in our conditions reducing the basal canopy volume of 0.250 m^3 per plant, increased damage between +5.0 and +30.4% (with a 90% probability). Furthermore, our estimation of the canopy contraction due to hailstorm indicated a reduction of the basal volume between -0.02 and -0.05 m^3 and the projected area between -0.02 and -0.09 m^2 (with a 95% of confidence).

Compared to previous studies available in the literature, our data offers rare field information to this scarcely investigated topic: (i) a precise monitoring of the canopy status few hours before the hailstorm with the LiDAR sensor, (ii) the effect of the hail impact on the canopy structure, (iii) the relationship between the damage observed on the bunch and the canopy LiDAR measurements.

Moreover, the Bayesian statistics approach adopted for some of our measurements remarks the opportunity to integrate existing knowledge, which is especially beneficial in

scenarios with limited data availability. These results could be useful for farmers and insurance companies to assess the risk of hail damage and estimate the extension of damage. Future research may utilize our estimates to accurately estimate forthcoming events.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11119-026-10353-6>.

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Data Availability Data will be available on request.

Declarations

Conflict of 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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