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The influence of temperature and solar radiation on phenols in berry skin and maturity parameters of *Vitis vinifera* L. cv. Riesling

Melanie Brandt[1*], Mathias Scheidweiler[1], Doris Rauhut[2], Claus-Dieter Patz[3], Frank Will[3], Holger Zorn[4] and Manfred Stoll[1]

[1]Hochschule Geisenheim University, Dpt of General and Organic Viticulture, Von-Lade-Str. 1, 65366 Geisenheim, Germany
[2]Hochschule Geisenheim University, Dpt of Microbiology and Biochemistry, Von-Lade-Str. 1, 65366 Geisenheim, Germany
[3]Hochschule Geisenheim University, Dpt of Beverage Research, Von-Lade-Str. 1, 65366 Geisenheim, Germany
[4]Justus Liebig University Giessen, Institute of Food Chemistry and Food Biotechnology, Heinrich-Buff-Ring 17, 35392 Giessen, Germany

Corresponding author: Melanie.Brandt@hs-gm.de

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ABSTRACT

Aim: This research was undertaken in the context of climate change and understanding how rising temperatures may interact with viticultural practices, used to manage fruit exposure in Riesling. An experimental system was designed to passively warm the bunch zone and separate the factors, heat and indirect heat by solar radiation.
Methods and results: Field experiments were conducted in 2016 and 2017 at an experimental site located near Rüdesheim in Germany. To increase bunch exposure compared to non-defoliated controls (CON), around 75% of the leaves were removed manually from the bunch zone in an early defoliation treatment at pea size (DEF_E; E-L 31) and later defoliation at véraison (DEF_L, E-L 35). An open heating system (OHS) was installed from pea size stage (E-L 31) onwards. Temperature, light penetration and canopy characterization were determined. Maturity measurements included determination of berry fresh weight, total soluble solids, available primary amino acids (N-OPA), pH, titratable acid and organic acids. For determination of the phenols, berry skin was freeze dried, extracted and analysed by HPLC-PDA.
Compared to the same position in the control vine rows, the temperature was more than 10 °C warmer inside the chamber, around 5 °C warmer at the opening of the chamber and at the upper end of the bunch zone, up to 3 °C warmer on a day with high solar radiation. On overcast days there was no temperature difference between these treatments.
The OHS treatment affected the ratio of malic and tartaric acid as well as the ratio of glucose and fructose, and produced smaller berries compared to both CON and DEF treatments. Phenols (flavanols, hydroxycinnamic acids, flavonols) in the berry skin were mostly affected by the defoliation. In both years, DEF_E had the highest amount of phenols, followed by the DEF_L. In 2016 OHS had nearly the same concentration of phenols compared to CON. In 2017, the concentrations of phenols were higher in OHS compared to CON.
Conclusion: Under future scenarios of increasing temperature conditions, strong changes will be expected for berry maturity parameters. It was found that using an experimental setup to passively heat the bunch zone, malic acid was reduced, smaller berries were produced, and the glucose/fructose ratio changed. For the defoliation treatments, phenol concentrations in berry skin were strongly affected by defoliation and to a lesser extent by higher temperature. Basic maturity parameters were relatively unaffected by defoliation.
Significance and impact of the study: Riesling is known for its fruity character and the importance of the sweetness and acidity balance for determining wine style. Under warmer temperature conditions the acidity content will decrease through faster malic acid respiration, impacting the wine´s profile. Higher phenol content could lead to an astringent taste and together with higher protein content, may provide a risk of haze in wine. Neither effect is desirable. In this study, increased bunch exposure following defoliation had a greater effect than temperature alone on phenols. Therefore, the vineyard and canopy management practice will need to be adapted.

KEYWORDS

Vitis vinifera, temperature, defoliation, phenols, maturity parameters

INTRODUCTION

Global surface temperature is expected to rise in the future, and a range of scenarios based on greenhouse gas emissions have been developed to predict the possible extent of these temperature changes (Intergovernmental Panel on Climate Change, 2014). In the lowest emission scenario, the temperature will increase up to 1.7 °C by the end of the century. In the highest emission scenario, reflecting present day emissions, a maximum increase of 4.8 °C is predicted (Cubasch *et al.*, 2013). Global warming influences agriculture, including viticulture. Riesling is a grapevine considered best suited to cooler climates and is the most planted grape variety in Germany. Therefore, it is important to know the influence of abiotic factors on berry composition, and to understand how viticulture practices can be adapted to cope with rising temperatures.

Defoliation is used in viticulture to improve the canopy microclimate, with the maintenance of berry health and improving berry composition being two of the main underlying objectives (Smart and Robinson, 1991). There are several studies which have investigated the influence of light on fruit composition. Recent studies with Riesling, Friedel *et al.* (2015) examined the influence of defoliation and shading treatments for maturity parameters and phenols. Defoliation changed the composition of flavonoids, amino acids and malic acid, but sugar accumulation was not significantly affected by changes in leaf area to fruit weight ratio. Komm and Moyer (2015) investigated the influence of fruit-zone leaf removal at prebloom, bloom and four weeks postbloom on fruit quality and phenols in berry skins. They found that leaf removal did not influence harvest total soluble solids (TSS), titratable acidity (TA) and pH, also phenolics in berry skin were not altered when the fruit-zone was defoliated before or up to four weeks postbloom. Neither study investigated the temperature effect when decoupled from the influence of light. Furthermore, most leaf removal research has been conducted with red varieties, particularly in relation to the effects on anthocyanins. Most studies regarding the effect of temperature on grapevine berry composition, also examined red varieties.

Bonada and Sadras (2015) published a review of methods to investigate the temperature effect on grapevines. Direct (comparison in time or space) and indirect (greenhouse/growth chambers or field experiments) methods were compared and the response of the berry composition to temperature were summarized. Gouot *et al.* (2019) published a review about grape berry flavonoid responses to high temperatures. It was concluded that changes in flavonoid composition correlates with temperature, caused by exceeding the threshold of biosynthesis. The duration of temperature and different periods of higher temperatures have been less well studied. Most critical experimental parameters in the reviewed studies were phenological stages, followed by day/night temperature regimes. Blancquaert *et al.* (2019) summarized the effect of abiotic factors on phenolic compounds in grape berry and concluded that flavonol concentration increased with higher light exposure as well as with water deficit. Exclusion of solar UV radiation decreased the flavonol concentration, while temperature had no effect on flavonols. As a number of these recently published reviews highlight, the influence of temperature on berry composition is of considerable importance for wine grape production.

In one of the more targeted studies, Spayd *et al.* (2002) separated the effect of sunlight and temperature on maturity parameters, anthocyanins and flavonols in Merlot berry skin by utilising different sampling techniques, UV-absorbing/transmitting foil and air blowers. For Riesling, which has not had interactive temperature and light effects examined in such detail, the temperature effect with a direct method (comparison in time) was investigated for TSS and TA by Duchêne and Schneider (2005), Bock *et al.* (2011), Urhausen *et al.* (2011) and Vršič and Vodovnik (2012). Jackson and Lombard (1993) reviewed the influence of temperature, light and water status on TSS, organic acids, colour compounds and aroma precursors, and the process of photosynthesis, which are all driven by enzymes. Riesling is known for its balance between sweetness and acidity, higher temperatures reduce titratable acidity due to malic acid reduction (Lakso and Kliewer, 1975). TSS was increased by warmer temperatures (Mira de Orduña, 2010) while extreme high temperatures have been shown to decrease sugar accumulation and ripening (Greer and Weston, 2010). Phenols cause browning reactions in white wine (Singleton, 1987) and lead to haze formation with proteins (Batista *et al.*, 2010; Ferreira *et al.*, 2001). Phenols are also

associated with a bitter taste and astringency (Arnold *et al.*, 1980; Singleton *et al.*, 1975).

The aim of this study was to separate the effect of light and temperature and to investigate their influence on maturity parameters and phenols. An open heating system (OHS) was established in the vineyard based on the experience of Sadras and Soar (2009). This set-up minimizes the effects on the light conditions in the bunch zone. To investigate the effect of solar radiation, defoliations were carried out in the bunch zone at different times. The impact of the open heating system and the effect of the defoliation are both dependent on the solar radiation. The warm air of the OHS tends to distribute a constant airflow around the entire bunch whilst defoliation and variable sun exposure of individual berries will create high temperature variability between fully exposed and lesser exposed berries.

MATERIALS AND METHODS

1. Experimental site

In 2016 and 2017 experiments were conducted using *Vitis vinifera* L. cv. Riesling (clone Gm 198-25; grafted on rootstock SO4-Gm47) planted in 2007 using a VSP trellis system (row distance 2.10 m; plant distance 1.05 m). The experimental site was located at Rüdesheim (Rheingau), Germany (49°59′20” N; 7°55′56” E).

2. Treatment

To heat the bunch zone passively, an open heating system (OHS) was installed at 21 days after flowering (DAF). This consisted of four 20 m long tent-like chambers, built with highly transparent greenhouse polyethylene sheet (FVG Sun Saver Clear 5-ST, 180 µm, 3-layer Coex film), each one spanning 18 treatment vines along the row with two buffer vines on either side. The outlet of the OHS was positioned in the middle of the bunch zone at 1 m above ground (Figure 1C) with an opening width between 10 cm and 20 cm. Figure 1A shows one side of the OHS and a close up of the opening placed in the middle of the bunch zone (Figure 1B). To avoid creating differences in water availability between OHS and other treatments, the chambers were rolled up during natural rainfall.

On both sides of the bunch zone approximately 75% of the leaves were manually removed either at pea size (DEF_E) or around véraison (DEF_L) using 18 vines per field replicate and treatment at E-L 31 (21 DAF) and E-L 35 (71 DAF) respectively (Coombe, 1995). Re-growing leaves were not removed. In the control treatment, no canopy manipulation occurred.

3. Field trial

Treatments were established in a randomized block design, using four field replicates per treatment. Flowering (E-L 23) occurred on June 15 in 2016 and on June 5 in 2017 respectively.

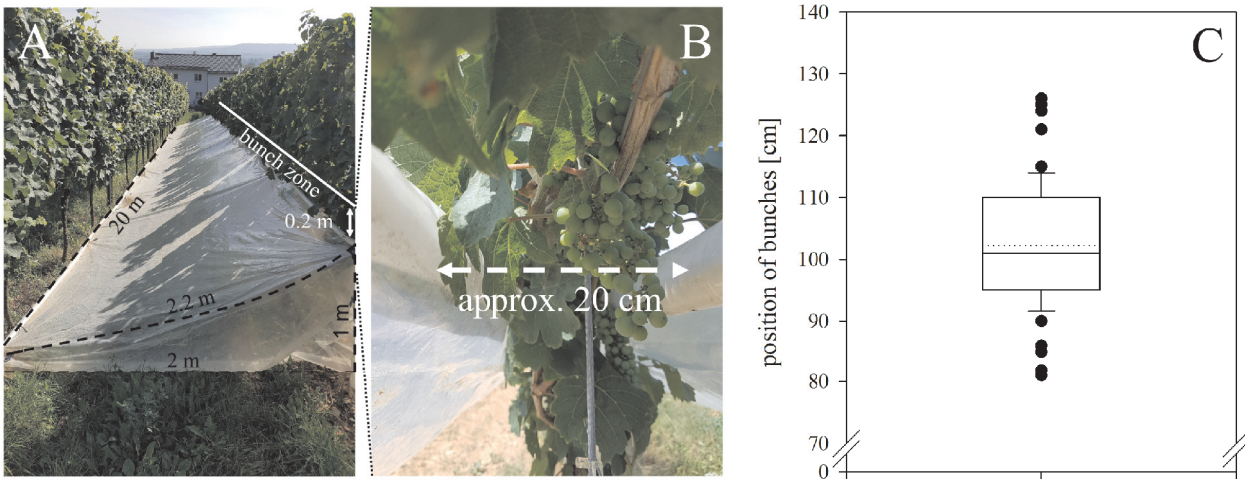

FIGURE 1. One side of the open heating system in the vineyard (A), close up of the opening of the open heating system in the middle of the bunch zone (B), bunch (n=67) height distribution above ground level (C).

The initiation of the treatments is expressed as days after flowering (DAF).

4. Sampling

Sampling for maturity analysis was conducted approximately every second week. Forty healthy berries (200 berries on the last sampling date) were randomly collected from both sides of the canopy for fruit composition measurements. To gain juice for analysis, the berries were pressed twice at 100 kPa for two minutes in a press (Longarone 85, QS System, Norderstedt, Germany) and centrifuged at room temperature (RT) for 5 min at 7830 rpm (6854 g) in 50 mL tubes (Eppendorf centrifuge 5430 R). For phenol analysis in berry skin, 20 berries per replicate were randomly sampled from both sides of the canopy. The berries remained intact including a small part of the stem, flushed with CO_2 immediately and frozen at -20 °C. Samples were taken on three dates per year.

3. Microclimate measurements

Relative humidity and temperature were recorded using data loggers (EL-USB-2, RH/Temp data logger) placed between 80 cm and 120 cm above ground level at 10 cm intervals. For canopy structure and light penetration into the bunch-zone, point quadrat was recorded according to Smart and Robinson (1991). The first measurement was performed shortly after DEF_E, and the second measurement after DEF_L. Percentage of gaps (PG), percentage of interior clusters (PIC), percentage of interior leaves (PIL) and leaf layer number (LLN) were calculated. Light conditions in the bunch zone were monitored using films consisting of a triacetylcellulose base and coated with a photosensitive azo dye (Taisei-Environmental and Landscape Group, Tokyo, Japan) and positioned as described by Bontempo *et al.* (2018). Films were placed in the bunch zone at a height of 110 cm. Measurements at every second vine resulted in nine films per replicate and 36 films in total per treatment. There were four measuring periods in 2017. For the first three periods, the films were placed in the vineyard on July 4, July 28 and August 22, removed after three days and the daily solar radiation was calculated. For the fourth measurement, the films were placed in the vineyard on September 12 and left in the field for one week prior to reading. For calculation of the solar radiation, the calibration curve of the manufacturer was used. Weather data were provided by the German Meteorological Service for the location Geisenheim at a distance of approximately 2 km from the experimental site. Long term phenological development for Riesling was recorded by Hochschule Geisenheim University.

4. Berry and juice analyses

The total soluble solids (TSS) content of fresh juice was determined using a handheld refractometer (HRKL32, A. Krüss, Germany). Yeast available nitrogen (N-OPA; N-acetyl-L-cysteine and o-phthaldialdehyde (OPA)) concentrations were measured according to Dukes and Butzke (1998) with a spectrophotometer (Specord 50 plus, Analytik Jena, Germany). To analyse the titratable acidity and the pH, a 719 S Titrino equipped with a 778 sample processor (Metrohm, Herisau Switzerland) was used. Organic acids (malic acid, tartaric acid, citric acid, shikimic acid, lactic acid, acetic acid) and monosaccharides (glucose, fructose) were analysed by HPLC (Agilent technologies 1100 series) equipped with a multi-wavelength detector (MWD) and a refractive index detector (RID) according to the method by Knoll *et al.* (2012) with adaptations. Organic acids were determined for frozen juice after thawing samples and heating to 65 °C for 12 min in a water bath to dissolve tartaric acid, citric acid was detected by MWD. For analysis of phenols in berry skin, the berries were peeled whilst frozen in an oxygen free CO_2 chamber. The skin was freeze dried, extracted and centrifuged. The supernatant was analysed by Thermo Finnigan Surveyo HPLC system (Dreieich, Germany) coupled to photo diode array detector (PDA) according to the chromatographic, detection and quantification method published by Friedel *et al.* (2015).

5. Data analysis

One-way analysis of variance (ANOVA) with subsequent pairwise multiple comparison (Student-Newmann-Keuls test) was carried out for normally distributed data (SigmaPlot version 11.0, Systat Software Inc.). Principal component analyses (PCA) were performed using auto scaling as data standardisation with MatLab R2016a software (The MathWorks, Natick, USA) with PLS toolbox version 8.1 (Eigenvector Research Inc., Manson, USA).

TABLE 1. Daily mean temperature, monthly sunshine hours and monthly precipitation for 30-year average (30-AVG; 1981-2010) as well as 2016 and 2017 at Geisenheim.

	Daily mean temperature [°C]			Monthly sunshine hours [h]			Monthly precipitation [mm]		
	30-AVG	2016	2017	30-AVG	2016	2017	30-AVG	2016	2017
April	10.3	9.5	9.9	179	159	192	35	58	5
May	14.7	15.0	15.8	208	195	221	52	78	76
June	17.7	18.0	20.0	212	157	256	50	97	46
July	19.7	20.3	20.3	231	198	212	59	16	87
August	19.0	19.8	19.1	214	246	203	45	28	72
September	14.8	18.6	14.0	150	215	128	49	16	45
October	10.2	10.0	12.1	96	62	97	48	70	32
April-October	**15.2**	**15.9**	**15.9**	**1289**	**1232**	**1309**	**338**	**363**	**363**

RESULTS

Compared to the 30-year average (30-AVG; 1981-2010), meteorological data for 2016 and 2017 differed dramatically between and within the seasons (Table 1). In May and June 2017, the temperature was warmer compared to the 30-AVG and 2016, which led to an early ripening. In 2016, from véraison onwards, it was hotter compared to the 30-AVG and 2017. The mean temperature for 2016 and 2017 from April to October was the same, and 0.7 °C higher compared to the 30-AVG. Growing degree days (GDD) for April until October were 1445 in 2016 and 1442 in 2017. Regarding the monthly sunshine hours (SSH), 2017 was sunnier compared to 2016 until August. The monthly SSH were low in June 2016 compared to the 30-AVG and to 2017 (100 SSH less). In August and September 2016 conditions were sunnier, especially during aroma development in September (+90 SSH) when compared to 2017. The monthly SSH from April to October were similar for the 30-AVG and 2017, whilst in 2016 SSH were 80 h less compared to 2017. Regarding the precipitation, 2016 was wet from April to June and afterwards dry until the middle of October compared to the 30-AVG. In 2017 the beginning of the growing season was drier compared to the 30-AVG and very wet in July and August. During the harvest period the precipitation was consistent with the 30-AVG.

The cumulative SSH and the cumulative precipitation were plotted from the day of budburst, referenced to the number of days from flowering (Figure 2). The first treatments (DEF_E and OHS) were established after flowering. Budburst was on April 26 in season 2016, which is the same as the 30-AVG for this variety, whilst for the 2017 season it was advanced by 14 days to April 12. Flowering occurred on June 15 in 2016, which is a day later than the 30-AVG, and on June 5 in 2017. Sunshine hours up to flowering differed for both seasons, with 93 SSH in 2016, and 215 SSH in 2017. In the next period until DEF_L was imposed, the cumulative SSH were similar; 364 SSH in 2016 and 323 SSH in 2017. Directly after DEF_L was initiated a very sunny period until harvest occurred in 2016, with 306 cumulative SSH whilst in 2017 only 212 cumulative SSH were recorded. At the beginning of berry development (flowering until DEF_E and OHS were initiated), about 120 more SSH were recorded in 2017 compared to 2016. At the end of the season during aroma development (initiation of DEF_L (véraison) until harvest), 2016 had about 90 cumulative SSH more than 2017. Precipitation was very high shortly after budburst until approximately 50 days after flowering in 2016 (Figure 2B), afterwards the season was dry. Reversed conditions occurred in 2017 where wet conditions after flowering occurred. In summary, 2016 was wet in the beginning and sunny at the end, 2017 was sunny in the beginning and wet at the end.

Figure 3A shows the diurnal temperature profile during two days at different heights within and above the OHS compared to CON on days with low (<2 SSH) or high radiation (>12 SSH). On days with low radiation there was hardly any effect on temperature within the OHS treatment

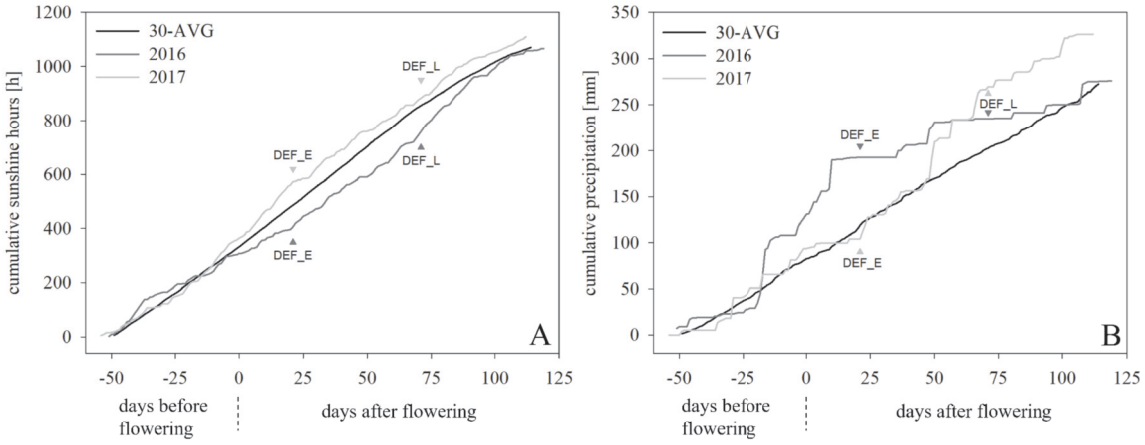

FIGURE 2. Comparison of cumulative sunshine hours (A) and cumulative precipitation (B) at Geisenheim for the 30-year average (30-AVG; 1981-2010), 2016 and 2017 seasons.
Different phenological stages are indicated below. Triangles represent the onset of the treatments.

TABLE 2. Point quadrat data for: percentage of gaps (PG), percentage of interior clusters (PIC), percentage of interior leaves (PIL) and leaf layer number (LLN) for 2016 and 2017 at two time points (after DEF_E and after DEF_L were applied).

	08.07.2016					05.07.2017				
	CON	DEF_E	DEF_L	OHS	P_ANOVA	CON	DEF_E	DEF_L	OHS	P_ANOVA
PG	4.50 b	18.00 a	n.m.	n.m.	0.022	3.50	7.50	2.00	2.00	0.076
PIC	81.32 a	12.52 b	n.m.	n.m.	<0.001	82.39 a	25.15 b	82.21 a	77.63 a	<0.001
PIL	27.19 a	9.11 b	n.m.	n.m.	0.029	33.38 a	14.35 b	33.54 a	31.67 a	<0.001
LLN	2.28 a	0.87 b	n.m.	n.m.	<0.001	2.68 a	1.13 b	2.74 a	2.63 a	<0.001
	31.08.2016					22.08.2017				
	CON	DEF_E	DEF_L	OHS	P_ANOVA	CON	DEF_E	DEF_L	OHS	P_ANOVA
PG	2.50	5.50	9.50	n.m.	0.078	1.50 c	4.00 b	7.50 a	1.00 c	<0.001
PIC	85.52 a	23.67 b	21.78 b	n.m.	<0.001	86.74 a	24.20 c	11.32 d	76.90 b	<0.001
PIL	37.29 a	13.34 b	11.21 b	n.m.	<0.001	36.27 a	14.53 c	14.60 c	28.63 b	<0.001
LLN	2.81 a	1.14 b	0.88 b	n.m.	<0.001	2.91 a	1.30 c	0.72 d	2.54 b	<0.001

Statistical differences between treatment means (n=4) at each point in time were assessed by one-way-ANOVA and post-hoc Student-Newmann-Keuls test; different letters indicate significant differences for the treatments, n.m., not measured.

compared to CON. On days with high radiation the data loggers recorded a temperature difference of up to 13 °C in the OHS compared to CON. At the opening of the OHS (100 cm) the temperature was up to 6 °C higher compared to CON. Higher temperatures in the OHS and at the opening were recorded for about eight hours. At 10 cm and 20 cm above the opening of the OHS the temperature effect lasted for about four hours with a maximum temperature difference compared to CON of 4 °C. For two periods in the developments of the fruits of each year; the intensity of radiation was grouped in low (<5 h) SSH days, intermediate (≥5 and <10 h) SSH days and high (≥10 h) SSH days (Figure 3B). The first period was after OHS installation until véraison (DEF_L) and the second period was after véraison until harvest. After véraison until harvest the number days with high SSH was more than three times higher in 2016 compared to 2017. The period before véraison is comparable for both years.

Details of the canopy structure and the light conditions inside the canopy are shown in Table 2 and Table 3. In 2016, DEF_E and CON were initially different for all parameters. At the second measuring, the percentage of interior clusters (PIC), percentage of interior leaves

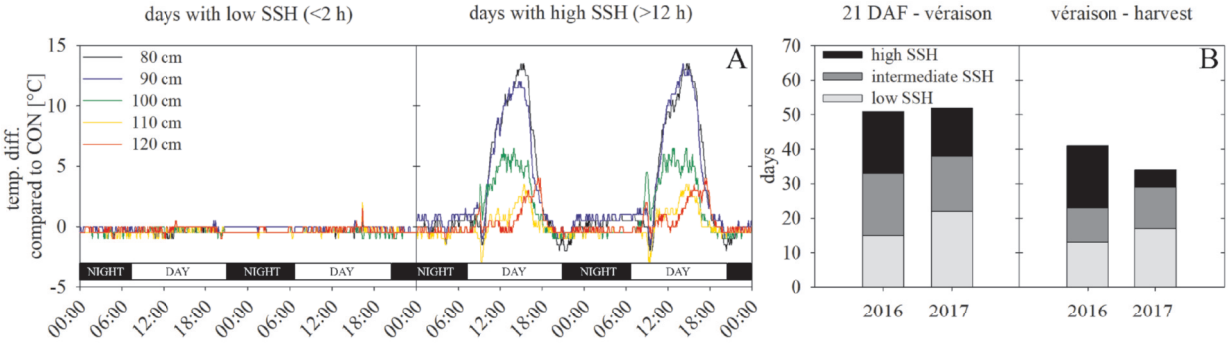

FIGURE 3. Temperature day courses recorded on (A) left, days with low sunshine hours (SSH, <2 h) and right, days with high SSH (>12 h) at different heights within the bunch zone. Middle height of the bunch zone and OHS opening refers to 100 cm; (B) number of days with low, intermediate and high SSH left 21 days after flowering (DAF) until véraison and right véraison until harvest in 2016 and 2017.

TABLE 3. Mean daily solar radiation [MJ/m²] during four measurement periods in 2017.

	CON	DEF_E	DEF_L	OHS	P_ANOVA
July 4 to 7	3.88	5.10	4.05	4.21	0.227
July 28 to 31	2.53 b	3.98 a	2.84 ab	2.98 ab	0.033
August 22 to 24	2.57 b	3.44 ab	4.11 a	3.07 b	0.010
September 12 to 19	1.46 b	1.71 ab	1.99 a	1.49 b	0.039

Statistical differences between treatment means (n=4) at each point in time were assessed by one-way-ANOVA and post-hoc Student-Newmann-Keuls test; different letters indicate significant differences for the treatments.

(PIL) and leaf layer number (LLN) showed a significant difference between DEFs and CON. At the first measuring in 2017, DEF_E differed significantly compared to the other treatments for PIC, PIL and LLN. Percentage of gaps (PG) in DEF_E was two to three times higher compared to the other treatments. After DEF_L was applied, a significant difference was observed between the treatments for all parameters. Regarding PIC and LLN, all treatments differed significantly between each other. DEF_E and DEF_L showed the lowest and almost the same values for PIL. In both years the defoliation treatments showed significant differences to CON. In 2017, CON and OHS did not show different conditions at the first measuring. At the second measuring there was a difference between CON and OHS for some parameters but substantially lower than the differences caused by the defoliation treatments.

No significant difference in solar radiation was found between treatments in the first sampling period (Table 3). Although DEF_E showed the highest amount of daily solar radiation compared to the other treatments. At the second time point a significant difference was found between DEF_E and CON. No significant difference was found for DEF_E and DEF_L or DEF_E and OHS. Comparing the means of the treatments, a clear difference between DEF_E and the other treatments occurred. At the third time point, shortly after DEF_L was applied, and at the fourth time point, solar radiation in DEF_L was significantly different to CON and OHS. DEF_E did not differ to the other treatments as only a single defoliation was applied.

Table 4 summarizes all harvest parameters for 2016 and 2017 at the end of the growing season. The influence of the treatments was significant for TSS concentration in 2016, but in 2017 no significant difference was recorded. At the beginning of véraison the berries of OHS had a higher concentration of TSS and a lower concentration of acids (Figure 4A). Compared to all other treatments, the ripening process was initially advanced for the OHS treatment, although the effect was greater in 2017 (Figure 4B). Prior to harvest the sugar accumulation rate of the OHS-treatment declined and was lower compared to the other treatments. In both years the lowest concentration in TSS was found for the OHS treatment at the last sampling date.

The glucose concentration and the fructose concentration were both significantly decreased

TABLE 4. Harvest parameters of treatments in 2016 (112 DAF) and 2017 (109 DAF).

	2016					2017				
	CON	DEF_E	DEF_L	OHS	P_ANOVA	CON	DEF_E	DEF_L	OHS	P_ANOVA
TSS [°Brix]	18.1 ab	18.7 a	18.6 a	17.0 b	0.017	19.4	19.0	18.9	18.3	0.070
Glucose [g/L]	85.4 a	88.8 a	87.7 a	79.0 b	0.018	92.8	90.9	89.4	87.0	0.114
Fructose [g/L]	87.2 ab	91.0 a	89.8 a	82.4 b	0.031	94.6	93.5	91.9	92.6	0.674
Glucose/Fructose	0.98 a	0.98 a	0.98 a	0.96 b	0.010	0.98 a	0.97 a	0.97 a	0.94 b	0.010
pH	2.88	2.90	2.93	2.90	0.290	2.87	2.85	2.89	2.91	0.101
TA [g/L]	10.5	10.5	10.1	9.9	0.098	12.5 a	12.2 a	12.0 a	10.0 b	<0.001
Tartaric acid [g/L]	6.3	6.5	6.1	6.4	0.075	7.0 a	7.1 a	6.7 b	7.1 a	0.034
Malic acid [g/L]	3.4	3.2	3.1	2.8	0.067	5.8 a	5.4 a	5.5 a	3.4 b	<0.001
Tartaric acid/ malic acid	1.90 b	2.04 b	1.97 b	2.33 a	0.028	1.21 b	1.31 b	1.22 b	2.13 a	0.015
Shikimic acid [mg/L]	37.3 a	35.9 a	30.2 b	33.8 a	0.005	37.0 a	35.1 a	32.6 b	29.8 c	<0.001
Citric acid [mg/L]	127.4	122.7	136.7	146.9	0.114	135.0	135.4	134.6	134.2	0.691
N-OPA [mg/L]	102.0	84.0	90.3	106.5	0.053	89.0	83.3	85.0	72.8	0.145
berry weight [g]	1.70 a	1.73 a	1.68 a	1.60 b	0.014	1.81 a	1.85 a	1.82 a	1.50 b	<0.001

Statistical differences between treatment means (n=4) at each point in time were assessed by one-way-ANOVA and post-hoc Student-Newmann-Keuls test; different letters indicate significant differences for the treatments.

by OHS compared to the other treatments in 2016; in 2017 no significant effects were observed. Nevertheless, in both years the ratio of glucose to fructose was significantly influenced by OHS (Table 4), the concentration of glucose decreased compared to the fructose concentration (Figure 4C,D). The malic acid concentration decreased faster in the OHS compared to the other treatments (Figure 4A,B), which caused a significant influence on the ratio of malic and tartaric acid (Table 4). In 2017, the warm and sunny period at the beginning of the season and at the installation of the OHS caused an early ripening and an intense heating effect. The malic acid concentration was approximately 4.5 g/L less at véraison (determined for translucent yellow green berries of CON) and at harvest approximately 2 g/L lower in OHS compared to the other treatments (Figure 4B). In 2016 the decline in the malic acid concentration was smaller (0.5 g/L) between OHS and the other treatments and the difference did not change during the whole season (Figure 4A).

In both years, DEF_L had the lowest concentration of tartaric acid (Table 4). In 2017, there was a significantly lower tartaric acid concentration for DEF_L compared to the other treatments. In both years, CON showed the highest concentration of shikimic acid. In 2016, the concentration of shikimic acid was the lowest for DEF_L, whilst OHS was slightly higher. In 2017, OHS and DEF_L also showed low concentrations, while OHS had the lowest concentration of shikimic acid compared to the other treatments. No significant differences were observed for pH, citric acid concentration and N-OPA content in both years. In 2016 the defoliation treatments showed lower values of N-OPA, while in 2017 OHS showed the lowest value. In both years the berry weight was significantly reduced by OHS. In 2016 the lower berry weight became apparent after véraison (Figure 4E), whereas in 2017 at véraison the berry weight of OHS was already significantly lower compared to the other treatments (Figure 4F).

The response of flavanols, hydroxycinnamic acids and flavonols, summarized as phenols, to light and heat differed dramatically within the treatments and with vintage (Table 5). The concentration of flavanols (procyandin B1, catechin, epicatechin) was always higher for the defoliation treatments in 2016. However, within this group no significant difference was observed between DEF_E and DEF_L. In 2017, there was

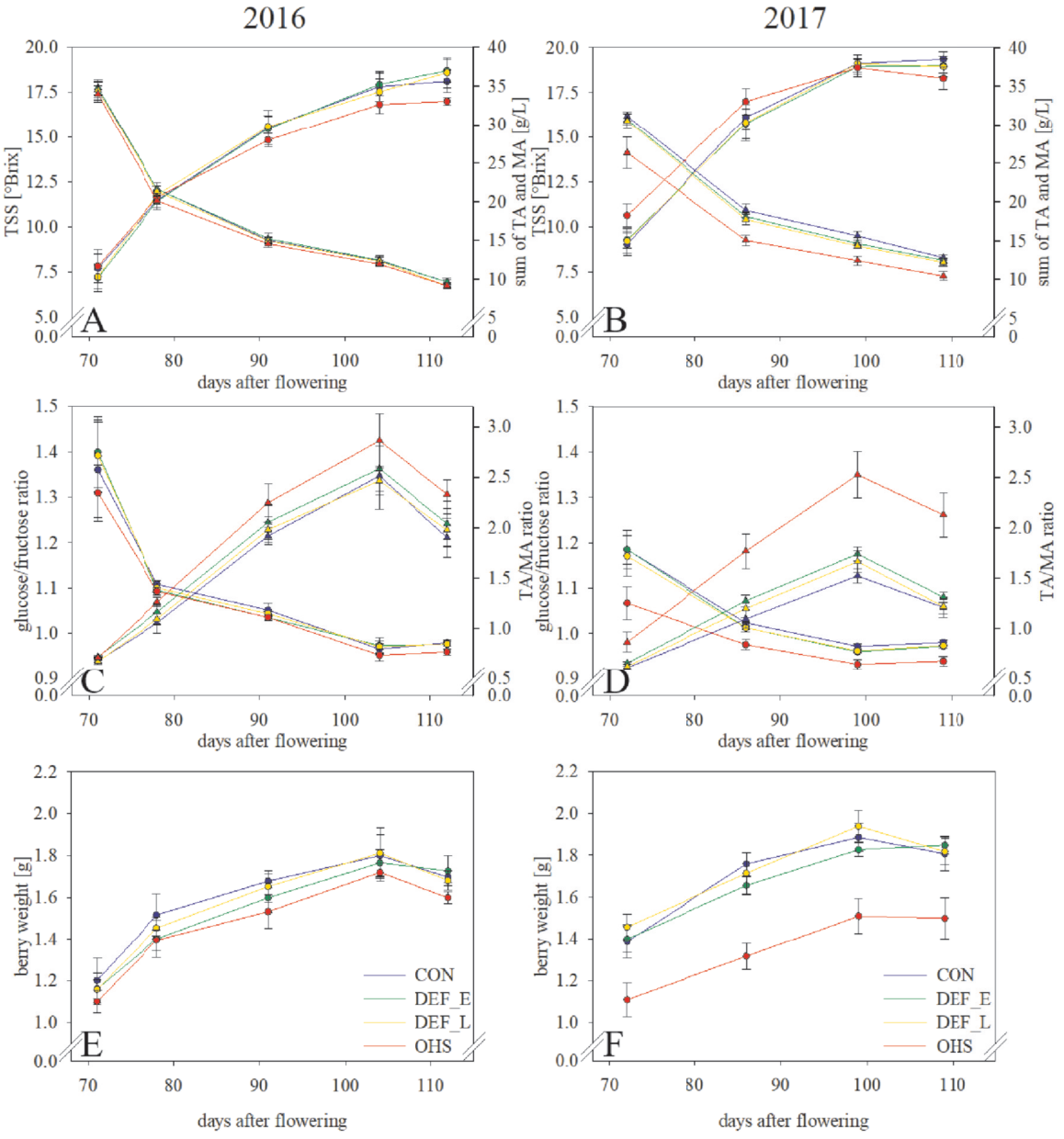

FIGURE 4. Development of TSS (●) and sum (▲) of tartaric acid (TA) and malic acid (MA) for 2016 (A) and 2017 (B), of glucose/fructose ratio (●) and TA/MA ratio (▲) for 2016 (C) and 2017 (D) and of berry weight in 2016 (E) and 2017 (F); means (n=4) ± SD.

no significant difference between the treatments for the same group of flavanols and the single compounds.

The concentration of hydroxycinnamic acids was the lowest in DEF_L and the highest in CON in 2016 and 2017. Only in 2016 were the results significant. In both years, CON had the highest concentration of caftaric acid and DEF_L had the highest concentration of fertaric acid. Comparing the years, there was no clear influence of the defoliations or the OHS-treatment on hydroxycinnamic acids, as a group or single compounds, except for fertaric acid, where the results were significant in both years.

The flavonol concentration was influenced most by the treatments. In both years, berries from the defoliation treatments had the highest concentration of flavonols and DEF_E always showed higher concentrations than DEF_L. In both years, que-3-rutinoside and que-3-glucuronide were highest for DEF_E. For DEF_L, the que-3-galactoside, que-3-glucoside,

TABLE 5. Concentration of phenols in berry skin fresh weight [µg/g] at the final berry sampling date of phenol analysis in 2016 (104 DAF) and 2017 (106 DAF).

	2016					2017				
	CON	DEF_E	DEF_L	OHS	P_ANOVA	CON	DEF_E	DEF_L	OHS	P_ANOVA
Flavanols										
Procyandin B1	67 b	95 a	82 ab	67 b	0.005	89	92	88	76	0.290
Catechin	48	67	63	47	0.051	57	56	49	52	0.605
Epicatechin	23	42	42	27	0.201	13	19	22	16	0.129
Sum flavanols	138 b	204 a	187 a	141 b	0.009	159	167	160	144	0.573
Hydroxycinnamic acids										
GRP	2.3	2.8	2.8	3.0	0.586	1.9 a	1.2 b	1.3 b	1.5 ab	0.031
Cumaroyl-glucose	21 a	21 a	17 b	18 b	0.037	27	27	22	25	0.067
Caftaric acid	583 a	515 ab	434 b	459 b	0.028	612	581	532	563	0.591
Coutaric acid	205 a	209 a	144 b	159 b	0.005	150	152	123	157	0.438
p-CGT	7.8	8.6	7.2	7.7	0.494	13.1	11.5	10.7	10.2	0.278
Caffeic acid	26.7	28.7	30.7	27.3	0.248	25.1	28.8	28.4	29.7	0.234
Fertaric acid	15 c	21 b	28 a	22 b	0.009	12 c	14 b	19 a	12 c	<0.001
Sum hydroxycin. acids	859 a	803 ab	661 b	689 ab	<0.001	838	813	735	796	0.646
Flavonols										
Que-3-rutinoside	28 b	81 a	33 b	27 b	<0.001	47 b	144 a	59 b	77 b	<0.001
Que-3-galactoside	33 c	88 b	106 a	46 c	<0.001	69 c	147 a	162 a	92 b	<0.001
Que-3-glucoside	167 c	413 b	561 a	235 c	<0.001	332 c	670 b	828 a	430 c	<0.001
Que-3-glucuronide	184 b	537 a	258 b	198 b	<0.001	286 b	720 a	291 b	396 b	<0.001
Que-3-xyloside	2.0 b	5.4 ab	6.8 a	4.2 ab	0.011	3.7 b	7.8 a	8.8 a	5.0 b	0.001
Que-3-arabinoside	17 b	62 a	55 a	24 b	<0.001	39 b	134 a	137 a	69 b	<0.001
Que-3-rhamnoside	34 c	120 a	147 a	56 b	0.004	79 d	251 b	359 a	129 c	<0.001
Sum flavonols	464 b	1306 a	1165 a	591 b	<0.001	856 c	2074 a	1843 a	1198 b	<0.001
Sum phenols	1460 b	2313 a	2013 a	1420 b	<0.001	1853 b	3054 a	2737 a	2138 b	<0.001

GRP= grape reaction product, p-CGT= p-coumaroylglycosyltartrate, Que= quercetin; statistical differences between treatment means (n=4) at each point in time were assessed by one-way-ANOVA and post-hoc Student-Newmann-Keuls test; different letters indicate significant differences for the treatments.

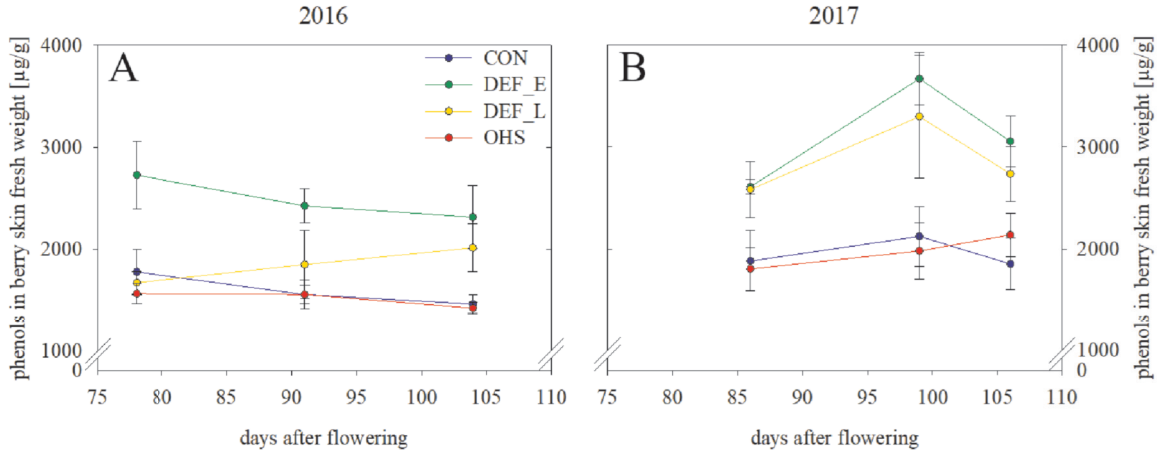

FIGURE 5. Changes in phenol concentration over time, from the beginning of aroma development to harvest in 2016 (A) and 2017 (B); means (n=4) ± SD.

que-3-xyloside and que-3-rhamnoside were amongst the highest. The concentration of a single flavonol in a defoliation treatment compared to CON was up to five times higher. In 2016, for example, the mean concentration of que-3-rhamnoside in berry skin was 34 µg/g in CON and 147 µg/g in DEF_L.

In 2016, the highest concentration of phenols was found in DEF_E, followed by DEF_L, CON and OHS. OHS showed higher concentration of flavonols but lower concentration of hydroxycinnamic acids compared to CON. All three groups of flavanols, hydroxycinnamic acids and flavonols summarized as phenols, showed significant differences. In 2017 only the flavonol group showed significant differences across the treatments. Regarding the sum of phenols, DEF_E had the highest concentration again followed by DEF_L. Although not significant, OHS showed higher concentrations of phenols compared to CON which was caused by higher amounts of flavonols. The sum of phenols of CON was approximately 400 µg/g higher in berry skin in 2016 compared to 2017. For both defoliations and OHS, a rise of approximately 700 µg/g phenols in berry skin was observed.

The development of the phenols can be found in Figure 5. At the beginning of aroma development in 2016 (Figure 5A), the concentrations of DEF_E differed strongly compared to the other treatments, mainly caused by almost three times higher flavonol concentrations (DEF_E: 1145 µg/g, CON: 468 µg/g, DEF_L 485 µg/g and OHS 417 µg/g). DEF_L was initiated one week (71 DAF) before sampling (78 DAF) and behaved consistent with CON at this point in time. However, DEF_L resulted in a strong formation of phenols, especially of flavonols during aroma development at the end of the season and did not differ from DEF_E by harvest. In 2017, and prior to the treatment, both defoliation trials showed the same concentration of phenols. The treatment DEF_L was initiated two weeks (71 DAF) before the first phenol sampling (86 DAF). The concentration of phenols increased until the second sampling date and decreased close to harvest.

Figure 6 shows a principal component analysis (PCA) of phenols and maturity data from the years 2016 and 2017. For 2017, the PCA uses the data from Table 4 and Table 5 with the phenol levels and maturity determined at 106 and 109 DAF respectively. For 2016, where there was an 8-day difference between the sampling for phenols at 104 DAF and harvest at 112 DAF, maturity data (not shown) from 104 DAF has been used instead for the PCA. At this point in time the concentrations of sugars, malic acid and N-OPA were lower; tartaric acid and titratable acidity (TA) were higher compared to the concentrations of 2017. PC1 was mostly associated with variation between the vintages, with some separation of treatment effects. PC2 discriminated between treatments within season. Besides the influence of the vintage, the CON treatment is separated from the DEF treatment by PC2; OHS is intermediate.

In 2017 the phenol content was twice to that in 2016 which can be seen in the loadings plot where the phenols are oriented on the right-hand side of PC1. The fertaric acid, epicatechin and coutaric acid are found to be negatively correlated to the rest of the phenols (vintage

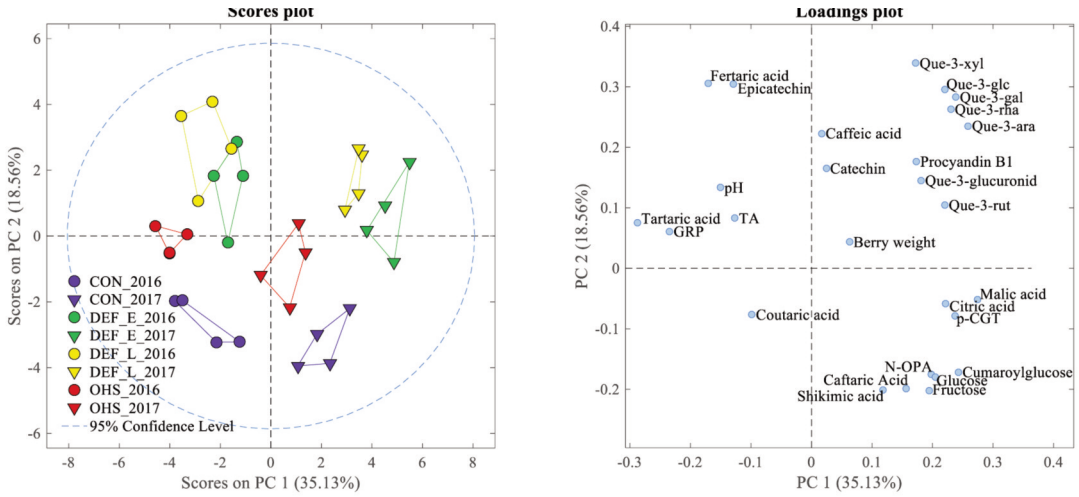

FIGURE 6. Scores and loadings plot of principal component analysis (PCA) of the last sampling date for phenols and corresponding maturity data in 2016 (104 DAF) and 2017 (106 DAF); TA= titratable acid, GRP= grape reaction product, p-CGT= p-coumaroylglycosyltartrate, Que= quercetin.

effect). In both vintages the treatments affect the concentration of the phenols. The tartaric acid and the total acidity are higher in 2016 samples than in 2017. The malic acid and the tartaric acid are negatively correlated as could also be seen in loadings plot.

DISCUSSION

This study investigated the impact of elevated temperatures on Riesling berry composition using an open heating system (OHS) or various defoliation treatments to increase bunch exposure to solar radiation. Whilst defoliation affects mainly the surface temperature of the exposed berries, the peak temperature of individual berries may vary dramatically in absolute maximum values and its duration (Smart and Sinclair, 1976). In contrast, OHS increases the air temperature through the bunch regardless of the sun exposure. The increase in air temperature introduced through the OHS was around 5 °C at the opening and up to 2 °C at the edge of the bunch zone. Sadras and Soar (2009) achieved a maximum effect of 2-4 °C at the bunch height and obtained similar results to those achieved in this study. Their row distance (3.0 m) was wider compared to our row distance (2.1 m) with reduced shading effects. However, the efficiency of such passive heating systems depends on the frequency of radiation days and sunshine hours which occurred more frequently at the experimental site located in Australia.

Characterization of canopy structure and light conditions inside the canopy by point quadrat and light sensitive films showed significant differences between control (CON) and defoliations (DEFs). The use of light sensitive films allowed quantification of the cumulative solar radiation inside the canopy over a short time period. The films were placed in the middle of the canopy and had the lowest sun exposure. It has been shown recently, that the light sensitive films are not overly sensitive to temperature (Bontempo *et al.*, 2018). A further advantage of the films is that they provide cumulative measurements of solar radiation over a measured time period. To relate point quadrat readings to quantified measurements using light sensitive films, it was concluded that the surface area of the films is rather small (20 mm x 35 mm), and that a film might be shaded by a bunch or a leaf. This may explain the different results for the treatments in 2017, where the first point quadrat result showed significant differences between the treatments whilst the measurement of solar radiation by the films did not show a significant difference over the same time period. This variation shows the need for different measurements to characterize the canopy structure and solar radiation in the canopy.

Temperature influences the phenological development of the vines. Higher temperatures lead to an earlier budburst, flowering and ripening. Temperature also has an impact on berry weight. Hale and Buttrose (1974) showed temperatures above 30 °C reduced the berry size. In 2017 the temperature effect of the OHS had a strong influence as the berry weight was 17% lower than the other treatments over the season. In 2016, a decrease in the berry weight of 5%

was observed at the end of the season. This less intense reduction in berry weight with OHS compared to CON observed in 2016 may be caused by the high precipitation and low sun radiation at the beginning of ripening. After véraison, effects of temperature on berry size are less noticeable (Keller, 2010). Bonada *et al.* (2015) used an open top chamber with and without irrigation and observed a decrease of 8% in berry weight for heated berries without irrigation, but little effect (-2%) on berry weight for heated berries with irrigation. Furthermore, higher temperatures are likely to increase to total soluble solids (TSS) and produce lower titratable acidity (TA) in Riesling (Bock *et al.*, 2011; Duchêne and Schneider, 2005; Urhausen *et al.*, 2011). For Riesling, a rise of approximately 0.6 °Brix per decade was observed between 1949-2010 in Franconia, Germany (Bock *et al.*, 2011). However, TSS accumulation can also be decreased by temperatures above 30 °C (Kriedemann and Smart, 1971). Greer and Weston (2010) showed in their studies also, the time period (flowering, fruit set, véraison, mid ripening) of hot weather conditions (40/25 °C day/night temperatures over 4 days) had an influence on the rate of sugar accumulation. In 2016, budburst was at the same date as for the 30-year average (30-AVG, 1981-2010). In 2017, the early warm period caused a 14 days earlier budburst compared to the 30-AVG. At the first sampling date in 2017 (72 days after flowering (DAF)), TSS was 1.5 °Brix higher in OHS compared to CON. At the last sampling date in 2017 (109 DAF), OHS had approximately 1 °Brix less compared to CON. At the beginning of the season the ripening of OHS was advanced compared to the other treatments. This result confirms the results of other studies, showing an earlier ripening caused by warmer temperatures. During the season, high temperatures from the OHS may have led to a decline in sugar accumulation and resulted in a lower TSS content. In 2016, at the beginning of sampling (71 DAF), no difference between CON and OHS was recorded while at the end of the season (112 DAF) OHS had 1 °Brix less compared to CON, as found in 2017. Defoliation treatments had no significant influence on TSS, which was also observed for Riesling by Friedel *et al.* (2015). In both years the glucose to fructose ratio significantly decreased for OHS compared to the other treatments. Kliewer (1967) showed a decrease in the glucose to fructose ratio in vintages with higher temperatures.

It has been noted in many other studies that the acidity content decreases under warmer temperatures due to malic acid respiration (Buttrose *et al.*, 1971; Lakso and Kliewer, 1975; Ruffner *et al.*, 1976), whereas the concentration of tartaric acid is unaffected (Kliewer, 1965; Rienth *et al.*, 2016). At the beginning of véraison in 2017, the mean malic acid concentration was 14.2 g/L in OHS compared to CON (19.4 g/L) a reduction of approximately 27%, while prior to harvest it was approximately 42% less in OHS (3.4 g/L) compared to CON (5.8 g/L). In 2016 the concentration of malic acid was approximately 3% less for OHS (19.9 g/L) compared to CON (20.6 g/L), for first sampling date and 18% less for OHS (2.8 g/L) compared to CON (3.4 g/L) at the last sampling date. The ratio of tartaric acid to malic acid is significantly influenced by temperature effects in both years. Tartaric acid is synthesized during early stages of berry development. In both years, DEF_L had the lowest concentration of tartaric acid, even though DEF_L and CON had the same conditions during early stages until véraison. In both years CON showed the highest values of shikimic acid at the last sampling date. In 2016, DEF_L had the lowest concentration of shikimic acid. This might be due to the intense sun radiation shortly after the defoliation. In 2017, OHS showed the lowest concentration of shikimic acid followed by DEF_L. In both years the results were significantly different. Even though the concentration of malic acid and consequently the TA were significantly decreased by OHS, no effect on the pH was observed. The yeast available nitrogen content expressed as N-OPA, was lower in 2016 for the DEFs compared to CON and OHS. Our results in 2016 point towards the results of Friedel *et al.* (2015), who showed that exposed berries had lower N-OPA concentrations compared to shaded berries. In 2017, the DEFs had similar concentrations compared to CON, whereas OHS showed the lowest concentration.

The sum of flavanols was significantly increased for DEFs compared to CON and OHS with a sunny period during aroma development in 2016. In 2017, no differences between treatments were observed during low levels of solar radiation in the aroma development period. Friedel *et al.* (2015) did not observe an influence of shading or leaf removal on flavanol concentrations, with only a slight increase in catechin. Koyama *et al.* (2012) showed a light-

induced increase in flavanol accumulation for higher porosity treatments when applied at flowering. At the first sampling date in 2016, higher flavanol levels occurred for DEF_E while at the last sampling date, DEF_E and DEF_L showed similar elevated levels compared to CON and OHS. In contrast to Friedel *et al.* (2015) an influence of defoliation was observed when high solar radiation levels occurred during aroma development. In contrast to Koyama *et al.* (2012), the DEF_L treatment showed higher flavanol concentrations. The influence of temperature on flavanol biosynthesis is not well understood (Gouot et al., 2019). The *in-vitro* studies of Ayenew *et al.* (2015) and Degu *et al.* (2016) found effects of high temperatures on flavanols in red berry skin and showed conflicting results, for epicatechin for example. Ayenew *et al.* (2015) reported a decrease in epicatechin and procyanidin, whilst Degu *et al.* (2016) showed an increase in epicatechin with higher temperatures.

The influence of the treatments on hydroxycinnamic acid concentration differed over time. In both years, DEF_L showed low concentrations of caftaric acid, coutaric acid and cumarolyglucose and high concentrations of caffeic acid and fertaric acid compared to CON. DEF_L and OHS had mostly similar concentrations. DEF_E showed similar concentrations compared to CON. A similar treatment effect comparing DEF_L and CON was observed by Friedel *et al.* (2015). Limited data is available for hydroxycinnamic acid in *Vitis vinifera,* with most studies investigating the influence of light.

The greatest influence of light was observed for flavonols through different timing of defoliation treatments. In 2016 at the first sampling date (78 DAF), DEF_L had the same concentrations of flavonols as CON and OHS, whilst DEF_E showed almost three times higher concentrations. During the aroma development and at the last sampling date (104 DAF), DEF_L showed almost the same flavonol concentrations as DEF_E, whereas CON and OHS remained almost unchanged from the earlier sampling dates. The flavonol concentration of DEF_E only increased by 10%, whereas with DEF_L the increase was 250%. In 2017, at the last sampling date (106 DAF) the increase of flavonols for OHS was twice as high compared to CON. DEF_E showed a 30% increase in flavonols and DEF_L a 20% increase. Both DEFs showed more than two times higher concentrations of flavonols compared to CON. From the implementation of DEF_E, until the first sampling date for phenols, 430 SSH were recorded in 57 days in 2016. The berries of DEF_L were exposed for 64 SSH in 6 days until the first sampling. In 2017 DEF_E had 424 SSH over 64 days and DEF_L 103 SSH over 12 days from treatment initiation until the first sampling. This may explain the different levels of flavonols for the early and late DEF at the first sampling date. In 2017, there was more time from treatment initiation until the first sampling point for DEF_L which was influenced by more SSH giving similar flavonol levels to DEF_E. In 2016, the time was too short to reach higher levels compared to CON at the first sampling date. From the first to the last sampling date 189 SSH (over 26 days) in 2016 and 94 SSH (over 23 days) in 2017 were recorded. The high solar radiation in 2016 produced a rapid increase in the concentration of flavonols for DEF_L. Mori *et al.* (2005) investigated the effect of elevated night temperatures (30 °C vs. 15 °C) and constant 30 °C day temperature on red grape berry flavonols. Similar to the findings of Spayd *et al.* (2002), Mori *et al.* (2005) also found no effect of temperature treatments on flavonols.

The PCA showed separation of vintages on PC1, and separation of the treatments of PC2. The impact of vintage was stronger than the treatment effect, which may reflect the contrasting weather conditions of the two seasons. However, the distribution of the treatments in both years was very similar, indicating similar relative responses of the defoliation and heating treatments compared to the control. Flavonols had strong loadings on PC1 and PC2, indicating their strong responsiveness to weather conditions and treatments. Phenols are produced via metabolic pathways which are driven by enzymes and influenced by temperature, light and plant water status (Jackson and Lombard, 1993). Consequently, a direct relationship between the concentration of phenols and the influence of defoliation and heat treatments cannot be determined. In summary, the phenol concentration was mainly impacted by defoliation. The impact of temperature on phenols was small or non-existent, depending on the timing of heat effects on the bunches.

Higher phenol content in berry skin leads to an astringent taste of the wine. For Riesling its

fruity character and a balance between sweetness and acidity is desired. Trying to mimic future scenarios of increasing temperature through OHS, it was found that malic acid was reduced, smaller berries were produced, and the glucose/fructose ratio changed with potential impacts on wine style. Furthermore, a high degree of bunch exposure strongly increased phenol content with potential impacts on astringency of the taste and, to a lesser extent, on sugar and acidity balance.

Defoliation practices have been considered as a powerful tool to improve berry health and quality. However, under higher temperature, these practices in Riesling will need to be considered more carefully in relation to timing and intensity in order to maintain a desired wine profile.

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