Reducing the source/sink ratio of grapevine to face global warming in a semi-arid climate: Effects on volatile composition of Cabernet Sauvignon grapes and wines

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1. Introduction

The volatile compounds in wines play an essential role in affecting their sensory profiles. Various volatile compounds in grapes and wines have complex changes during berries development and wine fermentation, which draw an extensive interest and attention of researchers. To improve the grape-derived aromas and wine aroma attributes through viticultural techniques is also the focus of many recent studies. In general, grape-derived compounds include norisoprenoids, terpenes, C6/C9 volatiles but also in wines. Moderate cluster exposure brought by distal leaf removal was beneficial for the accumulation of isoprenoids, which therefore increased the fruity and floral intensity of wines. The carry-over effect did not show in consecutively defoliated vines among vintages regarding the wine aroma profile.

2. Methods

2.1. Plant material

The heterogeneity of the vineyard environment caused high variability in grape metabolites and flavor profiles, and the phenomenon was more prominent in recent years of climate change. Herein, distal leaf removal was applied in semi-arid Xinjiang to adjust the source to sink ratio of grapevines for three consecutive years (2018–2020). The grape-derived volatiles showed high correlations with specific climate factors such as temperature changes in the growth period. Results showed that distal leaf removal increased the solar radiation reaching the clusters in the first few days after applying LR treatments while not affecting the temperature. The improvement in fruity and floral aroma intensity by distal leaf removal was founded not only in grape metabolites but also in wines. Moderate cluster exposure brought by distal leaf removal was beneficial for the accumulation of isoprenoids, which therefore increased the fruity and floral intensity of wines. The carry-over effect did not show in consecutively defoliated vines among vintages regarding the wine aroma profile.

3. Results

3.1. Volatile compounds

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4. Discussion

4.1. Climate impacts

The heterogeneity of the vineyard environment caused high variability in grape metabolites and flavor profiles, and the phenomenon was more prominent in recent years of climate change. Herein, distal leaf removal was applied in semi-arid Xinjiang to adjust the source to sink ratio of grapevines for three consecutive years (2018–2020). The grape-derived volatiles showed high correlations with specific climate factors such as temperature changes in the growth period. Results showed that distal leaf removal increased the solar radiation reaching the clusters in the first few days after applying LR treatments while not affecting the temperature. The improvement in fruity and floral aroma intensity by distal leaf removal was founded not only in grape metabolites but also in wines. Moderate cluster exposure brought by distal leaf removal was beneficial for the accumulation of isoprenoids, which therefore increased the fruity and floral intensity of wines. The carry-over effect did not show in consecutively defoliated vines among vintages regarding the wine aroma profile.

5. Conclusion

The heterogeneity of the vineyard environment caused high variability in grape metabolites and flavor profiles, and the phenomenon was more prominent in recent years of climate change. Herein, distal leaf removal was applied in semi-arid Xinjiang to adjust the source to sink ratio of grapevines for three consecutive years (2018–2020). The grape-derived volatiles showed high correlations with specific climate factors such as temperature changes in the growth period. Results showed that distal leaf removal increased the solar radiation reaching the clusters in the first few days after applying LR treatments while not affecting the temperature. The improvement in fruity and floral aroma intensity by distal leaf removal was founded not only in grape metabolites but also in wines. Moderate cluster exposure brought by distal leaf removal was beneficial for the accumulation of isoprenoids, which therefore increased the fruity and floral intensity of wines. The carry-over effect did not show in consecutively defoliated vines among vintages regarding the wine aroma profile.

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Conflict of interest

The authors declare no conflicts of interest.

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grapes, while in warm regions, the adverse effects of global warming on grape and wine composition, especially secondary metabolites, are widely reported (Gutierrez-Gamboa et al., 2021). As a new technique that was not reported until the last decade, distal leaf removal was proved to be effective in mitigating the adverse effects of global warming on grape and wine quality and delaying ripening (Lu et al., 2022b). Distal leaf removal was a canopy management technique by removing the functional leaves in the upper canopy and altering the source-to-sink ratios of grapevines (Gutierrez-Gamboa et al., 2021). Different from regular summer hedging, distal leaf removal did not involve the reduction of the major sink for nutrients (shoot) (Gutierrez-Gamboa et al., 2021), which was a relatively mild technique. Thus the accumulation of total soluble solids (TSS) was slowed down and the harvest date was delayed by distal leaf removal. This could compensate for the reduced phenology of grapevines caused by global warming and avoid harvesting grapes in a warmer climate. In previous studies, most researchers focused on the influence of distal leaf removal on grape phenolic compounds (Lanari et al., 2015; Lu et al., 2022b; Palliotti et al., 2013). However, the changes in aroma profiles in response to distal removal treatment were few reported. Only Zhang et al. (2017) showed that apical leaf removal had minimal influence on the aroma composition of Shiraz wines.

In Xinjiang, viticulture had a rapid development in recent decades because of the abundant sunlight and semi-arid climate which could effectively reduce the disease occurrence. In 2020, the viticulture area of winegrapes in Xinjiang was 23,400 ha which occupied 26.6 % of the total area in China. Despite the foreseeable potential in the wine industry, there was also some weakness in the wine of this region, for example, the not outstanding aroma performance. In this region, the heatwaves frequently occurred in the grape development stage, so viticulturists usually chose a thick vine canopy to protect grapes from sunburn, which caused a high source/sink ratio and also the excessive shading of clusters. It was hypothesized that moderate exposure could improve the grape aroma performance because sunlight was beneficial for accumulating isoprenoids. Overexposure technique such as basal leaf removal has been proved to result in a decline in norisoprenoids and monoterpenes in ripening grape berries in the dry-hot climate (He et al., 2020). But the changed position of leaf removal might make a difference. Besides, the Cabernet Sauvignon grape was a principal cultivar of this region. The high sugar accumulation rate in the grape ripening stage and long-lasting harvest period required a technique to achieve the consistent maturity of harvested grapes. Thus the distal leaf removal was applied to adjust the source/sink ratio of the grapevine and delay ripening. In the present study, the effect of distal leaf removal on aroma compounds in grapes and sensory attributes of wines was investigated. Our study provides a theoretical basis for the feasibility of applying distal removal treatment in a semi-arid climate to face climate change in the future and a better understanding of the grape volatiles in response to an altered microclimate.

2. Materials and methods

2.1. Chemicals

Sodium hydroxide, perchloric acid, phosphoric acid, acetic acid, citric acid, sodium citrate, sodium acetate, ascorbic acid, sulfuric acid and potassium metabisulphite were analytical grade chemicals and were purchased from Tianjin Chemical Factory. HPLC grade solvents, including ethanol, methanol and dichloromethane, were purchased from Honeywell (Marris, Township, NJ, USA). Polyvinylpolypyrrolidone and α-gluconic acid lactone were purchased from Sigma-Aldrich (St. Louis, MO, USA). Pure standards of volatile compounds were purchased from Sigma-Aldrich (St. Louis, MO, USA).

2.2. Experiment site and treatment

The experiment was performed in a commercial vineyard in the Manas region of Xinjiang (44° 24’N-86° 26’E, elevation 522 m) for three consecutive years (2018–2020). The experimental site had a typical semi-arid climate and the soil type was silt loam. The own-rooted Cabernet Sauvignon vines were planted in 2011 and used for the experiment. The vineyard has a northeast-southwest row orientation (52’) with vine and row spacing 1 m × 3 m. Grapevines were trained to a uniformly modified vertical shooting positioning (M-VSP) trellis system with 18–22 nodes per linear meter. Furrow irrigation was applied 750 m³·ha⁻¹ when the phenological stage reached budburst, anthesis, berries pea size, veraison, and preharvest (about three weeks before harvest).

For distal leaf removal treatment, the upper canopy leaves between the second and third wire (1.2 m to 1.6 m) were manually removed at the beginning of veraison (LR1) and post-veraison (LR2), as shown in Supplementary Fig. 1. In 2018, the treatments included LR1 and LR2. In 2019 and 2020, the treatments included two schemes: leaf removal in the same vines as in 2018 (1-LR1, 1-LR2), which explored the carry-over effect; leaf removal in different vines from the former vintage (2-LR1, 2-LR2), as repeated experiments among vintages. Untreated vines were the control (C). All the vines were summer pruned twice in the whole growing season, which was performed in berry set and pre-veraison to limit the canopy height within 1.9 m above the ground. Nine blocks for each treatment were randomly distributed in three adjacent rows each year. Three blocks were selected as a replicate, including 45 vines with similar vigor.

2.3. Mesoclimate of the vineyard and microclimate of grapevines

The meteorological data of the experimental site was obtained from China Meteorological Data Service Centre (https://cdc.cma.gov.cn/), which included the average daily temperature, rainfall and sunshine duration in the whole growing season (April to September) from 2018 to 2020. The microclimate data around the bunch zone of each treatment was monitored using a HOBO micro station, including a solar radiation sensor (S-LIB-M003, Onset, Bourne, MA, USA) and a temperature sensor (S-THB-M002, Onset, Bourne, MA, USA). The data were recorded every 5 min.

2.4. Berry sampling and winemaking

At harvest, 500 berries were sampled at harvest at the same TSS level to determine volatile compounds. Besides, approximately 20 kg bunches for each replicate were manually harvested for winemaking. The bunches were crushed into 20-L stainless steel containers and 0.8 g of SO₂ was added to the must at the same time. Then 0.4 g pectinase (Optivin, Australia) and 4 g commercial yeast (Lallemand, French) were added to the must. Alcohol fermentation was performed at a temperature-controlled workshop (24–26 °C). The skins were punched down twice a day. The alcohol fermentation was considered finished when the reducing sugar reached below 4 g/L. Then the wines were racked off with an addition of 0.02 g lactobacillus (Lalvin 31, Lallemand Inc, French). When malolactic fermentation was finished, 1.2 g SO₂ was added to wines for each container. The wines were then bottled in 750 mL bottles and stored at 10–15 °C for subsequent analysis.

2.5. Extraction of volatile compounds in berries

The extraction of volatile compounds in berries was according to Wang et al. (2020). For each replicate, about 60 g of frozen berries were de-seeded under liquid nitrogen. Then the de-seeded samples were grounded into powder with an addition of polyvinylpolypyrrolidone (1 g) and α-gluconic acid lactone (0.5 g). The frozen powder was transferred into 50 mL centrifuge tubes and melted at 4 °C for 8 h. The clear grape juice was obtained through centrifuging at 8000 × g for 15 min.
The free-form volatile compounds were extracted directly from the above clear juice. In brief, 5 mL of grape juice was added to a 20 mL vial containing a magnetic stirrer, 10 µL of internal standard (4-methyl-2-pentanol) and 1 g NaCl. For bound-form volatile compounds, 2 mL of the clear grape juice was added to Clevaert® PEP-SPE (150 mg/6 mL, Bonna-Agela Technologies, Tianjin, China) resins which had been activated with 10 mL of methanol and 10 mL of water. Then the resins were washed with 2 mL of water and 5 mL of dichloromethane to remove water-soluble compounds and free volatiles, respectively. The resins were eluted by methanol afterward and the methanolic substance was concentrated to dryness by a rotary evaporator under vacuum at 30 °C and was redissolved in 10 mL of citrate/phosphate buffer solution (0.2 M, pH = 2.5). After hydrolyzing under 100 °C for 1 h in citric acid, 5 mL of the solution was added to a 20 mL vial containing a magnetic stirrer, 10 µL of internal standard (4-methyl-2-pentanol) and 1 g NaCl. The volatile compounds in grapes were extracted by the headspace solid-phase micro-extraction (HS-SPME), as described by Lan et al. (2016). Both free and bound samples were placed in a CTC-Combi PAL autosampler (CTC Analytics, Zwingen, Switzerland) equipped with a 2-cm DVB/CAR/PDMS 50/30 µm SPME fiber (Supelco Inc., Bellefonte, PA., United States) and agitated at 500 rpm for 30 min at 40 °C. The SPME fiber was then inserted into the headspace to absorb aroma compounds at 40 °C for 30 min and was instantly desorbed into the gas chromatography (GC) injector for 8 min to desorb aroma compounds, and the injection temperature was set at 250 °C. The volatile compounds in wines followed the same procedure as the extraction of grape free volatiles.

2.6. Determination of volatile compounds in grapes and wines

The analysis of samples was performed on an Agilent 6890 gas chromatography (GC) coupled to an Agilent 5973 mass spectrometry (MS), fitted with an HP-INNOWAX capillary column (60 m × 0.25 mm, 0.25 µm, J and W Scientific, Folsom, CA, USA). The GC–MS conditions were settled according to Wang et al. (2019). The carrier gas was high purity helium with a flow rate of 1 mL/min. The oven program was set as follows: 50 °C for 1 min, increased to 220 °C at a rate of 3 °C/min, and held at 220 °C for 5 min. The temperature of the ion source and quadrupole were 250 °C and 150 °C, respectively. The full scan mode was applied to collect electron ionization mass data from m/z 30–350. The ionization voltage was set at 70 eV. The volatile compounds were identified using the Automated MassSpectral Deconvolution and Identification System (AMDIS), which could match the mass spectrum and RI with the reference standards in the NIST 11 MS database. The quantification of volatile compounds was according to the corresponding external standards, as described by Wang et al. (2019). The concentrations of those volatile compounds without corresponding standards were estimated with equations of standards having the same functional group and/or similar numbers of carbon atoms. The concentrations of volatile compounds were expressed as µg/L in wines and µg/kg of fresh berry weight in grapes.

2.7. Sensory analysis

As soon as the wines were bottled for two months, sensory evaluation was conducted. A panel of ten expert judges were selected from the local winery for sensory evaluation, with three females and seven males between the ages of 23 and 48. Ethical approval for the involvement of human subjects in this study was granted by China Agricultural University Research Ethics Committee, reference number CAUHR-20220711. For each treatment, wines for sensory evaluation were mixed from all three replicates since bottling. A blind tasting system was used to compare the wine samples with totally random order. The tasting sheet and detailed rules of scoring standards were according to China Rating System for Global Wine. Ratings were based on four elements: appearance, aroma, taste, and overall judgment, which accounted for 10 %, 30 %, 50 %, and 10 %, respectively. The wine tastings were conducted in transparent glasses at room temperature and in individual blocks. In each detailed item, points were awarded from 0 to 10 points (worst to best).

2.8. Statistical analysis

All measuring parameters had three replicates in this study. The variance analysis (ANOVA) was performed using SPSS version 22.0 at p < 0.05 (Duncan’s multiple range test or t-test). The figures were drawn using GraphPad Prism 8.0.2 and Origin 9.0 software. Principal component analysis (PCA) and orthogonal partial least squares discrimination analysis (OPLS-DA) were carried out using SIMCA 14.1.

3. Results and discussions

3.1. Mesoclimate of the vineyard and microclimate of grapevines

Vine development, grape ripening and wine sensory attributes are highly influenced by the physical environment in which the vines grow (Ferreira, 2010). In the semi-arid Xinjiang, the grapes had rapid sugar accumulation during ripening because of the hot climate and large daily temperature ranges. After applying LR treatments, the sugar accumulation rate was slowed down and the harvest date could be delayed for 4–10 days (Supplementary Table 1). The variable harvest dates would lead to varying climate conditions that each LR treatment went through. So the meteorological data during Cabernet Sauvignon grape development was calculated in each treatment of 2018, 2019 and 2020 growing seasons, as shown in Supplementary Table 2. Compared to the three vintages, the vintage 2020 was the driest year. The average temperature in 2020 was higher than in 2018 and 2019, and the cumulative rainfall in 2020 was less than in 2018 and 2019. Fig. 1a also showed the temperature changes from budburst to harvest in three vintages. From budburst to flowering, the average temperature in 2020 was higher than in 2018 and 2019, and the variation could be up to 3 °C (Supplementary Table 2). However, in the flowering-véraison period, the temperature in 2020 was lower than the other two vintages. For sunlight duration, the vintage 2018 had higher sunshine hours than 2019 and 2020. Similar to temperature, the variations in sunshine hours among the three vintages mainly occurred in two stages: budburst-flowering and flowering-véraison. From budburst to flowering, the average daily sunlight duration in 2019 was lower than the other two vintages (Fig. 1b). However, the vintage 2020 had the lowest cumulative sunlight duration in this stage because 2020 had an advanced phenological stage and the flowering time was about two weeks earlier than 2018 and 2019. Among all climate factors, temperature played a predominant role in affecting the phenological stages of grapevines. So even though there was lower sunlight in 2020 from budburst to flowering, the high temperature in this stage could also cause a significantly advanced growth stage. Although the harvest date in 2020 was about two weeks before 2018 and 2019, the growing degree days in three vintages were similar, which indicated that GDD was a reliable indicator for predicting the phenology of grapes (Verdugo-Vásquez et al., 2017).

After applying LR treatments, the temperature around clusters was not altered, as shown in Fig. 1c. Both LR1 and LR2 had little difference in temperature changes with control in the growing season. In the first few days after applying LR treatments, the solar radiation around clusters was increased, which was found in both LR1 and LR2 (Fig. 1d). However, the difference between LR treatments and control gradually narrowed in the latter period of the growing season (20 days after veraison to harvest for LR1, 28 days after veraison to harvest for LR2) as time went by. Supplementary Fig. 2 also showed the daily solar radiation changes around the clusters. On the third day after applying LR1, the solar radiation was increased by LR treatment, especially from 16:00 to 20:00 (Supplementary Fig. 2a). Similarly, on the fourteenth day after applying LR2, the solar radiation was also increased compared to
control, while the LR1 did not show a difference between control (Supplementary Fig. 2b). At preharvest, the three treatments had similar cumulative solar radiation throughout the day, with no obvious increase found in LR treatments (Supplementary Fig. 2c). This phenomenon showed that the removed upper leaves would increase the transmittance of the canopy, which increased the solar radiation reaching the clusters to a certain extent in the first few days after applying LR treatments. However, as described in a previous study (Lu et al., 2022b), the vines in the experimental site had high vigor with the vigorous growth of lateral shoots. So the increased transmittance of the canopy might be covered by the growth of lateral shoots, which caused little difference between LR treatments and control in the latter period of the growing season. The increased solar radiation around clusters did not cause an augment in temperature. The same result was also found by Young et al. (2016) that leaf and lateral shoot removal in the bunch zones altered the microclimate by increasing the exposure of the berries but did not affect the temperatures in the bunch zones. Although exposure to sunlight invariably results in increased temperatures. The air was circulating around clusters in field conditions rather than in a confined environment, which would lead to little change in temperatures with the increased solar radiation in our study.

3.2. Dissecting the influence of climate factors among vintages on volatile compounds of berries

The identified volatile compounds by GC–MS and their concentrations in berries were shown in Supplementary Table 3. According to structures, the volatile compounds could be sorted into the following categories: C6/C9 compounds, benzenes, higher alcohols, norisoprenoids, aldehydes/ketones, terpenes, acids and esters. Among them, the C6/C9 compounds, terpenes and norisoprenoids were the main grape-derived aromas that could maintain the variety characteristic in wines (González-Barreiro et al., 2015). So principal component analysis was used to identify the aroma profile variations in all treatments based on C6/C9 compounds, terpenes and norisoprenoids, as shown in Supplementary Fig. 3. The first two principal components explained 69.9 % of the total variance. PC1 (R2X[1]) accounted for 40 % of the total variance and could separate the samples from 2018 and 2020. It showed that berries in 2018 had more abundant C6/C9 compounds than in 2020. PC2 (R2X[2]) accounted for 29.9 % of the total variance and could separate the samples from 2019 to other two vintages. It showed that berries in 2018 had more scarce aroma profiles than other two vintages. To further investigate how climate factors among vintages affected the volatile compounds in berries, the Pearson correlation analysis was used to select highly correlated compounds (|r2| > 0.7) with each climate factor, as shown in Supplementary Table 4.

For C6/C9 compounds, the average max and min temperature in budburst-harvest, veraison-harvest, and budburst-flowering stages were all negatively correlated with two C6/C9 compounds: hexanal and (E)-2-hexenal. While the average max and min temperature from flowering to harvest were positively correlated with hexanal and (E)-2-hexenal in our study. C6/C9 compounds were abundant in various aromatically neutral
varieties and (E)-2-hexenal and hexanal were the most abundant C6 compounds in mature berries of Cabernet Sauvignon (González-Barreiro et al., 2015). Regarding the effects of temperatures on C6 compounds, the same result was also found by Wang et al. (2020) that total C6/C9 compounds were negatively correlated with the average daily temperature of the vineyard from flowering to harvest. Similarly, Ji and Dani (2008) reported that concentrations of 6-carbon aldehydes were higher in Traminette grapes grown on the cool site than those grown on the hot site. The daily temperature range from budburst-harvest was positively correlated with 1-hexanol, (Z)-3-hexen-1-ol, and 2-nonenal. Although the effect of diurnal temperature differences on volatile compounds was little reported, Xu et al. (2015) showed that diurnal temperature differences were positively correlated with (Z)-3-hexen-1-ol in berries, which was in agreement with our study.

For norisoprenoids, the average, max and min temperature in budburst-harvest, véraison-harvest, and budburst-flowering stages were negatively correlated with some free form norisoprenoids such as (E)-1-(2,3,6-trimethylphenyl)buta-1,3-diene (TPB), (Z)-β-damascenone and (E)-β-ionone. However, the temperature was positively correlated with mang bound form norisoprenoids such as (E)-β-damascenone (B), (Z)-β-damascenone (B), TPB (B). Regarding the effects of elevated temperatures on norisoprenoids, there were still inconsistent results in previous studies. Scherzinger and Al-Babili (2008) found that both cold (20 °C) and heat stress (38 °C) allowed to increase the expression of gene CCD, which played an essential role in the generation of norisoprenoids. However, Meng et al. (2020) found that the high temperature (37 °C) repressed the activity of the VvCCD4b promoter. In a previous study reported by our research team (Lu et al., 2022a), the Muscat Hamburg and Victoria grapes had a lower norisoprenoid concentration in the summer season characterized by high temperature under the double cropping system. However, the opposite result was found in the Cabernet Sauvignon grapes that the winter season berries had a higher norisoprenoid concentration than the summer season berries. In the present study, the high temperature days in budburst-harvest, véraison-harvest, and flowering-véraison stages were all negatively correlated with the concentration of (Z)-β-damascenone (B). For other climate factors, the cumulative sunlight duration from budburst to harvest was positively correlated with 6-methyl-5-hepten-2-one, geranylacetone, (E)-β-ionone and β-ionone (B), which indicated that the promotion of light exposure to norisoprenoid accumulation (Feng et al., 2015; Wang et al., 2020).

For terpenes, the average, max and min temperature in budburst-harvest, véraison-harvest, and budburst-flowering stages were negatively correlated with three free form terpenes such as endo-borneol, hotrienol and eucalyptol. Only the bound form citronellol was positively correlated with the average, max and min temperature in budburst-harvest, véraison-harvest, and budburst-flowering stages. It is generally considered that elevated temperature could inhibit the accumulation of terpenoids due to the increased loss by volatilization (Scafidi et al., 2013). Similar to norisoprenoids, mang terpenes were positively correlated with the cumulative sunlight duration from budburst to harvest.

3.3. Effects of distal leaf removal treatments on volatile compounds in berries

3.3.1. C6/C9 compounds

The main C6/C9 compounds that showed significant differences among treatments in at least one vintage were shown in Fig. 2. Although hexanal and (E)-2-hexenal were the most abundant C6/C9 compounds in berries, they were not affected by LR treatments. In 2018 and 2019, there was no significant difference among treatments regarding the concentration of hexanol and (E)-2-hexenal. In 2020, 1-LR1 had a lower hexanal concentration than 1-LR2 and 2-LR1 while showing no significant difference with control. 1-LR2 had a higher (E)-2-hexenal concentration than control and 1-LR1. For 1-hexanol, (E)-2-hexenal-1-ol, 1-nonanol and (Z)-3-nonen-1-ol, the promotion of their concentrations was confirmed in LR treatments. 1-LR1 (LR1) significantly increased the

![Graphs showing effects of leaf removal treatments on C6/C9 compounds](image-url)

**Fig. 2.** Effects of distal leaf removal treatments on C6/C9 compounds of Cabernet Sauvignon grapes in 2018, 2019 and 2020 growing seasons (μg/kg FW). Different letters within a plot indicate significant differences among treatments (Duncan’s multiple range test at $p < 0.05$).
3.3.2. Terpenes

Eighteen terpenes were detected by GC-MS in berries, which included eight free form compounds and ten bound form compounds, as shown in Supplementary Table 3. To better present how LR treatments affect the terpenes, the log2-fold was used to normalize the changes of each terpene concentration between LR treatments and control (LR/control), as shown in Fig. 3. The increase of many free-form terpenes such as citronellol, menthol, hotrienol was confirmed in LR treatments, all of which had higher concentrations in almost all LR treatments than in control in three vintages. Besides, the bound form α-terpinene also had a higher concentration in LR treatments. Only the concentration of α-calacorene was decreased by LR treatments. As the main compounds contributing to the floral/fruity odors of wines, terpenes were easily affected by many factors (Wen et al., 2015). The sunlight was one of the terroir factors that drew an increasing interest of researchers regarding how sunlight affected grape terpenes (Zhang et al., 2014). Skinkis et al. (2010) found that fruit from fully exposed clusters had 30% higher concentrations of potentially volatile terpenes than shaded fruit. Similarly, Sylvie et al. (2000) showed that the artificially shaded bunches showed lower levels of monoterpenes than sun-exposed berries and berries from naturally shaded bunches. So the increase of sunlight around clusters was usually beneficial for terpene accumulation, which was also found in our study. However, excessive sun exposure could also negatively affect the concentration of terpenes (Belancic et al., 1997).

In our previous study conducted in the same experimental site, various cluster exposure treatments resulted in a decline in the concentrations of monoterpenes in ripening grape berries (He et al., 2020), which showed the opposite result to the present study. This might be due to the different levels in cluster exposure caused by different leaf removal positions. As mentioned in the previous analysis, the distal leaf removal only increased the solar radiation reaching the clusters to a certain extent in the first few days after applying LR treatments. Sometimes, it was difficult to separate the environmental effects of temperature and light in a field setting (Azuma et al., 2012). In the semi-arid climate of Xinjiang, the excessive sun exposure caused by basal leaf removal might lead to the high temperature of berries, and the adverse effect of high temperature on terpene accumulation was also confirmed. But for the distal leaf removal, moderate sun exposure was more beneficial for terpene accumulation and could avoid high temperature in berries.

3.3.3. Norisoprenoids

The main norisoprenoids that showed significant differences among treatments in at least one vintage were shown in Fig. 4. For the selected free form norisoprenoids, (Z)-β-damascenone, (E)-β-ionone and TPB were affected constantly by LR treatments in different vintages. LR2 in 2018 and 2-LR1 in 2020 had significantly higher concentrations of (Z)-β-damascenone, (E)-β-ionone than control. Besides, all four LR treatments in 2019 and 2-LR2 in 2020 had a higher concentration of (E)-β-ionone than control. 2-LR2 significantly increased the (E)-β-damascenone concentration in 2019, while the opposite result showed in 2020. For bound form (E)-β-damascenone, only 1-LR2 significantly decreased its concentration in 2020 than control. For the bound form α-ionone, only 2-LR1 and 2-LR2 significantly increased its concentration in 2019. As reported, the formation of norisoprenoids in grape berries involved carotenoid breakdown and the formation of carotenoids occurred at prévéraison and decreased afterward (Yuan & Qian, 2016). In our study, the LR treatments were performed at and post prévéraison, which might not affect the formation but the degradation of carotenoids. The light appeared to increase carotenoid levels in green berries and decrease major carotenoid levels during ripening (Bureau et al., 2000). After prévéraison, the sunshine favored the degradation of carotenoids into norisoprenoids (Baumes et al., 2002), which might be the reason of the increased free form norisoprenoids, (Z)-β-damascenone, (E)-β-ionone and TPB found in LR treatments in our study.
caused by cluster exposure promoted the degradation of polyunsaturated fatty acids in grapes, as compounds that repressed the genes involved in yeast activity and the synthesis of esters during fermentation, leading to a higher concentration of esters in LR wines (Bubola et al., 2006). (iv) the greater UV radiation exposure but shaded berries contained less total amino acids than the exposed berries (Pereira et al., 2006).

Four possible reasons led to the ester changes in LR treatments: (i) the increased C6/C9 concentrations were found in LR grapes in the previous analysis, which could transform into more esters during fermentation (Dennis et al., 2012); (ii) the increased fatty acids concentrations in LR wines and also precursors of esters. Previous studies showed that in Cabernet Sauvignon wines, including C6 alcohols, acetate esters, ethyl esters, other esters, benzenes, terpenes, norisoprenoids, higher alcohols, fatty acids, as shown in Table 1. Among all compounds, ten compounds were significantly affected by LR treatments in a consistent way in at least two vintages, including four esters, one norisoprenoid compound, two higher alcohols and three fatty acids. For esters, LR treatments increased the concentrations of isoamyl acetate, 2-phenylethyl acetate, ethyl (S)-(−)-lactate and ethyl 3-methylbutyrate. It was well known that esters were the main fermentation-derived compounds that contributed to desired fruity and floral attributes to wines. Variables that were known to affect ester production in wines included the concentration of esters or their precursors originally from grapes, fermentation conditions, and the nutrients present, especially the concentration of nitrogen compounds and must solids (Sumby et al., 2010). In our study, all LR treatments and control were strictly performed in the same fermentation conditions and procedures. So the increased esters concentration in LR treatments might not be due to variations of fermentation conditions. Different letters within a row of each vintage indicate significant differences among treatments (Duncan’s multiple range test at p < 0.05).

### 3.4. Effects of distal leaf removal treatments on volatile compounds in wines

There were sixty-four volatile compounds identified by GC–MS in the Cabernet Sauvignon wines, including C6 alcohols, acetate esters, ethyl esters, other esters, benzenes, terpenes, norisoprenoids, higher alcohols, fatty acids, as shown in Table 1. Among all compounds, ten compounds were significantly affected by LR treatments in a consistent way in at least two vintages, including four esters, one norisoprenoid compound, two higher alcohols and three fatty acids. For esters, LR treatments increased the concentrations of isoamyl acetate, 2-phenylethyl acetate, ethyl (S)-(−)-lactate and ethyl 3-methylbutyrate. It was well known that esters were the main fermentation-derived compounds that contributed to desired fruity and floral attributes to wines. Variables that were known to affect ester production in wines included the concentration of esters or their precursors originally from grapes, fermentation conditions, and the nutrients present, especially the concentration of nitrogen compounds and must solids (Sumby et al., 2010). In our study, all LR treatments and control were strictly performed in the same fermentation conditions and procedures. So the increased esters concentration in LR treatments might not be due to variations of fermentation conditions. Different letters within a row of each vintage indicate significant differences among treatments (Duncan’s multiple range test at p < 0.05).

### 3.5. Effects of distal leaf removal treatments on odor activity values in wines

The odor activity values (OAV) were usually used to estimate the contribution of aroma compounds to the wine sensory profile by dividing their concentration to their odor threshold values (Bouzas-Cid et al., 2018). The identified volatile compounds and their thresholds and aroma series in Cabernet Sauvignon wines were shown in Supplementary Table 5. The main aroma series with high OAVs were as follows: fruity, floral, caramel, herbaceous, chemical and fatty, as shown in Fig. 5. LR treatments significantly increased the intensities of fruity, floral, and caramel, indicating a significant improvement in the wine aroma caused by LR treatments. In the three aroma series, β-damascenone contributed the highest OAV among all volatile compounds. As analyzed above (Table 1), the significant increase of β-damascenone was shown in LR treatments with a constant result among vintages, which therefore caused the increased fruity, floral, and caramel intensities in LR wines (Cai et al., 2014). The increased free-form β-damascenone was also observed in grapes, which indicated that the SST treatment could improve the fruity, floral, and caramel intensity in berries and then reflected on wines. Besides the β-damascenone, the esters such as isoamyl acetate, ethyl acetate, ethyl hexanoate also had high OAVs and contributed to fruity aroma to wines. The LR treatments significantly increased β-damascenone concentration in wines compared to control. In 2020, 1-LR1 and 2-LR2 both significantly increased β-damascenone concentration in wines compared to control. In the previous analysis, the LR treatments increased the free form (Z)-β-damascenone in grapes, which was in agreement with the results in wines. For terpenes, four compounds were detected in Cabernet Sauvignon wines in our study. However, different from the increased terpene concentrations in LR grapes, there were no significant differences between LR and control wines. Sometimes, it usually hard to associate grapes to the corresponding wines in some aspects. Wine fermentation is a complicated process during which aroma compounds experience great changes, which would result in a variation between berries and wines (Lu et al., 2021).

Values are reported as means ± SD of three biological replicates. Different letters within a row of each vintage indicate significant differences among treatments (Duncan’s multiple range test at p < 0.05).
| Parameters | 2018 | 2019 | 2020 |
|------------|------|------|------|
| C          | LR1  | LR2  |      |
| C          | LR1  | LR2  |      |
| C          | LR1  | LR2  |      |

### C6 alcohols

| 1-Hexanol          | 2,332.66a | 2,059.22b | 1,996.31b |
| (E)-3-Hexen-1-ol   | 84.44a    | 85.22a    | 63.33b    |
| (Z)-3-Hexen-1-ol   | 64.71a    | 54.91a    | 55.11a    |

### Acetate esters

| Ethyl acetate       | 69,124.51b | 88,658.55a | 86,626.75a |
| Isoamyl acetate     | 5,154.04a  | 7,342.56a  | 11,312.05a |
| Acetate esters      |           |           |           |

### Higher alcohols

| 1-Propanol          | 9,316.87a  | 10,095.14a | 9,939.45a  |
| Isobutanol          | 3,577.12b  | 50,674.13a | 42,863.63b |
| 1-Penten-3-ol       |           |           |           |

### Table 1

**Effects of upper leaf removal treatments on volatile compounds of Cabernet Sauvignon wines in 2018, 2019 and 2020 growing seasons (μg/L).**

| Parameters         | 2018 | 2019 | 2020 |
|--------------------|------|------|------|
| C                  | LR1  | LR2  |      |
| C                  | LR1  | LR2  |      |
| C                  | LR1  | LR2  |      |

### Higher alcohols

| 1-Propanol          | 9,316.87a  | 10,095.14a | 9,939.45a  |
| Isobutanol          | 3,577.12b  | 50,674.13a | 42,863.63b |
| 1-Penten-3-ol       |           |           |           |
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Table 1 continued

| Parameters | 2018 | 2019 | 2020 |
|------------|------|------|------|
| 1-Butanol  | 1,277.34a | 1,337.15a | 1,063.17b |
| 3-Methyl-1-butanol | 287,876.92a | 278,940.79a | 291,027.15a |
| 3-Methyl-1-pentanol | 3.95 | nd | 2.6 |
| 2-Octanol | nd | nd | nd |
| 2-Propyl-1-pentanol | nd | nd | 2.04 |
| 2-Ethyl-1-hexanol | nd | 2.88a | 1.68b |
| 2-Nonanol | nd | 2.99b | 4.13a |
| 1-Octanol | 22.11a | 19.48ab | 14.49b |
| 2,3-Butanediol | 1,410.68b | 1,648.98ab | 2,064.89a |
| 1-Decanol | 1.35a | 1.26a | 1.2a |
| 2-Methoxypropanoic acid | nd | nd | 2.04 |
| Butanoic acid | nd | nd | 2.04 |
| n-Decanoic acid | 629.68a | 449.2a | 787.3a |
| 3-Methylbutanoic acid | 496.65a | 539.26a | 511.44a |
| 2-Methylbutanoic acid | 349.24b | 410.09a | 362.82ab |

Values are reported as means ± SD of three biological replicates. Different letters within a row of each vintage indicate significant differences among treatments (Duncan’s multiple range test at p < 0.05).

3.6. Dissecting the influence of different leaf removal choices on volatile compounds of wines

The previous analysis focused on dissecting the variations of volatile compounds between LR treatments and control. There were two aspects that still remained to be investigated: leaf removal at different times and the carry-over effect on volatile compounds of wines.

3.6.1. Distal leaf removal in different times

In the present study, two time points were chosen to apply distal removal treatments: onset of véraison and post véraison. The two-way ANOVA was used to select the marker compounds that showed significant differences between LR1 (leaf removal at the onset of véraison) and LR2 (leaf removal at post véraison), as well as affected by vintage and their interaction effect, as shown in Supplementary Table 6. Nineteen volatiles showed significant differences between LR1 and LR2, including four terpenes, three aldehydes, three esters and two terpenes. Compared to LR1, LR2 significantly increased the concentrations of most ester esters such as ethyl octanoate, ethyl butanoate, ethyl hexanoate, ethyl decanoate, ethyl 9-decanedioate and ethyl dodecanoate in vintage 2018 and 2020 while showing no significant differences in 2019. Ethyl esters were formed via condensation of fatty acid-CoA with ethanol during fermentation and mainly contributed to the fruity aroma of wines. The timing of bunch exposure and berry maturity might be both responsible for the concentration of ethyl esters in wine, but how these two factors influence ester level in wine needs to be further investigated (Wang et al., 2018). In the present study, the clusters of LR2 were exposed later than LR1 and harvested earlier than LR1. The later removed leaves in LR2 might also provide an adequate source for primary metabolites. In a previous study, the latter and moderate leaf removal treatment accumulated more abundant amino acids in grapes than early leaf removal (Yue et al., 2019), which could produce more esters in wines during fermentation. Although LR2 increased the concentration of β-Linalool in wines compared to LR1, there were no significant differences in grapes between LR1 and LR2.

3.6.2. Carry over effect

In the present study, LR treatments were not only performed in the same vines in three consecutive years but also chose different vines from the former vintage in the second and third years. So the carry over effect of LR treatments could be evaluated. Regrading the volatile compounds in wines, the orthogonal partial least-squares discrimination analysis (OPLS-DA) was used to select the marker compounds that showed a difference between 1-LR (LR treatments in the same vines among vintage) and 2-LR (LR treatments in different vines of each vintage), as shown in Supplementary Fig. 4. In 2019, the 2-LR treatments had more abundant benzyl alcohol, ethyl (S)-(-)-lactate, 2-methoxypropanoic acid, 2-phenylethyl acetate, isoamyl acetate, isobutanol etc. than 1-LR, while 1-LR treatments had more abundant n-decanoic acid, ethyl hexanoate, 2-nonanol etc. than 2-LR. In 2020, the 2-LR treatments had more abundant α-terminal than 1-LR, while 1-LR treatments had more abundant citronellol, isoamyl octanoate, hexyl acetate, isopentyl hexanoate than 2-LR. Among all selected compounds, only hexyl acetate increased isoamyl acetate concentration in wines (Table 1), which also caused an augment in fruity aroma in wines (Cai et al., 2014). For herbaceous and chemical aromas in wines, there were no consistent results among vintages regarding the LR effect. Although the higher C6 aldehydes were found in berries in SST wines, their herbaceous note could transform into a fruity note (esters) during fermentation which contributed to an augment in fruity aroma in wines. For the fatty aroma, LR2 in 2018, all the LR treatments in 2019 and 2-LR2 in 2020 significantly increased its intensity in wines. In all identified fatty acids in wines, the hexanoic acid was in a high OAV and its concentration was significantly increased by LR treatments, which led to an increased fatty aroma in wines.
showed a consistent result in two years and it had a higher concentration in 1-LR treatments than 2-LR. Other compounds such as benzyl alcohol, phenylethyl alcohol and isoamyl acetate showed the opposite result in two years. So there was few carry over effect caused by LR treatments on volatile compounds in wines, which was in agreement with our previous study that whether LR in the same vines over consecutive years had limited effects on phenolic profiles and vine growth parameters (Lu et al., 2022b).

3.7. Sensory analysis of wines

Fig. 6 shows the sensory evaluation of Cabernet Sauvignon wines obtained from control (C) and LR treated grapevines in the 2018–2020 seasons. Supplementary Table 7 shows the appearance, aroma, taste, overall judgement, and total scores of each wine. The LR treatments had a higher total sensory score than control in 2018 and 2020 while showing the opposite result in 2019. In 2018, LR2 wine had a higher total score than control and LR1, especially in aroma performance (Supplementary Table 7), which was in agreement with the previous study.
In this study, distal leaf removal was found to be beneficial for the accumulation of C6 alcohols, terpenes and norisoprenoids in grapes due to the moderate exposure of clusters and more balanced source-sink vines caused by LR treatment. However, the increased C6 alcohols and terpenes in LR grapes did not show in LR wines. The increased esters and (E)-γ-damascenone were found in LR wines which caused a higher fruity and floral aroma intensity. Compared to leaf removal at the beginning of veraison, leaf removal at post-veraision had more ethyl esters concentrations in wines. The carry-over effect did not show in LR wines which indicated that LR in consecutive years in the same vines was practical for viticulture to face global warming and delay ripening.

4. Conclusion

In this study, distal leaf removal was found to be beneficial for the accumulation of C6 alcohols, terpenes and norisoprenoids in grapes due to the moderate exposure of clusters and more balanced source-sink vines caused by LR treatment. However, the increased C6 alcohols and terpenes in LR grapes did not show in LR wines. The increased esters and (E)-γ-damascenone were found in LR wines which caused a higher fruity and floral aroma intensity. Compared to leaf removal at the beginning of veraison, leaf removal at post-veraision had more ethyl esters concentrations in wines. The carry-over effect did not show in LR wines which indicated that LR in consecutive years in the same vines was practical for viticulture to face global warming and delay ripening.

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CRediT authorship contribution statement

Hao-Cheng Lu: Formal analysis, Data curation, Investigation, Writing – original draft, Visualization. Li Hu: Software, Investigation. Yao Liu: Software, Investigation. Chi-Fang Cheng: Resources. Wu Chen: Resources. Shu-De Li: Resources. Fei He: Supervision. Chang-Qing Duan: Supervision. Jun Wang: Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchx.2022.100449.

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