Scientia Horticulturae 347 (2025) 114196

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Research Paper

Reshaping grapevine canopy management under climate change scenarios: the role of conservative summer pruning on leaf physiology, berry microclimate, wine aromatic and sensory profile

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ARTICLE INFO

Keywords:
Vitis vinifera
Leaf-to-fruit ratio
Berry temperature
Berry microclimate
Juice composition
Wine aroma
Climate change
Pathogen-resistant varieties
PIWI

ABSTRACT

Canopy management in viticulture involves key agronomic practices aimed at balancing the leaf-to-fruit ratio and optimizing microclimates for leaves and bunches. In temperate-to-cool regions, intensive green pruning is essential for effective crop protection and aroma development. However, rising temperatures and stress conditions are prompting a re-evaluation of these practices to mitigate negative impacts from overexposed bunch-zones such as sugar accumulation, acidity loss, sunburn, anthocyanin degradation, and reduced vine longevity. This study explored alternative, more conservative green pruning methods in Guyot-trained Cabernet Franc and Nermantis (a pathogen-resistant hybrid) over two years to: i) reshape berry and leaf microclimate, ii) evaluate berry quality, and iii) assess wine aroma and sensory characteristics. Significant differences emerged between minimal and intensive canopy management strategies. Reduced intervention led to: 1) lower canopy porosity and bunch light exposure; 2) reduced leaf photoinhibition; 3) cooler berry temperatures; 4) better sugar-acid balance at harvest; and 5) higher anthocyanin levels. These effects held across contrasting seasons—2022 (hot, dry) and 2023 (cool, wet)—though driven by different putative mechanisms: differences in berry microclimate in 2022 and unbalanced leaf-to-fruit ratio in 2023. While wine chemistry showed little variation, aroma profiles were clearly affected. However, sensory analysis revealed varietal sensitivity, with Cabernet Franc more responsive than Nermantis, especially for aroma. Assuming summer pruning as a critical operation in the context of grapevine crop protection, the possibility to exploit the potential inherently higher tolerance to fungal pathogens of hybrid varieties is discussed.

1. Introduction

High-quality wine production is closely linked to distinct varietal specificity (Jones et al., 2005). However, in the past years, multifactorial environmental variables associated with climate change have increasingly pushed desired grape varieties beyond their historically defined thermal regions (Faralli et al., 2024; Jones and Davis, 2000). While in some regions, vintage wine quality has shown a linear improvement with increased thermal accumulation (Gambetta and Kurtural, 2021), this trend has only been observed under specific conditions: i) in defined varieties such as Cabernet Sauvignon, where the temperature sensitivity of methoxypyrazines can reduce undesirable vegetative aromas (Lacey et al., 1991); ii) in regions where ripening has historically been limited by low temperatures, and warming has extended the timeframe for both technological and phenolic maturity (Van Leeuwen et al., 2019). Nevertheless, a growing body of research highlights a consistent trend of increased warming (Faralli et al., 2024; Cameron et al., 2022; Xyrafis et al., 2022; Dinu et al., 2021; Van Leeuwen et al., 2019). This trend is expected to accelerate phenological development and cause an earlier onset of ripening, often under warmer-than-ideal conditions. Asynchronous maturity dynamics—such as rapid acidity depletion, reduced anthocyanin concentrations, increased sunburn incidents, and elevated

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https://doi.org/10.1016/j.scienta.2025.114196
Received 14 February 2025; Received in revised form 19 May 2025; Accepted 19 May 2025
Available online 24 May 2025

sugar levels—have been frequently observed (Palliotti et al., 2014). Collectively, these changes pose a significant threat to the preservation of wine typicity across many regions. Consequences include wines with higher alcohol content, lower acidity (leading to pre-fermentation microbiological instability), diminished color, and an undesirable aromatic profile, all of which have been widely reported as outcomes of climate change (Palliotti et al., 2014).

The wine sector urgently requires low-cost, effective strategies to mitigate the harmful effects of climate change on berry quality and wine characteristics. Extensive research in viticulture has proposed several alternatives. In the long term, viticulture may benefit from the different adaptability of grape varieties to higher thermal accumulation—-through latitudinal varietal shifts (Duchêne et al., 2010), altitudinal cultivation while maintaining the same variety (Arias et al., 2022), or rootstock-induced adaptability (Faralli et al., 2020). Additionally, recent evidence supports the role of tailored training systems in achieving specific oenological goals under varying environmental conditions (Del Zozzo and Poni, 2024). Hunter et al. (2021) also highlighted the influence of row orientation and canopy side on the light microclimate, berry temperature, and, consequently, ripeness level, as well as berry skin anthocyanin and phenol content in Shiraz. All these highly effective options, however, focus on future vineyard plantation and the issues associated with the current sector remain. For this reason, vineyard management has been targeted as the major contributor of the viticultural sector to a changing climate (Reta et al., 2025; Palliotti et al., 2014). Berry reflectants (Teker, 2023), biostimulants (Frioni et al., 2021), irrigation scheduling (Chaves et al., 2010), specific trimming approaches (exploiting competition; Santesteban et al., 2017), various degrees of source limitation (Palliotti et al., 2012), crop load (Previtali et al., 2021), hail nets (Pallotti et al., 2023), can protect the bunch and/or postpone ripening hence reducing negative effects resulting from a combination of radiative, thermal and, in some cases, water stress, and their combination on berry quality. All these possibilities, however, explicitly require additional costs and interventions in the vineyard for farmers. In this context, reducing intervention costs while preserving optimal microclimate for berry ripening may be an important target for several viticultural areas.

Canopy management in grapevine encloses a series of agronomic practices with the aim of optimizing a complex trade-off between canopy photosynthesis, productivity, berry quality and sanitary status (Poni et al., 2023). Shoot trimming/topping is a common method adopted in vertical-shoot positioning training systems with the aim of restraining canopy development. Additionally, the reduction of the leaf layers ensures higher light penetration and air circulation thus limiting the incidence of pathogens (Faralli et al., 2022). Bunch zone defoliation has a strongly phenology-dependent effect: when performed early during flowering, it can lead to source limitation due to the removal of photosynthetically active leaves (Intrigliolo et al., 2014). In contrast, defoliation at the pea-sized berry stage improves spray penetration and creates a drier microclimate, without significantly affecting total carbon assimilation (Würz et al., 2020). These techniques, consequently, are adopted with the major aim of optimizing crop protection that may result in a conflicting outcome when compared to microclimatic requirements associated with climate change. The ongoing implementation of novel *Vitis* hybrid varieties with putative mechanisms of tolerance to downy and powdery mildew (Töpfer and Trapp, 2022) will expand the possibility to reconsider such agronomic practices. Assuming uniform genetics, minimal intra-vineyard variability, and consistent leaf-to-fruit ratios, the bunch microclimate becomes the primary determinant of berry chemical composition at harvest within a given area. Intra-plant and intra-bunch variability play a hierarchical role in defining the kinetics of technological, aromatic, and phenolic ripening curves for individual berries. Although governed by distinct physiological mechanisms, these ripening processes often exhibit non-linear—frequently quadratic—responses to increasing multifactorial stress. Specifically, the rates of sugar accumulation, acidity degradation, and anthocyanin synthesis typically follow a pattern: i) optimal within a defined temperature range; ii) sub-optimal responses when stress intensity exceeds that range. Non-conservative summer pruning practices can then amplify these relationships and increase ripening asynchronicity, particularly under the compounding effects of climate change.

In this work, four experiments were conducted in 2022 and 2023 with the aim of testing conservative canopy management approaches as possible options to modulate the effects of climate change on i) leaf physiology and canopy photosynthesis, ii) light penetration and canopy porosity at different canopy level and bunch zone, iii) juice chemical parameters, iv) anthocyanins concentration and composition, v) wine aromatic and sensory profile. Two varieties, including a novel pathogen resistant variety, were tested. The results provide a series of potential canopy ideotypes that may be exploited to protect wine typicity in the near future for vertical shoot positioning training systems.

2. Materials and methods

2.1. Vineyard establishment

The experiments were conducted in 2022 and 2023 in two commercial and irrigated vineyards. The vineyards were located i) in San Michele all'Adige (46.193455N, 11.138043E, 230 m a.s.l. - Trentino Alto-Adige, Italy) with cv Cabernet Franc (CF) and ii) in Pochi (46.236849N, 11.223917E, 450 m a.s.l. - Trentino Alto-Adige, Italy) with cv Nermantis (NER, pathogen-resistant variety resulting from a breeding program at Fondazione Edmund Mach, registered both in the *Vitis* Italian and International Variety Catalogue VIVC). The two varieties were grafted onto SO4 rootstock and planted in 2003 (CF) and 2018 (NER) in clay-loam soils, respectively. Vines of both varieties had a between-row and within-row spacing of 2 m x 1 m, and row orientation was E-W for CF and NE-SW for NER. Vines were Guyot trained and pruned to two spurs and one fruiting cane, (with a total of 12-14 buds per vine) and trained to a vertical shoot positioning trellis system. Vines were irrigated during the growing seasons via drip irrigation according to evapotranspiration requirements and via farm irrigation scheduling, ensuring a minimal deficit in irrigation pre-harvest. Environmental data were obtained from the San Michele all'Adige weather station (205 m a.s.l., 46.183484N 11.120556E) and growing degree days were calculated as the difference between the daily mean temperature and the base temperature (10°C). When the mean temperature was below base temperature, we automatically assigned a value of 0.

2.2. Experimental design

In 2022 (Experiment 1) and for both vineyards, the experimental design compared three ideotypes of canopy management: (1) control farm (Control) in which shoot trimming was applied two times over the season (post-flowering – BBCH 71-73; post-veraison – BBCH 81-83) and bunch zone defoliation was applied only on the North-exposed side of the canopy (leaf position up to 6 removed); (2) severe green pruning (SGP) in which shoot trimming was applied two times over the season (post-flowering – BBCH 71-73; post-veraison – BBCH 81-83), bunch zone defoliation was applied on both sides of the canopy (leaf position up to 6 removed) and lateral shoots were weekly removed after the first trimming; (3) no green pruning (NGP) in which shoot trimming was not applied while shoots were bundled and twisted around the top catch wire (post-flowering – BBCH 71-73) and bunch zone defoliation was not applied. Treatments were arranged in a randomized design in 4 blocks with a total of 48 vines per treatment. In 2023 (Experiment 2) and for both vineyards, the experimental design followed a two-factorial design while the ideotypes applied in 2022 were replicated within the different combinations: defoliation (no bunch-zone defoliation (ND), bunch-zone defoliation at BBCH73 (BZD73 - leaf position up to 6 removed) and bunch-zone defoliation at BBCH81 (BZD81 - leaf position up to 6 removed); and trimming: shoot trimming (ST, carried out two times over the season (post-flowering – BBCH 71-73; post-veraison – BBCH 81-83)) and shoot bundling and twisting around the last wire (SB, carried at BBCH 73-75). Treatments were arranged in a randomized design in 4 blocks with a total of 24 vines per treatment combination. All treatments listed above were applied manually while plant protection treatments as well as fertilization followed standard practices and scheduling for the region. In NER (pathogen-resistant hybrid), the application of fungicides was carried out only two times (mid-flowering – BBCH 65-67, pre-veraison – BBCH 77-79).

2.3. *Morpho-physiological evaluations*

2.3.1. *Leaf physiology*

In Experiment 1, leaf physiological parameters were assessed dynamically over two to four specific days post-veraison (BBCH81-89) on both the vineyards during sunny and warm days. All measurements and for all traits were assessed on both canopy sides (North and South as less or more sun-exposed), for the photosynthetically active (12-15 leaves of productive shoots) and apical leaves as well as (when possible) on the bunch zone. Leaf temperature was monitored via an infrared thermometer (Fluke 62 Max, Fluke, USA) on different organs as explained above and over the course of the day (from 8AM until 5PM) in a randomized manner between treatments to avoid time effect (n=8 leaf/bunch per treatment). On the same days and in the same spot used for leaf temperature a clip for dark-adaptation was then applied for dark-adapted chlorophyll fluorescence analysis carried out after 30 min of dark adaptation with a Handy PEA (Hansatech Instruments Ltd, UK).

2.3.2. *Canopy light interception/penetration assessments*

Canopy porosity was assessed after all treatments application (post BBCH83) with an SS1 SunScan Plant Canopy Analyzer (Delta-T Devices Ltd, Cambridge, UK) by assessing the fraction of above canopy photosynthetically active radiation (PAR) measured with a BF3 Sunshine sensor (Delta-T Devices, UK) and the PAR incident on the bunch zone and on the photosynthetically active part of the canopy. The SunScan probe was inserted horizontally inside the row allowing spatial evaluation of PAR inside the canopy (n=6 plants per treatment including three vines per three blocks). Canopy porosity was then calculated as the percentage of light penetrated inside the canopy to the total external PAR. Hemispherical photographs were collected in 2022 in a post-veraison period using a Nikon Coolpix 4500 digital camera, equipped with a Nikon FC-E8 fisheye converter (Nikon Corp., Tokyo, Japan). The photographs were taken facing upwards by keeping the lens horizontal. The camera body was oriented perpendicular to the row orientation. This setup provides a full-frame hemispherical picture. The maximum size of the images is 2272×1704 pixels. A professional tripod (190 Pro, Manfrotto, Italy) equipped with a 329RC4 3-way head (Manfrotto, Italy) was used to maintain the camera stable and at horizontal level during image acquisition. The resulting images gave a 180-degree view in all directions, with the zenith at the centre and the horizon at the edges of the photograph. Gap Light Analyzer 2.0 (GLA) (Frazer et al., 1999) was used to process the hemispherical pictures. The procedure began with the configuration, which included the definition of the latitude, and eventually slope and aspect of the site, number of angular sectors to divide the hemisphere, day or time interval for the calculations of the sun path, and transmitted radiation. We used 45 Zenith and 90 Azimuth regions to obtain 2×4° sky regions. The blue channel was used for all the image analyses performed. This channel is usually the best one to separate the canopy from the sky (Frazer et al., 1999; Nobis and Hunziker, 2005; Zorer et al., 2013, 2017). A threshold value was then set manually for the separation of canopy and sky elements, producing a binary black and white image, corresponding to pixels with no and 100% transmittance, respectively. For each sky sector, the percentage of canopy openness, transmitted direct, diffuse, and global radiation was calculated as a proxy of light microclimate on the bunch zone, as a result of canopy management. All calculations were performed for the same time interval specified in the configuration procedure.

2.3.3. *Canopy characteristics, estimated leaf area, vine balance and Ravaz index*

In Experiment 1 and 2, total leaf area was destructively estimated at harvest by counting the number of shoots per vine and total leaf weight. To obtain the total leaf area (m^2 $vine^{-1}$), the mean weight of known area (1 cm^2 for 20 leaves) was used to multiply by the total leaf weight. Subsequently, total leaf area was used to calculate the leaf-to-fruit ratio (m^2 kg^{-1}) based on yield data detailed in the section below (n=6-12). Point quadrat analysis was also performed to assess the number of leaf and leaf layers at bunch and canopy levels, as detailed by (Faralli et al., 2022). At the end of each season, pruning weight was carried out in n=6-12 vines per treatment and Ravaz index (kg kg^{-1}) was calculated as the ratio between fruit yield (as below) and pruning weight.

2.3.4. *Yield and yield components*

Prior to harvest, the number of shoots per vine, the number of bunches per vine and the average weight of the bunch (mean weight of 5 bunches per vine) were recorded for each treatment (n=20 vines per treatment). Vine yield was calculated as number of bunches multiplied by bunch weight.

2.3.5. *Berry juice analysis*

Harvest was carried out according to industrial dates for all experiments (20 September for Cabernet Franc and 13 September for Nermantis in Experiment 1 (2022) - 27 September for Cabernet Franc and 22 September for Nermantis in Experiment 2 (2023)). At harvest, the bunches (n=5 for each vine) for all the treatments were harvested, and assembled in n = 8 to 16 replicates per treatment (2022 and 2023 respectively), according to the experimental plan. Bunches were then crushed-destemmed and pressed with at the same pressure for each sample. Samples of fresh juice were then analysed for pH, total soluble solids (TSS - °Brix), titratable acidity (TA - g/L as tartaric acid), tartaric and malic acid concentration (g/L), and yeast available nitrogen (YAN) (mg/L) using a WineScan Fourier Transform Infrared (FTIR) spectrometer (FOSS, Hillerφd, Denmark).

2.3.6. *Anthocyanins and polyphenols analysis*

The extraction of the total anthocyanins and polyphenols of the peel was carried out using the method shown in Faralli et al. (2022) (n=8-16), while analysis of total anthocyanins and polyphenols was carried out via WineScan FTIR (FOSS, Hillerφd, Denmark). In addition, the skins of 20 per treatment bunches were also extracted with 250 mL of methanol overnight to determines the concentration of malvidin, delphinidin, cyanidin, petunidin and peonidin, and then the extract was filtered to remove solid parts and stored back at -20°C until the analyses following the method in Arapitsas et al. (2012). Analysis was performed using an Acquity UPLC system (Waters, Milford, MA, USA) coupled to a Xevo TQ MS system equipped with an electrospray (ESI) source (Waters). The column used was a reverse phase (RP) Acquity UPLC BEH C18 (1.7 μm, 2.1 × 150 mm, Waters), protected with an Acquity UPLC BEH C18 guard (1.7 μm, 2.1 × 5 mm, Waters), at 40 °C with a flow rate of 0.4 mL/min. 2 μL were injected by an auto-sampler at 6 °C. Purified water was used as solvent A and methanol as solvent B, both containing 5% (v/v) of formic acid. Anthocyanins for which standards were not available were quantified relative to the calibration curve constructed for malvidin 3-glucoside. Data processing was performed using the MassLynx 4.1 and Target Lynx software (Waters).

2.3.7. *Winemaking and chemical analysis*

For all treatments in 2022 and for ST-BZD73 and SB-ND in 2023 - contrasting canopy management as SGP vs NGP in 2022 - and on the same day the remaining grapes on each vine were harvested and blended. Grapes were transported to the winery. Winemaking was performed according to a previous protocol employed for the vinification (Roman et al., 2019). After crushing and destemming, grapes were added with potassium metabisulfite (40 mg/L) and inoculated with 200 mg/L of a commercial active dry yeast (Mosaic, Oenobrands, France) previously rehydrated in distilled water at 37°C for 30 min. 24 h after yeast inoculation, 10 mg/L of lactic acid bacteria were added to the fermenting media (PN4; Lallemand, France) along with nutrient supplementation (250 mg/L; Natuferm bright; Oenobrands, France). Maceration was managed for 7 days punching down the cap twice a day. Following fermentations, wines were supplemented with potassium metabisulfite (100 mg/L) and racked three times, prior to sensory analysis. Chemical analysis of wines is reported in Supplementary Tables 1 and 2.

2.3.8. *Wine volatile analysis: sample preparation, extraction and GC-MS/MS analysis*

Sample preparation and extraction of the free aroma compounds were performed according to the method described in Carlin et al. (2022). Solid-phase extraction was performed using Isolute® ENV+ (Biotage Biotage, Uppsala, Sweden) cartridges filled with 200 mg of stationary phase and pre-conditioned with 4 mL of dichloromethane, followed by 4 mL of methanol and 4 mL of model wine. A total of 50 mL of wine mixed with 100 mL of internal standard (n-heptanol 250 mg/L) was loaded onto the cartridge, which was then washed with 3 mL of water. The cartridges were dried for 10 min and eluted with 2 mL of dichloromethane directly into the injection vials. The Agilent Intuvo 9000 system for fast GC coupled with an Agilent 7010B triple quadrupole mass spectrometer (Agilent Technologies, Santa Clara, CA, USA) equipped with an electronic ionization source operating at 70 eV were used for the analysis. Separation was achieved by injecting 1 μL in split mode (1:10) into a DB-Wax Ultra Inert column (30 m × 0.25-mm id × 0.25-μm film thickness, Agilent Technology, Santa Clara, CA, USA). The GC oven's initial temperature was 40°C for 2 min, ramped up by 10°C/min to reach 55°C, then by 20°C/min until 165°C, by 40°C/min to 240°C for 1.5 min, and finally by 50°C/min to 250°C and kept at this temperature for an additional 4 min (16 total runtime). Helium was used as the carrier gas (with a flow of 1.2 mL/min). The mass spectra were acquired in multiple reaction monitoring modes. Nitrogen was used as the collision gas, with a flow of 1.5 mL/min, in addition to helium at 4.0 mL/min as the quench gas. The transfer line and source temperature were set at 250°C and 230°C, respectively. The data acquisition and subsequent quantification analyses were performed using the MassHunter Workstation software (Agilent Technologies, Santa Clara, CA, USA) as previously described in Carlin et al. (2022).

2.3.9. *Sensory evaluation*

2.3.9.1. Triangle test. Triangle tests (Amerine et al., 2013) were conducted to assess the impact of canopy management on the overall perception of wine odor and flavor. Two panels of semi-trained subjects (panel 2022: n = 56, female = 21.9%, mean age = 22.3 years old; panel 2023: n = 56, female = 22.6%; mean age = 21.1 years old) from the Viticulture and Enology Bachelor program at the University of Trento were involved. Red wine samples from 2 varieties (Cabernet Franc - CF; Nermantis - NER) and 2 canopy management (No green pruning – NGP; Severe green pruning - SGP) were assessed. Samples were served in 80 cc black plastic glasses covered with plastic lids and labelled by a 3-digit codes. A 20 mL portion of wine was served at 18°C ± 2°C for each evaluation sample. Four triangle tests were conducted in total: two for Cabernet Franc and two for Nermantis. Each variety was evaluated under two sensory modalities: odor (smelling) in the first two tests and flavour (tasting) in the latter two tests. The variety was counterbalanced over participants within evaluation modalities. For each triangle test, six triads (AAB, ABA, BAA, BBA, ABB and BAB) were counterbalanced over participants to ensure balanced comparison across canopy management conditions within each variety (CF-NSP vs. CF-SGP). For each triangle test, participants evaluated the samples from left to right and were instructed to indicate the sample that differed from the other two (forced choice). A 60-second pause between triads was observed to minimize sensory fatigue and restore perceptual ability.

2.3.9.2. Descriptive evaluation. A rapid descriptive test, adapted from the rate-all-that-apply (RATA) method (Ares et al., 2014), was conducted to assess the sensory properties of the samples obtained through the different canopy management applications. Subjects previously involved in the triangle tests were considered for the evaluation (panel 2023: n = 52; panel 2024: n = 49). Red wine samples from 2 varieties (CF, NER) and 3 canopy management (NGP; SGP; commercial control - CON) were considered. Samples were presented in 500 cc black glass glasses covered with plastic lids and identified by a 3-digit codes. A quantity of 35 mL served at 18°C ± 2°C was considered. The order of sample presentation was randomized for each judge. A 60-second pause was observed between samples to restore perceptual ability.

For each sample, subjects were first asked to smell the sample and describe the perceived odors, and then to taste and describe the perceived flavours. The descriptors referred to the wine odor and flavor wheel (Aromaster, 2010) as well as attributes of basic tastes and chemesthetic sensations (Supplementary Table 2). Judges had the option of selecting only the macro-category without being required to complete the selection of the subcategory descriptors or the single descriptors. Both macro-category and subcategory descriptors were presented in a fixed order across judges and followed the conventional graphic design of the wine sensory wheel. For the applicable descriptors, judges were then asked to evaluate their intensity on a linear scale (0 = "weak"; 50 = "moderate"; 100 = "strong"). For both methods, the evaluation was replicated for wine samples from 2022 and 2023 experiments. The triangle and descriptive tests were conducted in a 1-day session for each method in May 2023 (panel 2023) and May 2024 (panel 2024). All the sensory analyses were performed in a sensory laboratory equipped with individual booths under white light and compliant with EN ISO 8589:2010/A1:2014. Data were collected via EyeQuestion online software (www.eyequestion.com, Logic8, The Netherlands).

2.4. *Statistical analysis*

All the phenotypic and environmental data were analysed via Rstudio (R Core Team, 2024) by using either the stats, agricolae or ggplot2 packages. All traits were subjected to two-way ANOVA and one-way ANOVA depending on factor number. Association between traits was assessed via linear or segmented regression. All data were check for normality and equality of variance through visual assessment of distribution and residuals versus fitted values. Means separation ($p < 0.05$) was carried out via Tukey's test.

For each triangle test, the critical number of correct responses to reject H_0 at $\alpha = 0.05$ was obtained from the binomial distribution using guessing model (ISO 4120:2021 Sensory analysis — Methodology — Triangle test). The analysis was performed using EyeOpenR software Version 5.12.12. For the descriptive evaluation, the mean intensity of the attributes for the macro-categories and subcategories of odors and flavors (Supplementary Table 2) was obtained by averaging each judge's intensity scores for the attributes within each respective macro-category or subcategory. The averaged intensity scores were subjected to ANOVA (factor: canopy management). The retained descriptors (first attempt: p-value < 0.05; second attempt: p-value < 0.20) were subjected to principal component analysis (Meyners et al., 2016). The analysis included a bootstrapping procedure with resampling (n = 1000), considering virtual panels of 20 subjects and centering scores within subjects. The retained descriptors were also subjected to a Hotelling's T-squared test to assess the overall differences between the levels of the factor of interest (Le and Husson, 2008). The analyses were performed using

Jamovi software Version 2.4.1, SEDA module 1.2.0.

3. Results

3.1. Environmental conditions

In 2022, mean temperatures from June to September were in a range between 20 and 30°C with highest peaks around the end of July (DOY 200-205). This led to sharp increases in GDD10 and reference evapotranspiration during the summer period associated with minimal rainfall events (Fig. 1A–D). In 2023, two specific heatwaves events occurred around the end of June and the end of August, although overall mean temperature was slightly lower than in 2022 although with similar GDD10 accumulation at the end of the growing season. This was accompanied by a generalized lower evapotranspiration request and higher rainfall during the growing season (Fig. 1E–H).

3.2. Vine yield and balance

In 2022, no differences were observed between treatments in terms of mean bunch weight, number of shoots per plant, vine yield pruning weight and Ravaz index (Table 1, $p > 0.05$) and for both varieties. However, significant variation was observed for leaf area that was greater in NGP compared to control and in particular SGP for both Cabernet Franc and Nermantis ($p < 0.001$) from around 2 m^2 $plant^{-1}$ to up to 5 m^2 $plant^{-1}$. This led to a significant raise in the leaf-to-fruit ratio from 0.9 to 2-3 m^2 kg^{-1} in control and NGP vines, respectively ($p < 0.007$ and $p < 0.008$ for Cabernet Franc and Nermantis respectively; Table 1). Overall, significant differences were observed for mean bunch weight, yield and pruning weight between varieties with Cabernet Franc being more productive (mean bunch weight ~185 g) compared to Nermantis (mean bunch weight ~155 g; $p < 0.001$).

In 2023, similar trends were observed compared to 2022 with no differences between treatments for mean bunch weight, number of shoots per plant, vine yield and Ravaz index (Table 2, $p > 0.05$) and for both varieties while trimming was significant for pruning weight in Nermantis ($p = 0.035$, higher in SB than ST). The major effect on leaf area was associated with SB having more total leaf area ($p < 0.001$) and, hence, higher leaf-to-fruit ratio ($p<0.001$) in both the varieties. Overall, in 2023, Nermantis resulted in a slightly greater yield compared to Cabernet Franc ($p < 0.05$).

3.3. Leaf physiology and canopy light dynamics

In 2022, NGP vines resulted in higher leaves intercepted via point quadrat analysis when compared to Control and in particular SGP vines (Fig. 2A). A higher number of intercepted leaves were observed in the apical and central area of the canopy while a lower number was observed in the bunch zone, for both varieties ($p < 0.001$ both varieties). Cabernet Franc had a higher canopy thickness than Nermantis ($p < 0.05$). In 2023 (Fig. 2B), no effects from trimming were observed while significant effects were detected for position (low canopy thickness at bunch zone level, $p < 0.001$ for both the varieties) and for defoliation (greater canopy thickness in ND treatments at bunch-zone level, $p < 0.001$ for both varieties).

In 2022, SGP vine intercepted a higher degree of direct light ($p < 0.001$ and $p = 0.002$ for Nermantis and Cabernet Franc) when compared to control and NGP as well as diffuse light ($p < 0.001$) (Fig. 3A and C). This was associated with a general higher canopy porosity in SGP (around 50%) on the bunch zone and at canopy level that was significantly reduced (10 to 20%) in NGP treatments in both varieties ($p < 0.001$) (Fig. 3B and D).

In 2022, under hot summer conditions (around 36°C at 14:00) reduction in F_v/F_m was observed for SGP in Cabernet Franc as compared to NGP (Fig. 4A). This was not evident for Nermantis although the factor time was still significant (Fig. 4B, $p < 0.001$). Berry temperature in 2022 (Fig. 4C), was significantly reduced for NGP compared to SGP and control (South-exposed side of the rows) in both varieties ($p < 0.001$) and by up to 5°C. Dynamics of berry temperature in Cabernet Franc highlighted a significantly higher berry temperature in SGP than NGP since 10:00. Conversely, significant differences between Control and NGP were observed at 13-15:00 only (Fig. 4D).

3.4. Juice composition, anthocyanins and polyphenols

At maturity, in 2022, treatments had differential effects in terms of juice chemical composition. While in Cabernet Franc, NGP-treated vines showed higher °Brix and malic acid concentrations (by up to 20%) when compared to SGP-treated vines, in Nermantis, no significant differences were observed apart from lower pH and higher tartaric acid concentrations in SGP vines (Table 3). Overall Nermantis resulted in a lower °Brix and higher acidity than Cabernet Franc ($p < 0.001$).

In 2023, trimming had significant effects on °Brix for both varieties ($p < 0.001$ and $p = 0.002$ for Nermantis and Cabernet Franc, respectively) with a general increase by 1 °Brix on average for both varieties in

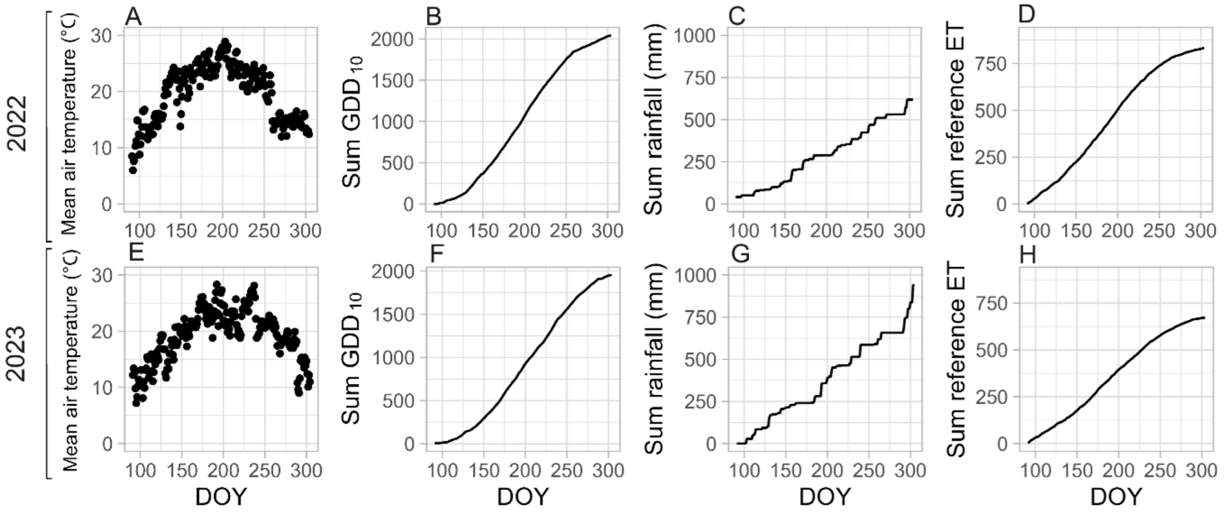

Fig. 1. Time course of daily mean air temperature (°C; A and E), cumulative growing degree days on base 10 (GDD10; B and F), cumulative rainfall (mm; C and G) and cumulative reference evapotranspiration (ET (mm); D and H) during 2022 and 2023. DOY represents the day of the year and covers the period between 1st of April and 31st October.

Table 1

Mean bunch weight, number of shoots per plant, vine yield, total leaf area at harvest, leaf-to-fruit ratio, pruning weight and Ravaz index for 2022 experiments (Cabernet Franc and Nermantis) and values are means ($n = 6$ to 45). Data were analyzed with one-way analysis of variance (ANOVA). The p-value is shown in the table while the p-value for variety comparison is shown in the text. In the table, Control is the trimmed and asymmetrically defoliated canopy treatment, SGP represents the severe green pruning (total bunch-zone defoliation at BBCH73 and shoot trimming) while NGP represents the no green pruning canopy ideotype (no defoliation and shoots were twisted around the upper wires and not trimmed).

Variety	Treatment	Mean bunch weight (g)	Number of shoots (plant $^{-1}$)	Yield (kg plant $^{-1}$)	Leaf area (m^2 plant^{-1})	Leaf-to-fruit ratio (m^2 kg^{-1})	Pruning weight (kg plant^{-1})	Ravaz index (kg/kg)
Cabernet Franc	Control	192.8	9.0	2.7	3.5	1.39	0.5	6.0
	SGP	174.3	9.0	2.5	2.1	0.87	0.5	5.0
	NGP	193.9	9.2	2.86	5.4	1.90	0.6	5.6
	p-value	*0.321*	*0.977*	*0.306*	*<0.001****	*0.007***	*0.442*	*0.485*
Nermantis	Control	149.2	8.6	2.1	2.4	1.5	0.2	9.6
	SGP	160.3	8.4	2.2	2.0	0.9	0.2	12.5
	NGP	148.6	9.6	2.1	5.3	3.5	0.3	9.3
	p-value	*0.681*	*0.102*	*0.901*	*<0.001****	*0.008***	*0.132*	*0.292*

Table 2

Mean bunch weight, number of shoots per plant, vine yield, total leaf area at harvest, leaf-to-fruit ratio, pruning weight and Ravaz index for 2023 experiments (Cabernet Franc and Nermantis) and values are means ($n = 6$ to 45 depending on the trait assessed). Data were analyzed with two-way analysis of variance (ANOVA) with two levels of shoot growth control (ST, shoot trimming/topping and SB, shoot bundling and twisting on the upper wire and not trimmed) and three levels of defoliation (ND, not defoliated, BZD73, bunch zone defoliation at BBCH73, BZD81, bunch zone defoliation at BBCH81). The p-value for each factor and their interaction are shown in the table while the p-value for variety comparison is shown in the text.

Variety	Control of shoot growth	Defoliation	Mean bunch weight (g)	Number of shoots (plant $^{-1}$)	Yield (kg plant $^{-1}$)	Leaf area (m^2 plant^{-1})	Leaf-to-fruit ratio (m^2 kg^{-1})	Pruning weight (kg plant^{-1})	Ravaz index (kg/kg)
Cabernet Franc	ST	ND	195.1	9.3	2.2	2.2	1.1	0.5	6.3
		BZD73	194.0	9.4	1.9	2.0	1.0	0.5	4.6
		BZD81	228.4	10.1	2.4	2.0	0.8	0.5	5.3
	SB	ND	243.7	10.4	2.8	5.6	2.2	0.5	5.4
		BZD73	214.8	9.2	2.3	4.9	2.1	0.6	5.2
		BZD81	221.0	9.1	2.2	5.4	3.0	0.8	3.2
		Trimming p-value	0.128	0.960	0.330	<0.001	<0.001	0.151268	0.513
		Defoliation p-value	0.435	0.719	0.464	0.152	0.672	0.457996	0.555
		T x D p value	0.240	0.301	0.448	0.467	0.318	0.610516	0.679
		ND	200.5	14.2	2.6	2.0	0.8	0.3	9.6
Nermantis	ST	BZD73	210.3	13.0	2.8	1.9	0.7	0.2	11.2
		BZD81	199.5	13.6	2.8	2.0	0.7	0.4	8.2
		ND	214.1	13.8	3.2	5.6	1.6	0.6	7.4
	SB	BZD73	218.4	15.0	2.9	4.9	1.6	0.4	7.3
		BZD81	186.9	13.2	2.6	5.1	2.1	0.4	7.7
		Trimming p-value	0.786	0.623	0.581	<0.001	<0.001	0.035	0.118
		Defoliation p-value	0.299	0.290	0.802	0.494	0.401	0.496	0.744
		T x D p value	0.599	0.782	0.384	0.710	0.369	0.365	0.592

SB vines (Table 4). Similarly, trimming influenced titratable acidity, with an overall increase on SB vines in Cabernet Franc, while ND showed higher titratable acidity compared to BZD73 and 81 for both varieties. This was mainly associated to a maintenance in malic acid concentration for SB and ND (trimming and defoliation $p < 0.001$) in Cabernet Franc, while in Nermantis, defoliation only resulted in a significant effect ($p < 0.001$). Overall, Nermantis resulted in a lower °Brix and higher acidity than Cabernet Franc ($p < 0.001$).

Significant differences were observed between varieties, with Nermantis possessing higher skin anthocyanin concentration than Cabernet Franc (2500 mg kg^{-1} vs 500 mg kg^{-1} on average, respectively). Reducing canopy porosity (NGP) equated to greater total anthocyanins concentration compared to SGP in both varieties in 2022 (Fig. 5A, $p = 0.011$ and $p < 0.001$ for Cabernet Franc and Nermantis). This was mainly associated with a higher total malvidin while most of the other anthocyanins were found unaffected (Supplementary Fig. 1). On the contrary, total polyphenols did not change in Cabernet Franc, while a reduction was observed for SGP vines in Nermantis compared to control vines. In 2023, SB increased anthocyanin concentration in both varieties compared to ST ($p = 0.003$ and $p = 0.002$ in Cabernet Franc and Nermantis), while no significant effects were observed for Defoliation treatments (Fig. 5B). Total skin polyphenols were higher in SB ($p < 0.001$) for both varieties and compared to ST, while defoliation was significant for Cabernet Franc only with a reduction in skin polyphenols in ND vines compared to BZD73 ($p = 0.002$).

3.5. *Wine aromatic profile and sensory analysis*

Aromatic profile and wine composition significantly differ between varieties, as expected (Fig. 6A and F, Supplementary Table 1). While minimal differences were observed between treatments for wine composition (Supplementary Table 1) significant effects were recorded on aroma compounds concentrations with specific clusters present between treatments (Fig. 6A and F). For instance, in Cabernet franc, TDN,

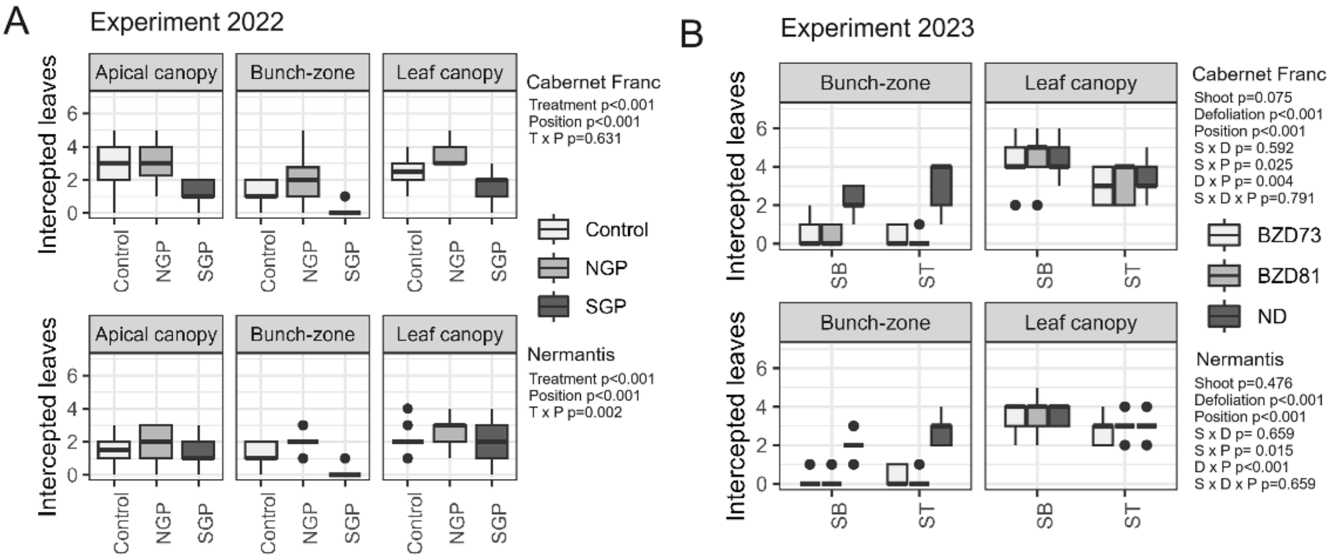

Fig. 2. Analysis of canopy width dynamics. In A and B (2022 and 23, respectively) point quadrat analysis was carried out to assess the number of leaves intercepted in three (2022, apical, bunch-zone, mid-leaf canopy) and two (2023, bunch-zone, mid-leaf canopy) canopy areas. In A, data were analysed with two-way ANOVA with treatment (canopy) and position as factors (n = 18). In B, data were analysed with three-way ANOVA with shoot control, defoliation and position as factors (n = 10).

safranal and α-terpineol (Fig. 6B–D) were reduced in the NGP treatment ($p < 0.1$ - $p < 0.05$). On the contrary, methyl salicylate were significantly higher in the NGP treatment compared to Control and SGP ($p < 0.001$). Similarly, in Nermantis specific trends in reducing aroma compounds concentrations were observed in NGP treatment compared to Control and, in particular, SGP ($p < 0.05$, Fig. 6G–J).

The results of the triangle test indicate an effect of canopy management treatments in Cabernet Franc at the sensory profile level. Significant differences in smell in the 2022 experiment and in flavor in the 2023 experiment were observed, while no significant differences were found in Nermantis (Table 5). Considering both experiments and varieties, there were no significant differences between the olfactory and the flavor level (44.6% vs. 37.9%; p-value = 0.15).

A selection of sensory descriptors were used with a p-value threshold of <0.05 from ANOVA (factor: canopy management). Only 3 descriptors were retained in the 2022 experiment (o-Vegetal, o-Floral, Sweet) and 2 in the 2023 experiment (o-Fruity, Sparkling). Based on the significant descriptors, Hotelling's test revealed a significant difference between the samples treated with SGP or NGP in the 2022 experiment ($p = 0.008$) but not in the 2023 experiment ($p = 0.08$). Overall, the results of the descriptive evaluation align with those of the discrimination test, indicating that the differences in the sensory profile between canopy management techniques are primarily associated with the olfactory component. The resulting perceptual map (Fig. 7) shows that in both experiments, the SGP condition was positively associated with fruity odor and negatively to vegetal odor, while the NGP condition was positively associated with vegetal odor and negatively to fruity odor. Based on the selected descriptors, Hotelling's test revealed a significant difference between the samples treated with SGP or NGP in both the 2022 experiment ($p = 0.005$) and 2023 experiment ($p = 0.006$).

4. Discussion

4.1. Reducing canopy porosity affects canopy light environment, leaf physiology, and bunch microclimate

Trade-offs between berry quality, disease incidence and environmental pressure are determinants of grapevine canopy management choices. In our experiments, no observations of cluster rot or differences in pathogens incidence were recorded (data not shown) between treatments, suggesting that, at the given environmental conditions of 2022 and 2023 and owing to the successful farm pest management control, bunch-zone defoliation was a not critical operation for optimizing plant protection. In our work, minimizing canopy management intervention (NGP or SB-ND) provided several desirable effects in a context of multiple summer stress conditions compared to control (Control or ST-BZD73 or 81), in particular: 1) reducing canopy-to-bunch-zone light penetration via increasing canopy thickness; 2) reducing leaf overexposure via potential synergistic effects between microclimatic conditions (low direct light and high humidity); 3) limiting cluster over-exposure via a lower canopy porosity. The effect of thick canopies on leaf physiology (in our case the quantum yield of photosystem II – F_v/F_m) under multiple summer stresses was already observed, and putatively associated with modifications in localized leaf vapor pressure deficit (VPD) and radiation levels (as well as their interactive effects; Faralli et al., 2022; Hunter et al., 2020). We confirmed that under high temperatures, the leaf quantum yield of PSII is maintained in thick, less summer-pruned canopies. Assuming berry temperature as a key driving factor in the fine-tuning of berry composition (Hunter et al., 2021; Hunter et al., 2017), passive (diffusive) and active (direct) sunlight bunch interception is critical in shaping wine style and typicity. For instance, Hunter et al. (2021), in a work on vine row orientation, provided quantitative evidence of a detrimental effect of excessive direct sunlight on anthocyanins, titratable acidity and sugar accumulation (faster). In our study, avoiding bunch-zone leaf removal led to a general maintenance of up to two leaves at bunch-zone level that equated to a drop in canopy porosity from 75 to 25% on average. This paralleled a similar drop in direct light (active) intercepted by the bunch for both varieties and a subsequent reduction in berry temperature (up to 5°C on warm days). This was indeed achieved by maintaining leaf area on the bunch-zone but also followed by shoot bundling in which no trimming was applied, thus providing additional shading area on the top of the training system. Considering summer pruning as a cost-intensive operation and assuming the complex dynamics that govern bud differentiation (Lopes et al., 2020) and shoot morphogenesis (Hunter et al., 2021), mainly driven by light quality and temperature within the canopy between anthesis and veraison, multiannual works are required to refine these potential applications.

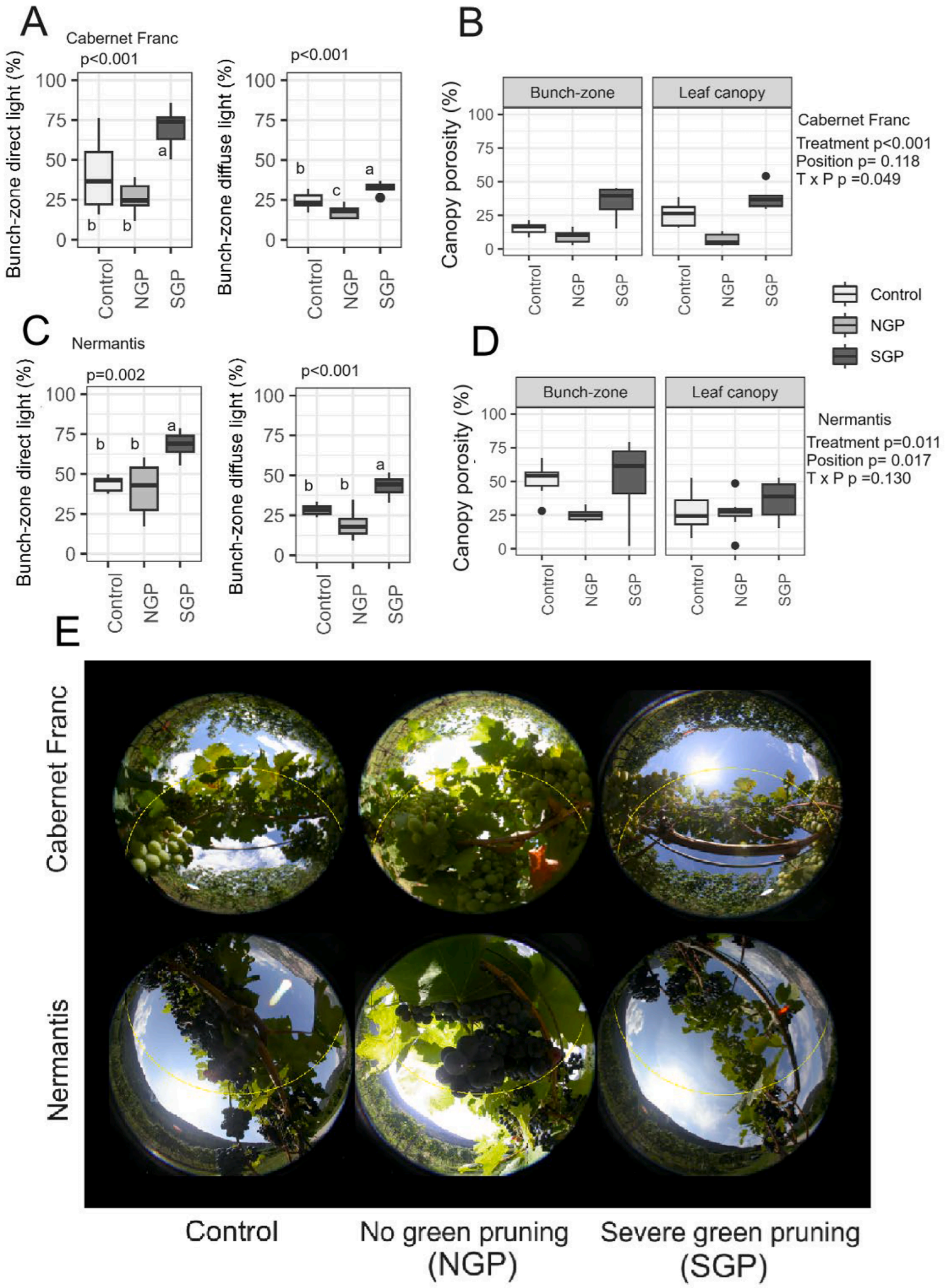

Fig. 3. In A and C, bunch-zone direct and diffuse light estimated with hemispherical images are shown for each experiment and treatment. Data were analysed with one-way ANOVA. In B and D, canopy porosity for bunch zone and leaf canopy are shown for the two experiments (Cabernet Franc and Nermantis), data were analysed with two-way ANOVA with treatment (canopy) and position as factors (n = 8). In E, example of hemispherical pictures taken just below the fruiting cane, for Control, NGP and SGP in both the experiments in 2022. The yellow line represents the sun path for the specific day of image collection.

4.2. Bunch microclimate is key to couple sugar accumulation and malic acid degradation assuming a given pre-veraison pool while synchronization of phenolic ripening has multiple, putatively synergistic, determinants

The necessary re-evaluation of canopy management in the context of climate change has been recently reviewed (Poni et al., 2023). Upon several possible operations, shoot positioning, trimming and leaf removal may be flexibly targeted to drive ripening toward specific oenological aims and to create an optimal bunch microclimate post-veraison. For both the years and for both the varieties, the higher leaf-to-fruit ratio equated to higher °Brix compared to low leaf-to-fruit ratio treatments. This trend was expected due to the higher availability of assimilates - mainly photosynthetically active area - throughout the growing season of NGP and ST-BZD73 or 81 treatments and majorly associated with trimming factor in 2023. This however was accompanied by higher titratable acidity, particularly driven by a generally higher maintenance of malic acid. This dynamic was evident in 2022 and in 2023, with both trimming and defoliation resulting significant ($p<0.001$). Assuming an insensitivity of tartaric acid to environmental changes, apart from dilution/concentration dynamics following changes in berry water content (Pérez-Álvarez et al., 2021), malic acid degradation in berries starts post-veraison and continues up until harvest. Higher berry temperatures are often associated with faster malic acid degradation, malate being a substrate for berry respiration: a process that increases juice pH at harvest and reduces titratable acidity. We confirm that maintaining leaf area at the bunch level increases malic

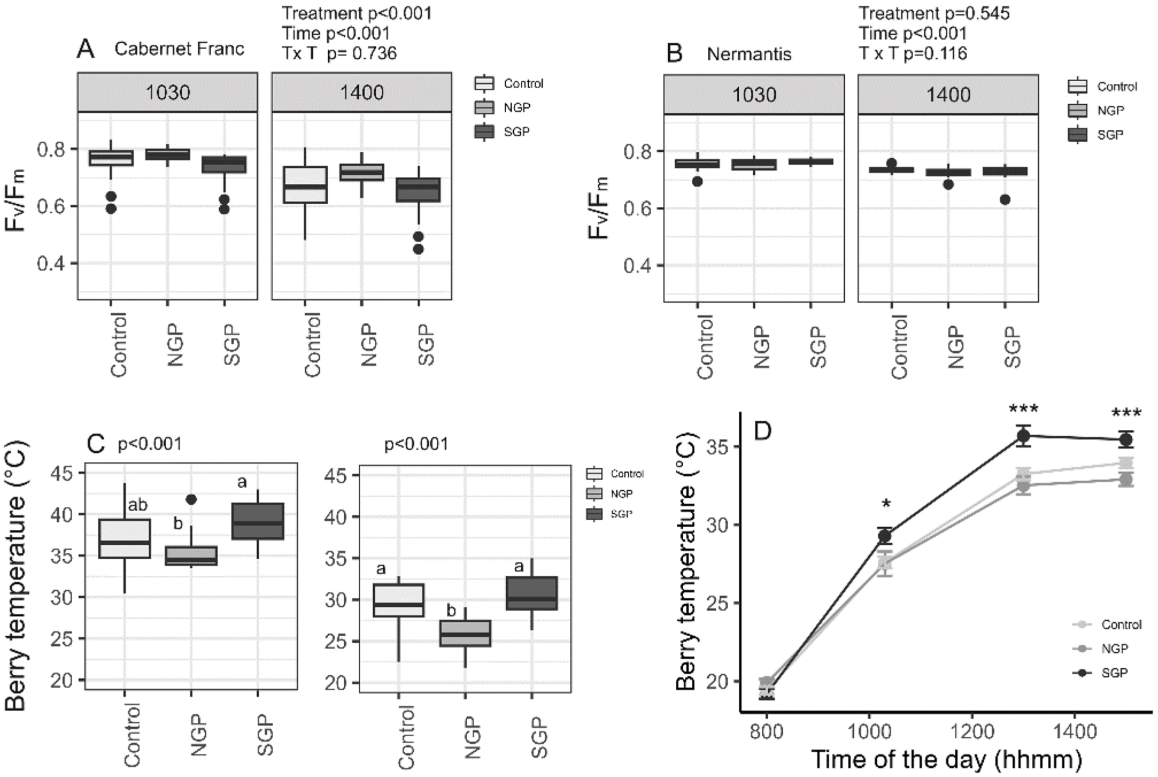

Fig. 4. A and B) Quantum yield of photosystem II in dark-adapted leaves collected on the most sun-exposed side of the row and collected at 10:30 or 14:00. Data are from 2022 (n=20) and for Cabernet Franc (A, 28th August 2022) and Nermantis (B, 30th August 2022). Data were analysed with two-way ANOVA with treatment (canopy) and position as factors and p-values are shown in the graph. C) Berry temperature post-veraison at midday ($n = 30$) for Cabernet Franc (left) and Nermantis (right). Data are from 2022 ($n = 30$) and for Cabernet Franc (28th August 2022) and Nermantis (30th August 2022). Data were analysed with one-way ANOVA, p-values are shown in the graph, and different letters indicate significant differences between treatments according to Tukey's test. In D, the dynamic of berry temperature is shown for Cabernet Franc. Data were analysed with one-way ANOVA ($n = 30$) and asterisks represent significant variation between treatments (* $p < 0.05$, *** $p < 0.001$). Data are means ± standard error of the mean (SEM).

Table 3
Total soluble solids (°Brix), pH, titratable acidity, malic acid, tartaric acid and potassium concentration in juice for 2022 experiments (Cabernet Franc and Nermantis). Values are means ($n = 8$-12). Data were analysed with one-way analysis of variance (ANOVA). The p-value is shown in the table while the p-value for variety comparison is shown in the text. In the table, Control is the trimmed and asymmetrically defoliated canopy treatment, SGP represents the severe green pruning (total bunch-zone defoliation at BBCH73 and shoot trimming) while NGP represents the no green pruning canopy ideotype (no defoliation and shoots were twisted around the upper wires and not trimmed).

Variety	Treatment	°Brix	pH	Titratable acidity (g L^{-1})	Malic acid (g L^{-1})	Tartaric acid (g L^{-1})	Potassium (g L^{-1})
Cabernet Franc	Control	25.8	3.5	3.4	1.0	6.4	1.8
	SGP	24.7	3.5	3.5	0.8	6.4	1.7
	NGP	25.8	3.5	3.3	1.0	6.4	1.8
	p-value	0.001	0.988	0.542	0.007	0.989	0.026
Nermantis	Control	22.5	3.4	5.0	2.3	6.3	1.6
	SGP	21.9	3.3	5.3	2.3	6.5	1.5
	NGP	21.8	3.4	5.1	2.4	6.1	1.6
	p-value	0.263	0.033	0.08	0.512	0.001	0.043

acid at harvest (and titratable acidity), although trimming was also significant for Cabernet franc, suggesting the potential microclimatic effect of shoot bundling at bunch level.

Overall, maintaining canopy density led to a ripening shift in which °Brix and acidity were higher at the technological maturity in the control. While this may be counterintuitive in the context of the postponing ripening techniques (for instance, ripening shifted toward a cooler period via delaying ripening approaches), our data suggests that these options may indeed lead to early harvest, yet with significantly higher acidity level in the juice. In essence, conservative canopy management may be a non-mutually exclusive approach to a delaying ripening program to expand the time frame of harvest period in large-scale vineyards. Similarly, berry anthocyanin concentrations were overall higher in conservative treatments (NGP and SB-ND) compared to heavily pruned vines. As for malic acid, phenolic maturity is somehow affected by berry microclimate as i) mean berry temperature above 35°C can significantly reduce anthocyanins biosynthesis (Mori et al., 2007), although ii) nighttime temperature being a major variable in defining the total concentration at harvest. Conversely, long-lasting evidence suggests leaf-to-fruit ratio as a major driver of phenolic accumulation in grapevine, mainly as a result of bunch thinning experiments. Indeed, a recent review confirmed the centrality of an increased leaf-to-fruit ratio

Table 4

Total soluble solids (°Brix), pH, titratable acidity, malic acid, tartaric acid and potassium concentration in juice for 2022 experiments (Cabernet Franc and Nermantis). Values are means (n = 6). Data were analyzed with two-way analysis of variance (ANOVA) with two levels of shoot growth control (ST, shoot trimming/topping and SB, shoot bundling and twisting on the upper wire and not trimmed) and three levels of defoliation (ND, not defoliated, BZD73, bunch zone defoliation at BBCH73, BZD81, bunch zone defoliation at BBCH81). The p-value for each factor and their interaction are shown in the table while the p-value for variety comparison is shown in the text.

Variety	Control of shoot growth	Defoliation	°Brix	pH	Titratable acidity (g L^{-1})	Malic acid (g L^{-1})	Tartaric acid (g L^{-1})	Potassium (g L^{-1})
Cabernet Franc	ST	ND	23.2	3.6	4.0	1.3	7.0	2.1
		BZD73	23.4	3.5	3.8	1.1	6.7	1.9
		BZD81	24.0	3.6	3.9	1.2	6.8	2.0
	SB	ND	24.7	3.5	4.3	1.6	6.7	2.0
		BZD73	24.3	3.5	4.0	1.2	6.8	1.9
		BZD81	24.6	3.5	4.0	1.3	6.9	2.0
		Trimming p value	0.000	0.053	0.000	0.001	0.462	0.628
		Defoliation p value	0.218	0.041	0.000	0.000	0.445	0.027
		T x D p value	0.256	0.417	0.701	0.166	0.067	0.532
Nermantis	ST	ND	22.1	3.3	6.7	3.2	7.2	1.8
		BZD73	22.5	3.3	6.3	2.8	7.1	1.7
		BZD81	22.4	3.3	6.3	3.2	6.8	1.8
	SB	ND	23.2	3.3	6.6	3.3	6.8	1.8
		BZD73	23.5	3.3	6.1	2.8	6.8	1.8
		BZD81	23.3	3.4	6.4	2.9	7.1	1.9
		Trimming p value	0.002	0.210	0.713	0.764	0.276	0.001
		Defoliation p value	0.603	0.123	0.002	0.001	0.781	0.101
		T x D p value	0.945	0.024	0.716	0.122	0.052	0.147

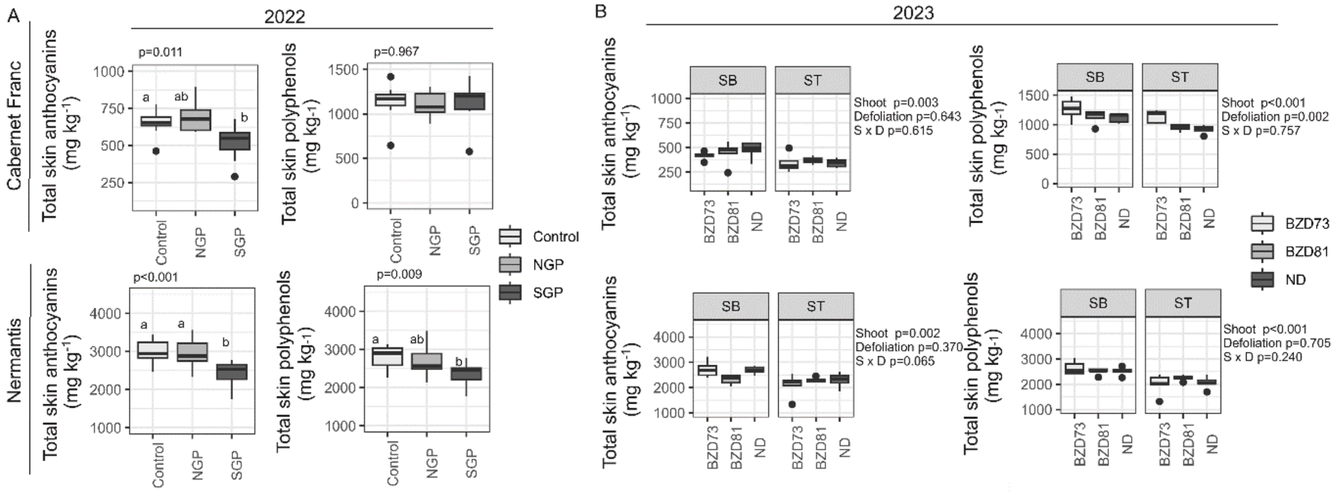

Fig. 5. Total skin anthocyanins and polyphenols at harvest for Cabernet Franc and Nermantis and from experiments 2022 and 2023 (n=6-12). In A (2022) data were analyzed with one-way analysis of variance (ANOVA) and p-value is shown for each trait assessed. When present, different letters indicate significant differences between treatments according to Tukey's test. In B (2023), data were analyzed with two-way analysis of variance (ANOVA) with two levels of shoot growth control (ST, shoot trimming/topping and SB, shoot bundling and twisting on the upper wire and not trimmed) and three levels of defoliation (ND, not defoliated, BZD73, bunch zone defoliation at BBCH73, BZD81, bunch zone defoliation at BBCH81).

on phenolic maturity, with anthocyanins being responsive to reducing bunch number per vine (in this case driven by bunch thinning; VanderWeide et al., 2024). Our data suggest probable complementarity of the two dynamics, in particular: 1) in 2022, microclimate was a major influence on phenolic maturity, as anthocyanin biosynthesis in the SGP treatment was hampered by dry and hot conditions; 2) in 2023, relatively cooler and wetter than 2022, slightly sub-optimal temperature reduced the mean anthocyanins concentration compared to 2022 for both varieties and therefore the higher leaf-to-fruit ratio putatively guided the increased anthocyanins concentration in SB-ND treatments, with minimal effects from bunch microclimate conditions. This trend was particularly significant and important for Cabernet franc, a variety possessing limited capacity of anthocyanin accumulation (between 400 and 700 mg kg^{-1}) while Nermantis showed a unique color potential (up to 3000 mg kg^{-1}). Our work provides evidence of a potential compensatory effect of the bunch-zone to shoot-positioning/trimming choice that should be explored with additional experimental work.

4.3. Conservative pruning influences some volatile compounds but does not significantly affect the sensory profile of the wines at the given environmental conditions

The data on volatile compounds indicate that canopy management treatments lead to certain modifications. It was observed that in both Cabernet and Nermantis wines, the SGP treatment, associated with increased light exposure, induced a higher production of norisoprenoids. This effect has been previously reported in various studies (Ghiglieno et al., 2023; Marais et al., 2017; Pons et al., 2017) and it was attributed to the production of carotenoids, which have a photoprotective function (Joubert et al., 2016). Nermantis, in particular, showed notable

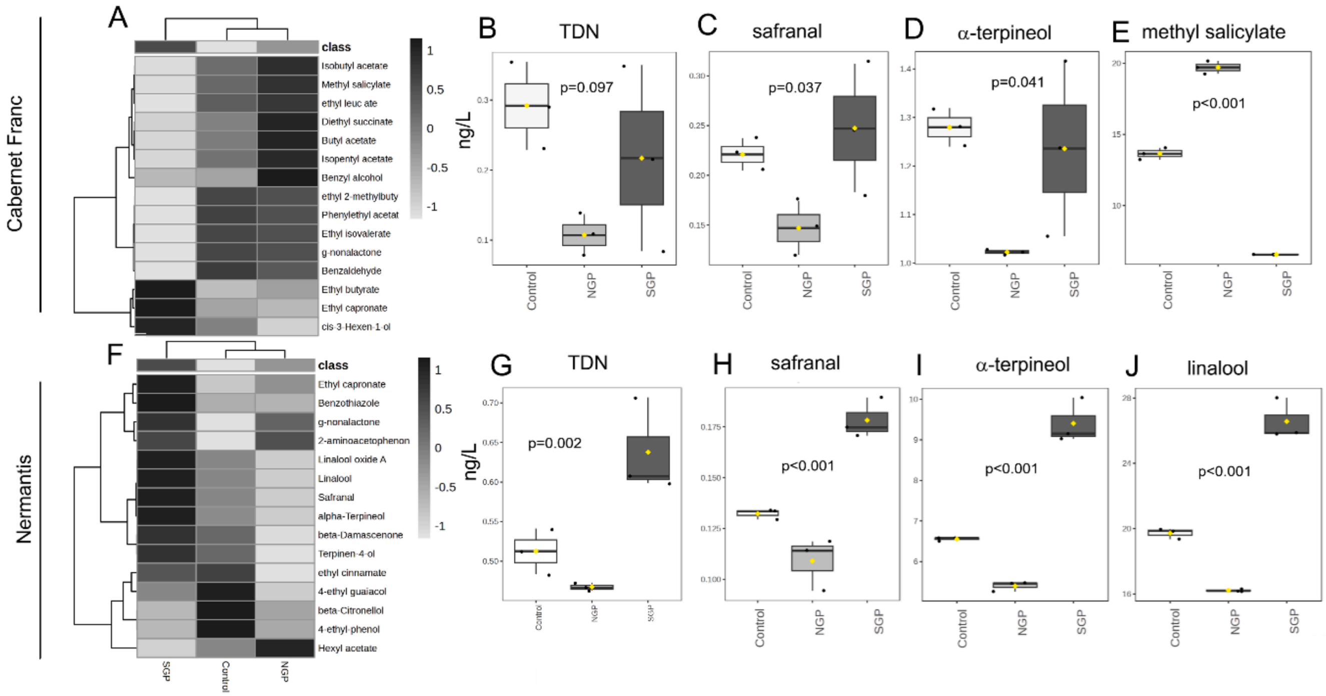

Fig. 6. Heat map for Cabernet Franc and Nermantis (A and F, respectively) showing significant differences in the wine aromatic profile. Boxes represent normalized values (1 to -1) and compared to the mean. Control is the trimmed and asymmetrically defoliated canopy treatment, SGP represents the severe green pruning (total bunch-zone defoliation at BBCH73 and shoot trimming) while NGP represents the no green pruning canopy ideotype (no defoliation and shoots were twisted around the upper wires and not trimmed). In B,C,D and E (Cabernet franc) and G, H, I, and J (Nermantis) specific differences between treatments are shown and for 1,1,6-trimethyl-1,2-dihydronaphtalene (TDN), safranal, alfa-terpineol and methyl salicylate. Data were analyzed with one-way analysis of variance (ANOVA) and p-value is shown for each trait assessed.

Table 5
Sensory triangle test correct responses and p-value on samples from 2022 (A) and 2023 (B) experiments. CF: Cabernet Franc; NER: Nermantis; NGP: No green pruning; SGP: Severe green pruning; vs: in comparison with. Bold numbers indicate samples statistically different at $p < 0.05$.

A

Sensory modality	Sample A	*vs*	Sample B	% Correct identification	p-value
Smell	CF - SGP		CF - NGP	53.5	0.002
Smell	NER - SGP		NER - NGP	41.1	0.139
Flavor	CF - SGP		CF - NGP	35.7	0.360
Flavor	NER - SGP		NER - NGP	30.3	0.727

B

Sensory modality	Sample A	*vs*	Sample B	% Correct identification	p-value
Smell	CF - SGP		CF - NGP	41.1	0.139
Smell	NER - SGP		NER - NGP	42.8	0.087
Flavor	CF - SGP		CF - NGP	46.4	0.028
Flavor	NER - SGP		NER - NGP	39.3	0.209

concentrations of monoterpenes such as linalool and α-terpineol, especially in the treatments with higher light exposure. The amount of linalool in the SGP treatment approached the sensory threshold and could contribute to the floral notes of the wine. Of interest is the potential rearrangement of linalool during aging, which could result in the formation of 1,8-cineole, imparting balsamic notes at very low concentrations (2 μg/L) (Arapitsas et al., 2024; Poitou et al., 2017). Both Cabernet and Nermantis wines showed higher concentrations of ethyl esters in the more defoliated treatments. These esters may contribute to the fruity aroma of the wines. The elevated levels of ethyl esters could be explained by a greater level of direct cumulative radiation of the grapes at harvest.

However, no major differences on the sensory properties of Nermantis were found while limited differences on Cabernet Franc were observed, suggesting that the impact of canopy management may be dependent on the grapevine variety. The effects of leaf removal on the sensory properties of samples exhibited trends consistent with previous studies conducted on other grapevine varieties (Sauvignon Blanc), including a higher intensity in fruity notes and lower intensity of vegetal notes (Šuklje et al., 2014; Coniberti et al., 2013; Arnold and Bledsoe, 1990). The sensory differentiation between severe green pruning and no green pruning conditions could be due to the higher concentrations of ethyl esters such as butyrate, pentanoate, hexanoate, octanoate and decanoate that could impart fruity notes.

Although canopy management and pruning techniques influence various physiological and chemical aspects of the grapevine, the sensory characteristics of the wines appeared to be only marginally affected by the application of conservative summer pruning. This suggests that, under the specific environmental conditions of the study, this approach may not substantially alter the flavour and taste qualities of the wines, making it a viable practice for maintaining grapevine physiological fitness and yield without compromising wine sensory quality. However, it is important to consider that the effects of pruning might vary under different environmental and climatic conditions, and future research may be necessary to fully understand its long-term impact on wine sensory attributes.

4.4. *Pathogen-resistant varieties as the future candidate for canopy management flexibility*

In our experiments no specific incidence of pathogens and bunch rot were observed (data not shown) in both Cabernet Franc (*Vitis vinifera*) and Nermantis (pathogen-resistant variety), potentially due to the

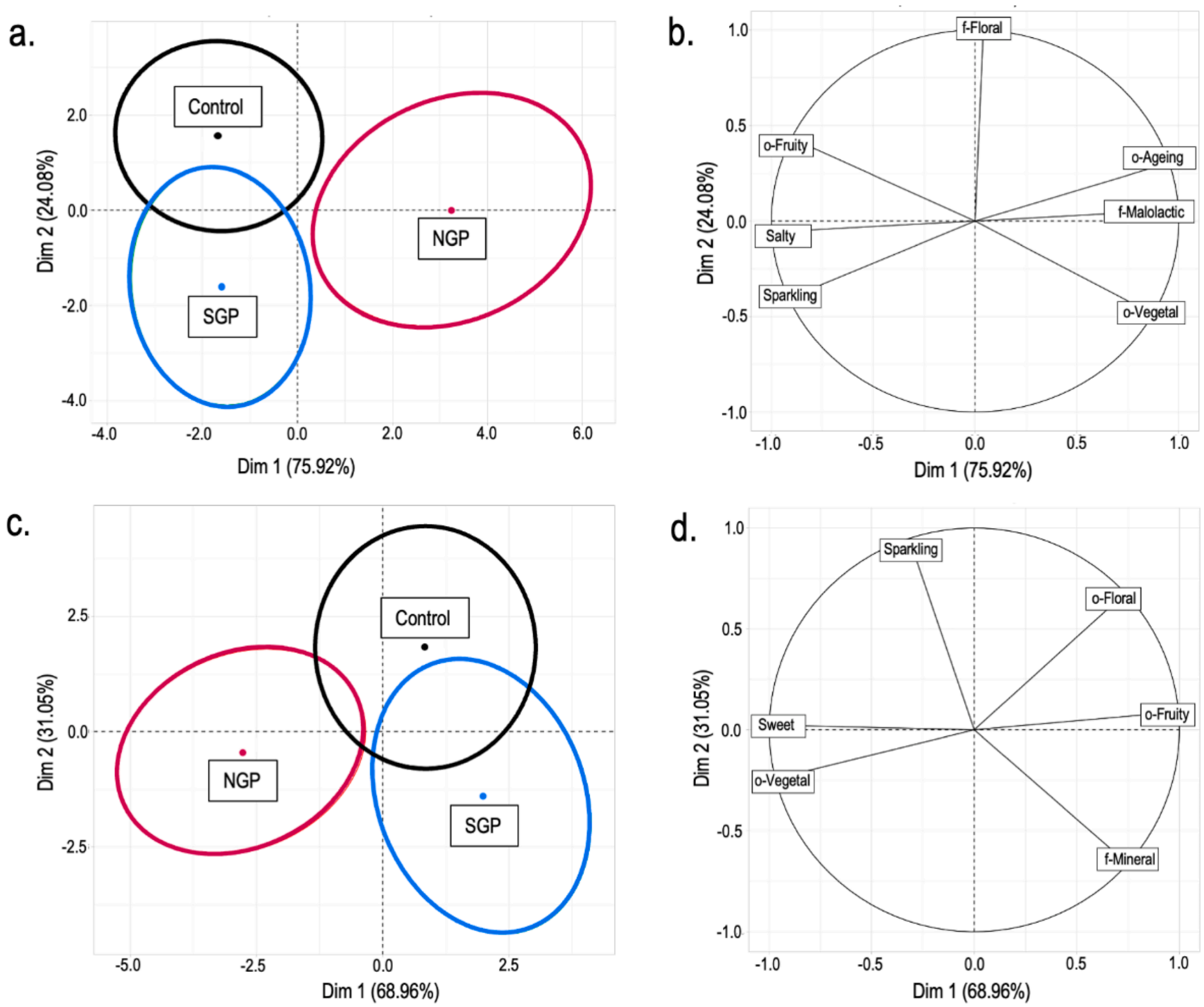

Fig. 7. Score plots (A, C) and correlation loading plots (B, D) from PCA with resampling, based on RATA attributes of wine samples subjected to Severe Green Pruning (SGP), No Green Pruning (NGP), and commercial (Control) canopy management. Samples from the harvest 2022 (above) and 2023 (below).

optimal plant protection scheme applied by the farm. However, it is indeed important to indicate the centrality of canopy management (bunch-zone defoliation and low density canopies) in vineyard crop protection, especially in cool and humid areas, where treatment penetration and bunch ventilation as well as high intercepted radiation is critical in the context of pathogens control (Hall et al., 2018; Austin and Wilcox, 2012). While the plasticity of some interventions such as defoliation does provide significant flexibility to the viticulturists, the environmental unpredictability makes such choices complex. The development of pathogen-resistant varieties is gradually providing viticulturists with hybrids possessing novel levels of tolerance to downy and powdery mildew and reasonable oenological interest. Some studies have already observed interesting traits of adaptation to disadvantageous conditions in some hybrids, including limited water availability and high temperature (Calderan et al., 2023; Poni et al., 2017). Due to their inherently higher tolerance to fungal pathogen (in particular to downy and powdery mildew), the "crop protection" purpose of canopy intervention toward a thin, more ventilated canopy may, at least for the pathogens mentioned above, cease. As today and to our knowledge, this is the first report of differential canopy management in a pathogen-resistant variety that may open novel avenues for hypothesizing a harmonized summer pruning scheme in which bunch protection from multiple summer stresses, optimal microclimate for ripening and crop protection may coexist. In the near future, studies are anyway required to confirm these findings in different pathogen-resistant varieties and different viticultural basin.

5. Conclusions

This work provides evidence of the potential usefulness of reducing summer pruning interventions, as previously hypothesized (Poni et al., 2023; Faralli et al., 2022). While leaf physiology (lower photoinhibition) and berry chemical parameters (more synchronous sugar accumulation-to-acidity breakdown dynamics, higher anthocyanins concentration) were significantly modulated by canopy management, only minimal effects on olfactory sensorial properties were observed in wine. The aroma profile of the wines suggests that sub-optimal environmental conditions were present for fully exploiting the aroma profile for the varieties tested and therefore only under specific circumstances such as very dry and hit years, these approaches should be applied. However, the overall warming is already threatening wine typicity in several traditional winemaking areas (Faralli et al., 2024; Gambetta and Kurtural, 2021; Van Leeuwen et al., 2019; Jones et al., 2005), and thicker, less defoliated canopies may already be applied in warm areas, and in the near future, for cooler viticultural areas. While the crop protection-bunch protection trade-off may be still a problematic decision in *Vitis vinifera*, pathogen resistant varieties may overcome this issue and providing an additional source of possibilities to reduce the impact of climate change on viticulture via conservative canopy management. The varietal differences observed in this study, with Cabernet Franc exhibiting greater responsiveness compared to Nermantis, highlight the need to investigate these approaches across a broader range of cultivars and pedoclimatic conditions. Extensive research is required to better characterize the preferential effects under dry and hot environmental conditions of the conservative summer pruning approach.

Supplementary descriptions

Supplementary Fig. 1. Concentration of anthocyanins at harvest for Cabernet Franc and Nermantis in 2022 (n=6). Data were analyzed with one-way analysis of variance (ANOVA) and p-value is shown for each trait assessed. When present, different letters indicate significant differences between treatments according to Tukey's test. Control is the trimmed and asymmetrically defoliated canopy treatment, SGP represents the severe green pruning (total bunch-zone defoliation at BBCH73 and shoot trimming) while NGP represents the no green pruning canopy ideotype (no defoliation and shoots were twisted around the upper wires and not trimmed). In the boxplot, horizontal lines within boxes indicate the median, and boxes indicate the upper (75%) and lower (25%) quartiles. Whiskers indicate the ranges of the minimum and maximum values.

Supplementary Table 1. Wine composition recorded for the 2022–2023 vintages from Cabernet Franc and Nermantis vines subjected to different canopy management approaches.

Supplementary Table 2. List of attributes employed in the rate-all-that-apply (RATA) question assessment of red wine samples.

CRediT authorship contribution statement

Michele Faralli: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Danny Cliceri:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Roberto Zanzotti:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Roberto Zorer:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Data curation. **Marco Stefanini:** Resources, Methodology, Funding acquisition, Conceptualization. **Andrea Angeli:** Supervision, Methodology, Investigation. **Stefano Zanoni:** Writing – review & editing, Validation, Investigation, Data curation. **Urska Vrhovsek:** Resources, Methodology, Funding acquisition, Formal analysis, Data curation. **Tomas Roman:** Writing – review & editing, Validation, Methodology, Investigation. **Flavia Gasperi:** Writing – review & editing, Validation, Methodology, Investigation, Funding acquisition, Conceptualization. **Silvia Carlin:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Massimo Bertamini:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Michele Faralli reports administrative support was provided by University of Trento. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Elena Santoro for organising and preparing all the samples for the sensory evaluation, as well as the bachelor students that participated at the two panels and the ones that helped in the sample preparation.

We also thank Giulia Betta and Cinzia Dorigatti for their help throughout all harvest period in bunch ripening analysis.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scienta.2025.114196.

Data availability

Data will be made available on request.

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