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ORIGINAL RESEARCH ARTICLE

Delayed grape ripening by intermittent shading to counter global warming depends on carry-over effects and water deficit conditions

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ABSTRACT

Grapevine phenology is continuously advancing due to global warming, exposing berry ripening to increasingly drier and hotter episodes that can dramatically affect yield and berry quality. This study aimed to analyse whether intermittent shading produced by panels placed over the plants can delay berry ripening to counter the impact of global warming on phenology. A two-year outdoor trial repeated on two batches of young potted grapevine (cv. Syrah) was conducted in Montpellier (South of France). Shading was created in a row using 2 m-wide horizontal panels placed 2.4 m above the ground. A moderate water deficit was also applied at the start of veraison to half the plants in both full sun (without panels) and shaded conditions to mimic usual field conditions. Variables related to budburst, flowering, veraison and sugar at harvest were analysed in all treatments. Although intermittent shading did not significantly modify air temperature within the canopy when cumulated over the growing season, the panels substantially delayed veraison by up to more than 30 days under well-watered conditions. The most marked phenological shifts were noted in the second year of treatment between flowering and veraison when carbon demand sharply increased during berry formation, suggesting there was a carry-over effect likely due to limited carbon assimilation. This was accompanied by sharp decreases in berry diameter and sugar content per berry at harvest. Higher berry growth and sugar loading were maintained when shading was combined with water deficit. However, the trigger effect of water deficit on veraison almost halved the phenological delay caused by the panels. Overall, a cooler period for ripening could be achieved with panels over the vines but at the expense of berry size and sugar amount in berries. It can be concluded that shading intensity and duration should be adapted to evaporative and soil water conditions to benefit from the phenological delay caused by panels, without altering production in the long term.

KEYWORDS: Grapevine, shading, phenology, water-deficit, cumulative effect

INTRODUCTION

Climate change is threatening agriculture with an increasing frequency of heat waves, drought episodes and extreme climatic events (Pörtner *et al.*, 2021). The threat is particularly significant for crops completing their productive cycle in warm and dry seasons, such as grapevine (Hannah *et al.*, 2013). By accelerating the phenological development of the vines, global warming results in the ripening period shifting to hotter and drier conditions in midsummer (Duchêne *et al.*, 2010; van Leeuwen and Darriet, 2016). This, in turn, can cause yield loss due to growth arrest or dehydration of berries, resulting in high sugar concentration and wines that are too high in alcohol and bland (Jones and Davis, 2000).

Several technological breakthroughs are currently being tested to protect grapevine from dry and hot summers, such as nebulisation (Paciello *et al.*, 2017), shading nets (Lu *et al.*, 2021) or application of kaolin on canopies (Cataldo *et al.*, 2022). Agrivoltaics, which consists of installing photovoltaic panels over a crop, is a more recent promising solution to mitigate the undesired effects of climate change on crops, while meeting the increasing demand for green energy (Weselek *et al.*, 2019). This innovative concept, which combines crop and energy production within the same area, is booming all over the world (Dupraz *et al.*, 2011; Mamun *et al.*, 2022). It has proved efficient for vegetable crops (Elamri *et al.*, 2018; Laub *et al.*, 2022; Valle *et al.*, 2017) and could also benefit vineyards located in drought-prone areas with high levels of temperature and radiation. Recent trials in Korea reported similar production between three types of solar panels (normal, bifacial and transparent) without any substantial loss in grape yield (Cho *et al.*, 2020). Using agrivoltaics on grapevine could also reduce the temperature at crop level, thereby counteracting the phenological acceleration induced by global warming and improving ripening conditions. Moreover, the use of agrivoltaic systems can potentially protect fruit from getting burnt by direct sunlight during periods of high temperature and excess solar radiation (Pereira *et al.*, 2006; Gambetta *et al.*, 2021). However, the effects of agrivoltaics and intermittent shading are still poorly documented (Weselek *et al.*, 2019; Mamun *et al.*, 2022), requiring further investigation, especially in grapevine.

Most studies on the impact of shade on grapevine has focused on permanent shading nets, which consistently reduce light intensity. Such shading typically alters carbon assimilation at leaf level (Cartechini and Palliotti, 1995; Greer *et al.*, 2011). A series of physiological acclimations, called the shade avoidance syndrome, may partly compensate for this reduced assimilation due to low radiation (Ballaré and Pierik, 2017; Niinemets, 2010). Shading can also benefit the crop by inducing stomatal closure and reducing evaporative demand, which in turn lowers water stress (Caravia *et al.*, 2016; Oliveira *et al.*, 2014). In addition, shading protects the crop from excess radiation, which can cause oxidative stress, notably when combined with water deficit (Caravia *et al.*, 2016).

Each of the main phenological stages in grapevine, although mainly driven by temperature (Lebon *et al.*, 2004; Zapata *et al.*, 2015), may also be influenced by the above-mentioned changes in carbon assimilation and water relationships in response to shading. Budburst not only depends on winter temperature but also on the remobilisation of carbon stored in roots and perennial parts during the preceding year (Zapata *et al.*, 2004). Flowering follows as the result of a long-lasting process overlapping two consecutive years (Lebon *et al.*, 2008). It begins with the differentiation of inflorescence primordia in the spring of one year which lasts until dormancy, and continues into the spring of the following year with flowering controlled by high temperature and high light intensity (Carmona *et al.*, 2007; Vasconcelos *et al.*, 2009). After pollination and fruit setting, berry growth follows a double sigmoidal pattern interrupted by a lag phase. At the end of the lag phase, berries start to accumulate sugar then change colour (veraison) (Conde *et al.*, 2017). Ripening mostly coincides with the second growth phase. Non-irrigated vineyards commonly experience soil water deficit during the late stages. When moderate, water deficit accelerates ripening by increasing plant temperature and promoting ABA biosynthesis, which favours the onset of sugar accumulation and veraison (Kuhn *et al.*, 2014). Water deficit during ripening also leads to a higher concentration of metabolites in berries due to lower water accumulation or higher water losses, which improve harvest quality provided that water stress and berry dehydration are not too severe (Chaves *et al.*, 2010; van Leeuwen *et al.*, 2009; Martínez-Lüscher *et al.*, 2016). By contrast, severe water deficit can also shorten the fruit-set to veraison period and slow down sugar accumulation, thus delaying maturity (Martínez-Lüscher *et al.*, 2015; Martínez-Lüscher *et al.*, 2016). Shading can be expected to moderate these soil water deficit effects on plant phenology, yet little research has been carried out to evaluate the combined effects of water stress and shading on grapevine development (Pallas and Christophe, 2015).

In spite of the various and sometimes opposing influences of shading on plant physiology, delayed veraison has been consistently reported in response to permanent shading on parts or the totality of the vine during long periods of the plant cycle (Cartechini and Palliotti, 1995; Lu *et al.*, 2021). However, panels produce intra-day alternations of shaded and unshaded periods that may alter phenology and ripening in a different way to permanent shading. Moreover, effects may vary with repeated shading over years. For example, it can be questioned whether hindered carbon storage due to unfavourable climate in a given year (Dayer *et al.*, 2013; Vaillant-Gaveau *et al.*, 2014) can modify phenology in the following years. It is crucial to fill these knowledge gaps in order to be able to better design agrivoltaic systems and increase their efficiency.

This study examines whether daily transient shading, such as that produced by panels above plants, benefits grapevine by delaying phenology and lowering temperature during ripening as expected from previous experiments using permanent shading.

To achieve this aim, experiments were conducted on young potted graftings that were installed under shading panels. The resulting impact on temperature at the canopy level - being the primary driver of plant development - was first examined. To account for any possible cumulative effects of shading over years, we also characterised the effects on phenology, berry development and sugar accumulation in two consecutive years of treatment. Moreover, since grapevine is often grown in drought prone areas where moderate soil drying favors harvest quality, we compared shading effects under two soil water conditions: well-watered and moderate water deficit.

MATERIALS AND METHODS

1. Plant material and growth conditions and treatments

The experiments were conducted outdoors at the Institut Agro Montpellier (South France, 43.617 °N, 3.856 °E) on 2- to 3-year-old potted grapevines (cv. Syrah clone 747, grafted on 110 Richter clone 163, VCR, France), which were submitted to different treatments for two consecutive years. Experiments began in 2018 with a first batch of plants, and the results for the first and second year of treatment were annotated 2018_1 and 2019_2 respectively. A second batch of plants was experimented on 2019 and 2020 and the results were similarly annotated 2019_1 and 2020_2. Prior to the experiments, the plants were grown with one shoot in 3-L pots with optimal ferti-irrigation during one year. In the spring preceding the first year of experiments, the plants were re-potted in 9-L pots containing a 30:70 (v/v) mixture of loamy soil and organic compost (Portoleau, Klasmann-Deilmann, France). The plants were then pruned to one newly developed primary shoot and vertically trained. To prevent the plants from touching the panels, the primary shoots were trimmed to just above the 20th leaf position from the shoot base in mid-June in the first year of treatment, or to above the 15th leaf position of the same plants in the second year due to the longer shoots. All axillary buds were removed except one that was left to grow until the end of July and another one until leaf fall. These secondary shoots were bent during their development before they touched the panel. With this training system, the row width remained below 40 cm. Plants bore 1 or 2 clusters on their primary axes.

Rows of potted grapevines were orientated NNW-SSE with 1.70 m between rows. For the shading treatment with panels (P), a row of joint, horizontal, opaque panels (2 m wide, approx. 20 m long) was installed coaxially with a row of vines at 2.40 m above ground level (Supplementary Figure 1). The panels were made of twinwall polycarbonate; their upper surfaces were painted white to avoid excessive heating and their under surfaces painted black. The objective was to reduce available radiation under the panels by about 50 % by following conclusions from pioneering work in agrivoltaics (Marrou *et al.*, 2012). One row of control plants was exposed to full sun conditions (FS) without any influence from panels. These light or shading treatments (FS, P) were applied to both batches of plants in two successive years from budburst

of the first year (2018 and 2019 for the first and second batch of plants) until harvest of the following year.

Before veraison in each experimental year, the plants were drip-irrigated up to 8 times a day with a mean of 1.9 g water per g of dry soil in order to maintain well-watered conditions (WW). At veraison, when the berries in FS conditions were just beginning to turn red, half the plants of each light treatment were kept well-watered, while the other half was submitted to moderate soil water deficit (WD) by restricting irrigation until the soil contained no more than 1.1 g water per g of dry soil. This level was maintained thereafter by continuously weighing the pots using a series of load cells placed under the pots and manually irrigating three times a week. Half the plants of both batches were submitted to this WD treatment in two consecutive years in combination with either FS or P treatments. Predawn and midday leaf water potential were measured during ripening on bright sunny days with a pressure chamber (Schölander *et al.*, 1965) once both watering regimes had been applied and had stabilised.

2. Climate and microclimate

Hourly weather data were collected using a reference weather station mounted higher than usual at a height of 2.90 m within the experimental area so that it was just beyond the influence of the panels. Shading by any surrounding obstacles was avoided. For each light treatment, air temperature and relative humidity were also measured within the canopy at mid-plant height (1.10 m from ground) using ventilated probes (HMP 155, Vaisala, Helsinki, Finland) that were protected from direct radiation (MET21, Campbell Scientific Ltd, Leicestershire, UK). Photosynthetic photon flux density (PPFD) was measured with two quantum sensors (Skye Instruments Ltd, Wales, UK) installed at the same height as the latter probes in the canopy, but about 10 cm from the row axis on either side of the row. All these data were collected every 30 s, averaged every 12 min and stored in a datalogger (CR1000, Campbell Scientific Ltd, Shepshed, Leicestershire, UK). Some temperature data were missing (22 % in total, mostly before budburst in 2018 and 2020) and missing values were simulated by a multilinear model using data from the reference weather station. The best-fit model was selected each month for each treatment using the stepAIC function (R package MASS). The data from the sensors installed at the height of 1.10 m within the row were considered to characterise the microclimate within the canopy close to the buds. In addition to a reference thermal time (growing degree-days, GDD), which was calculated by cumulating daily mean temperature recorded by the reference weather station minus a base temperature of 10 °C (Lebon *et al.*, 2004), the temperature recorded at plant level by HMP probes was also used to compute GDD specific to each light treatment.

3. Phenology

Budburst, flowering and veraison were monitored three times a week in the morning on all plants. Budburst was determined when the bud reached stage 4 of the modified scale of Eichhorn and Lorenz (Coombe, 1995).

The proportion of flowers with fallen caps on each inflorescence, and the proportion of coloured berries on each cluster were determined at least once a week around flowering and veraison. When there were 2 clusters on a plant the mean was calculated. A logistic model was fit to the progression of these proportions on each plant as a function of day of year (DOY) or thermal time. DOY or thermal time corresponding to flowering or veraison were determined when the respective proportion had reached 50 % (Lebon *et al.*, 2008). The daily rate of berry colour change per plant (%/d) was calculated using the difference in days estimated with the logistic fit between 30 % and 70 % veraison.

4. Berry growth, ripening and harvest

Berry diameter was monitored between pea-size stage and harvest in 2020 (on the second batch of plants) or between veraison and harvest in 2019 (on both batches) using a digital calliper. Berry diameter was not measured on the first batch of plants in their first year of treatment (2018_1). White corrector was used to mark three berries per cluster in the top, middle and bottom segments of one cluster per plant of 6 plants per treatment (Hulands *et al.*, 2013). The diameter of each berry was determined as the average of two transversal measurements in orthogonal directions.

For both batches of plants in all experimental years, total soluble solids (TSS, °Brix) were determined at least twice a week during ripening using a refractometer (RS PRO, Canada) on 2 to 4 berries per cluster and 3 clusters per treatment. The clusters were all harvested on the same day per treatment when mean TSS reached 21 °Brix. For some treatments, the increase in °Brix was so slow that harvest had to take place before the 21 °Brix target was reached; i.e., on 17 September in 2019 and 28 September in 2020. For the plants that had under two years of treatment (2019_2, 2020_2), a preliminary harvest was also carried out with a target of 19 °Brix. The clusters were harvested after 17:00 and stored at -60 °C in plastic bags pending analysis. The total number of berries and the number of green berries per cluster were counted manually on frozen material, then the clusters were rapidly weighed without rachis and peduncles. Mean berry weight per cluster was derived from cluster weight and berry number. The clusters were thawed and then crushed to make a juice that was centrifuged for 3 min at 12000 g. A few mL of supernatant was used for TSS determination and the remainder was stored again at -60 °C for further analysis.

Sugar (glucose and fructose) concentration in juice supernatant was measured following the method described in Bigard *et al.* (2019). Briefly, juice supernatant was thawed, diluted in 0.2 N HCl (1/10 v/v), filtered through a 0.2 µm cellulose acetate membrane and injected into a high-performance liquid chromatography column (Aminex HPX-87H, Bio-Rad®, Hercules, CA, USA) to determine glucose and fructose concentrations. For each cluster, the mean amount of sugar per berry was computed as the product of sugar concentration ([Sugar], g/L) by mean berry volume. Mean berry volume for each cluster was estimated as the ratio of mean berry weight to mean density of berries, which was derived

from the close linear relationship with sugar concentration that was drawn from published data (Bigard *et al.*, 2019): density = 1.007 + 4.01 10⁻⁴ [Sugar] (R² = 0.98).

5. Statistical analyses

All statistical tests were performed using R (version 4.1.1; R Core Team, 2021). Normality and homogeneity of variance were controlled using Shapiro-Wilks's and Bartlett's tests. Comparison of treatments used Wilcoxon or Kruskal-Wallis test with the Bonferroni correction when data deviated from normality or homogeneity of variance. Two-way analysis of variance (Anova) and analysis of covariance (Ancova) were performed with `lm()` and `Anova()` functions of the 'car' package.

RESULTS

1. Mostly similar weather in all experimental years

The three experimental years were compared in terms of daily weather data and GDD as from 1st January (calculated from air temperature recorded by the reference station above the panels at a height of 2.90 m) (Figure 1). Overall, the air temperature patterns were very similar in both years. Only slight differences in daily min or max temperature were observed during certain periods between years (Figure 1A). As a result, the difference in GDD at the end of August (DOY 243) was less than 5 % between the hottest year 2020 (1938.8 °Cd) and the coldest one 2019 (1854.1 °Cd, Figure 1B). Differences in cumulative GDD between years was even lower when calculated from DOY 80, which is roughly the beginning of the vegetative phase (Figure 1B insert).

Daily radiation evolved during the year within the usual Gaussian envelope, as was expected for the region (Figure 1C). Low daily radiation below the envelope was due to cloudy days with comparable frequency between years, except in May when cloudy days were more frequent for 2018 than for the other years. As a consequence, from about DOY 80 onwards, cumulative radiation remained approximately 5 % lower in 2018 than in 2019 and 2020 (Figure 1D). The year 2018 was the rainiest, with 718.5 mm of rainfall from January to September compared to 209 mm in 2019 and 373 mm in 2020, and with the differences occurring mostly before flowering and after harvest (Figure 1E, F). In most cases, rainfall occurred before veraison or after harvest; i.e., outside of the period of water deficit. When rain fell during the water deficit period, it did not disturb the water regime in the pots. The manual adjustment of pot weight 3 times a week helped to maintain the soil water content at no higher than the target of 1.1 g water per g of dry soil. Overall, the rainfall did not influence the water deficit conditions. This can be explained by the runoff from the foliage and the small surface area of the pots (20 cm diameter) which prevented most of the rainwater from getting inside them. Leaf water potential was measured at predawn and around midday (when the plants under the panels were shaded) for each treatment over the three seasons. On average, the regular irrigation of the pots with targeted weights maintained similar predawn leaf water

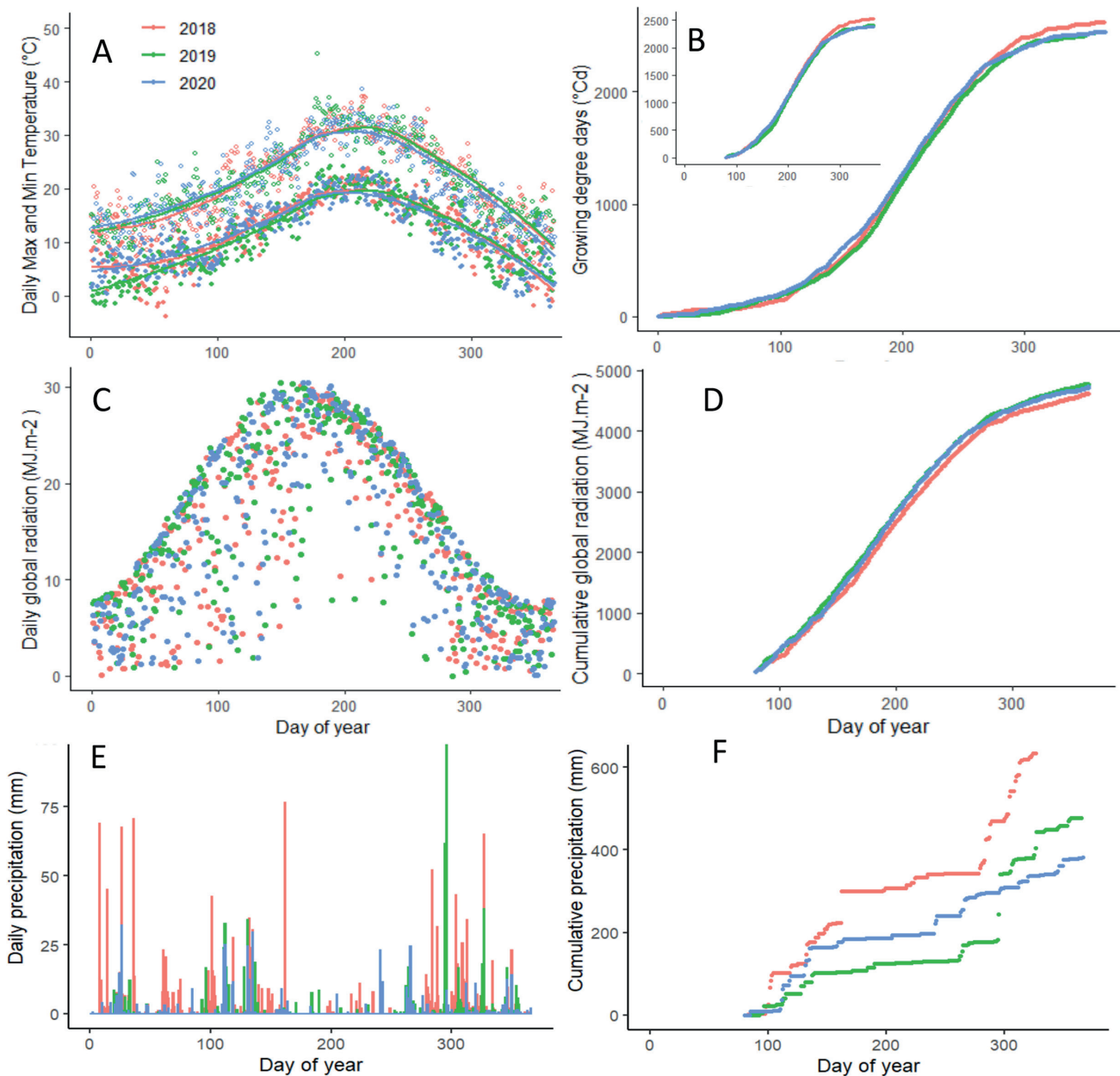


FIGURE 1. Climate characteristics during the experiments as recorded with a reference station installed at a height of 2.9 m within the experimental area beyond the influence of the panels:

A) maximum (empty circle) and minimum (filled circle) air temperature; B) growing degree days cumulated after 1st of January or as from day of year 80 (insert); C) daily global radiation; D) global radiation cumulated as from day of year 80; E) daily precipitation and F) cumulative precipitation as from day of year 80.

potential in the FS and P treatments, with higher values under well-watered conditions (-0.12 ± 0.06 MPa before veraison and -0.18 ± 0.08 MPa after veraison) than when water deficit stabilised after veraison (-0.37 ± 0.24 MPa). For well-watered plants, at midday, leaf water potential was lower in FS conditions (-0.75 ± 0.21 MPa before veraison and -0.93 ± 0.25 MPa after veraison) than under panels (-0.49 ± 0.15 MPa before veraison and -0.69 ± 0.26 MPa after veraison), confirming the expected benefit of shading on plant water status. The effect of panels on midday water potential was conserved when water deficit stabilised after veraison (-1.20 ± 0.38 MPa in FS conditions and -0.99 ± 0.42 MPa under panels).

2. Very slight effects of the panels on air temperature within the canopy, with opposite influences in the morning and the afternoon.

The panels generated a moving strip of shade which crossed over the rows every day. As a result, the plants were shaded daily from approximately 10:30 until 16:15 at summer solstice and from approximately 10:30 until 14:45 at the time of harvest; the maximum duration of the shading provided by the panels was thus 5 hr 45 min. A shading ratio characterising treatment P relative to FS was calculated using quantum sensors placed at a height of 1.10 m on each side of the row in each condition.

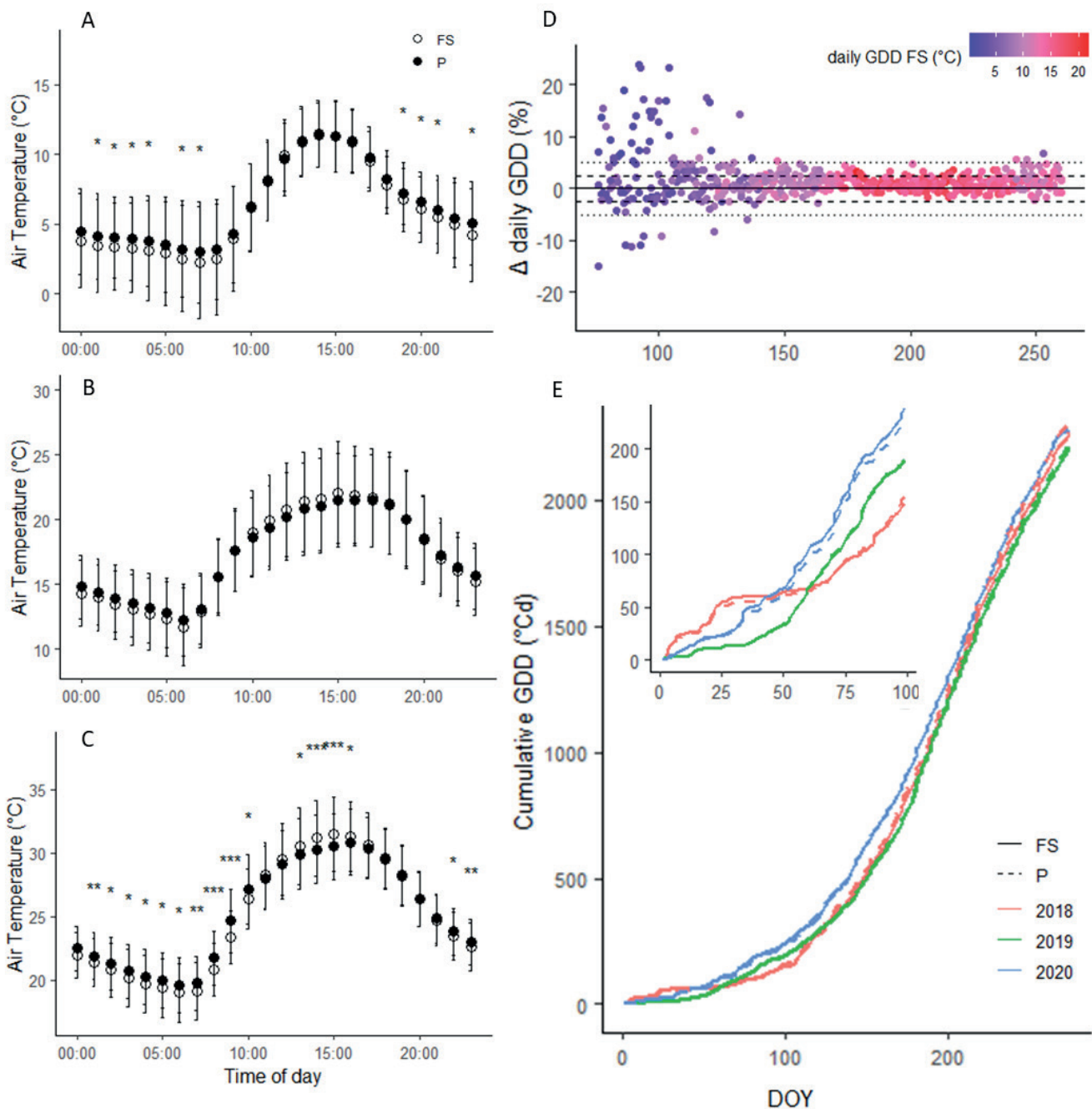


FIGURE 2. Comparison of air temperature measured within the canopy in full sun (FS) and under panels (P) and corresponding growing degree days (GDD).

Daily pattern of temperature measured within the canopy in full sun conditions (FS, white symbols) and under panels (P, black symbols) in A) the whole of January 2019, B) May 2019, and C) August 2019. Points are hourly average \pm sd for whole month, $n = 29$ to 31 . The difference between the two conditions was tested for each hour with a Wilcoxon test and reported when significant as follows: ***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$. Relative difference in daily GDD (Δ daily GDD %) between FS and P conditions with respect to FS as a function of day of year (DOY), from DOY 75 to DOY 260 (D). Dashed and dotted lines indicate 2.5 % and 5 % difference respectively between light treatments. Colour represents daily GDD in FS conditions as shown on the inserted scale. Cumulative GDD as from 1st January for the three experimental years in FS (solid line) and P (dashed line) conditions (E). Insert shows cumulative GDD over the first 100 days of each experimental year.

The daily cumulated values recorded below the panels (treatment P) were divided by those recorded in the rows outside of the panels (treatment FS) to estimate the shading ratio. The ratio varied with plant development, sun elevation during the day and the season and between sunny and cloudy days (not shown). The shading ratio estimated during the whole plant cycle on sunny days averaged 55 %.

Air temperature was also measured within the canopy for both light treatments in order to determine whether the panels had influenced phenology by changing air temperature close to the plants. Consistent with the shading patterns produced by the panels, different daily patterns of air temperature within the canopy were observed depending on DOY (Figure 2A-C).

In winter, the air temperature within the canopy in P and FS conditions was similar during the day, but it was slightly and significantly warmer under the panels during the night (Figure 2A). In the spring and summer, the air temperature within the canopy was also slightly higher under the panels during the night. However, in contrast to the winter responses, the air temperature in the daytime within the canopy was slightly cooler under the panels than in FS conditions, specifically during the period of the day when the rows were shaded, as illustrated for May and August 2019 (Figure 2B, C). In May 2019, for example, at the end of the nights, when reference air temperature reached its daily minimum, the panels increased the air temperature within the canopy by a monthly average of 0.53 °C, whereas they decreased this temperature by 0.58 °C at around 15:00 when the reference air temperature peaked at

its daily maximum value. Overall, during most of the plant cycle, the higher temperatures for P than FS during the day tended to compensate for the lower temperatures at night. This resulted in only slight differences in daily GDD between P and FS when calculated from the hourly air temperature within the canopy (Figure 2D). Higher differences in daily GDD between P and FS occurred mostly during the early and late periods of the year outside the plant cycle, with a low daily mean temperature (Figure 2D, insert) that did not contribute substantially to the GDD cumulated over longer periods of the plant cycle. Overall, when cumulated after 1st January, only a slight difference was found in terms of GDD between the P and FS treatments, which did not exceed 2 % relative to FS conditions (Figure 2E).

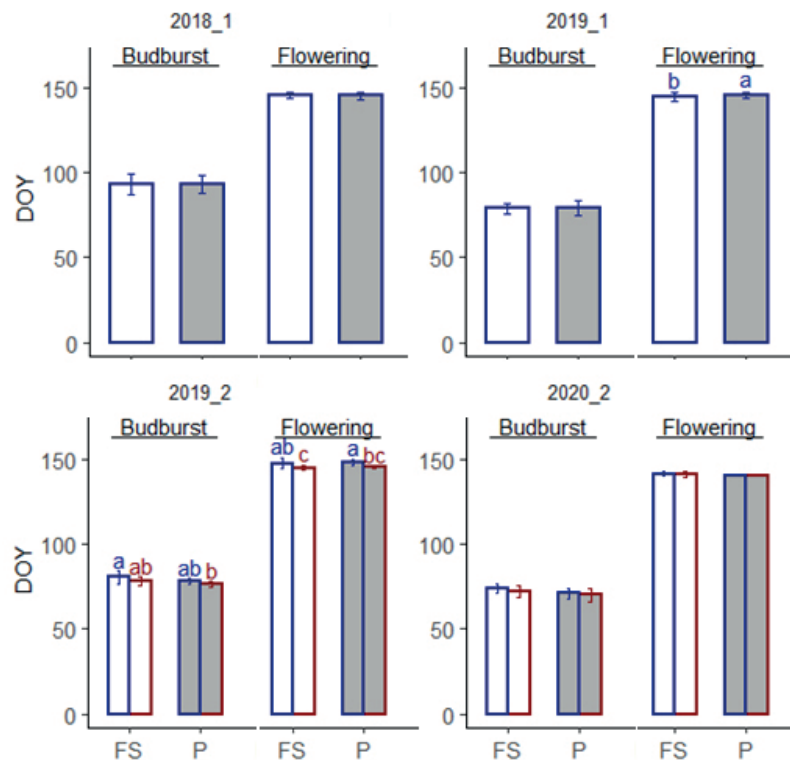


FIGURE 3. Effect of shading and watering treatments on budburst and flowering dates of potted Syrah vines (first batch in left plots, second batch in right plots) during their first year (2018_1, 2019_1, upper plots) and second year of treatment (2019_2, 2020_2, lower plots).

Full sun conditions (FS, non-shaded bars) or shading with panels (P, shaded bars) were applied during two plant cycles and were combined with well-watered (WW, blue) or water deficit (WD, red) conditions applied between veraison and harvest each year. In the first year for the two batches 2018_1 and 2019_1, WD was not distinguished from WW, since the plants were not concerned by this treatment that began at veraison. For each plot and each phenological stage, a two-way Anova (***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$) and, when appropriate, a comparison of treatments were run (different letters indicating significant differences at $p < 0.05$).

3. Only weak effects of the treatments on budburst and flowering dates

Budburst date primarily and substantially varied depending on the year, occurring earlier in 2020 (DOY 72) compared to 2019 (DOY 79) and much earlier in 2018 (DOY 93), which was the coldest year. Cumulative GDD during that period varied in the same way between years (Figure 2E insert):

from 1st January until budburst, it was mostly conserved, except in 2020, when it was slightly higher by approximately 30 °Cd for FS WW (control) conditions (Table 1).

The panels did not significantly change budburst date in the first year of treatment (2018_1 and 2019_1 in Figure 3). In the second year of treatment (2019_2 and 2020_2 for both batches of plants), budburst occurred slightly but significantly earlier

TABLE 1. Comparison of growing degree days (GDD, °Cd) cumulated from 1st January to budburst and from budburst to flowering or veraison of potted Syrah plants in full sun (FS) and under shading panels (P) under well-watered (WW) and water deficit (WD) regimes for one year (2018_1, 2019_1) or two years (2019_2, 2020_2). 2018_1 and 2019_2 corresponds to the first batch of plants and 2019_1 and 2020_2 to the second batch. GDD was calculated from the temperature measured within the canopy in FS a P conditions.

Batch and year	Treatment	01/01 to budburst		Budburst to flowering		Budburst to veraison	
		GDD (°Cd)	n	GDD (°Cd)	n	GDD (°Cd)	n
2018_1	FS WW	124.5 ± 8.4 b	61	348.5 ± 18.1 b	28	1178.5 ± 39.3 b	18
	FS WD	-		-		1152.2 ± 25.1 b	7
	P WW	131.2 ± 9.8 a	35	362.3 ± 11 a	26	1261.5 ± 51.6 a	10
	P WD	-		-		1240.6 ± 42.5 a	10
2019_1	FS WW	123 ± 9.4 a	43	326.9 ± 18.5 b	24	1211.5 ± 16.5 b	7
	FS WD	-		-		1209.7 ± 14.4 b	6
	P WW	122.3 ± 10.4 a	38	344.7 ± 19.3 a	15	1430.1 ± 66.4 a	4
	P WD	-		-		1260.5 ± 13.9 a	3
2019_2	FS WW	124.9 ± 7.3 a	8	348.3 ± 27.7 ab	8	1183.6 ± 35 c	8
	FS WD	120.3 ± 7.1 a	8	333.5 ± 17.4 b	8	1163.2 ± 31 c	8
	P WW	122.2 ± 4.7 a	12	362.2 ± 17.5 a	12	1595.8 ± 34.6 a	11
	P WD	117.5 ± 4.8 a	8	340.2 ± 3.5 b	8	1366.2 ± 58.7 b	7
2020_2	FS WW	156.8 ± 12.2 a	9	386.3 ± 16.3 a	7	1178 ± 83.7 b	7
	FS WD	145.8 ± 16.8 ab	12	396.4 ± 16.4 a	11	1200.9 ± 73.5 b	12
	P WW	135.6 ± 15.3 b	7	399.5 ± 12.2 a	6	1518.4 ± 30 a	6
	P WD	130.8 ± 15.7 b	7	396.2 ± 12.5 a	6	1426.7 ± 71.3 a	6
			01/01 to budburst	Budburst to flowering	Budburst to veraison		
	Factor						
Anova p-values main factors	All experiments	Shade	ns	***	***		
		Irrig	**	ns	***		
		Year	***	***	***		
		Rep	***	***	***		
Anova p-values interactions	All experiments	Shade:Irrig	ns	0.094	***		
		Shade:Year	***	ns	***		
		Irrig:Year	ns	ns	***		
		Shade:Rep	***	ns	***		
		Irrig:Rep	-	-	*		
	Batch and year						
Anova p-values per batch and year	2018_1	Shade	***	**	***		
		Irrig	-	-	0.079		
		Shade:Irrig	-	-	ns		
	2019_1	Shade	ns	**	***		
		Irrig	-	-	***		
		Shade:Irrig	-	-	***		
	2019_2	Shade	ns	0.098	***		
		Irrig	*	**	***		
		Shade:Irrig	ns	ns	***		
	2020_2	Shade	**	ns	***		
		Irrig	ns	ns	ns		
		Shade:Irrig	ns	ns	*		

Means are compared for each batch of plants and year of treatment with Kruskal-wallis test and Bonferroni correction. Same letters indicate that no significant difference was detected ($p > 0.05$). Four-way Anova was run for the following factors: light conditions (Shade; FS or P), watering regime (Irrig; WW or WD), experimental year (Year; 2018 to 2020), first (_1) or second year of treatment (_2) (Rep). Shade, Irrig and the interaction Shade:Irrig were also tested with two-way Anova for each batch of plants and year of treatment. Results of Anova are indicated as follows: *, $p < 0.05$, **, $p < 0.01$, ***, $p < 0.001$, ns: not significant.

(by about 2 days) in shaded (P) plants than in unshaded (FS) plants. In addition, when considering both P and FS plants in the second year, the water deficit applied during ripening in the first experimental year slightly advanced budburst date compared to the well-watered conditions ($p < 0.05$). As a result, among all treatments and years, the earliest budburst date was observed in the second year for plants subjected to both shading and water deficit, but still by a narrow margin (Figure 3).

The flowering date hardly varied between years and treatments, ranging from DOY 140.2 to DOY 147.6 (Figure 3), which was even less scattered than the budburst date. However, a slight, significant effect of the year was observed, which was mostly attributable to the earlier flowering in 2020, as was the case for budburst. Due to the similar effect of the year on budburst and flowering dates, the number of days from budburst to flowering was logically more stable (between 66.7 and 70.7 days) than the flowering date, except in 2018. This suggests that the flowering date was simply determined by the number of days after budburst. The year 2018 was found to be an exception, with budburst occurring much later (likely due to an unusually cold period in late winter), which slightly influenced the flowering date. GDD did not explain the slight differences in flowering dates, whether GDD cumulated after 1st January (Supplementary table 1) or after budburst (Table 1).

The panels over the vines did not change the flowering date (Figure 3), with less than a 1.5 day difference between FS and P treatments for any given year and watering regime. The water deficit applied during the ripening of the berries in the first year of the experiment (2018_1) slightly but significantly advanced the flowering of the plants in the second year (2019_2): by about 2.5 days in both P and FS conditions (Figure 3). However, this advance was not observed in 2020_2 for the batch of plants that experienced water deficit in 2019_1. Interestingly, this variable effect of watering regime on flowering date in the second year of treatment between the two batches of plants (2019_2 and 2020_2) was absent when considering the time interval after budburst (Table 1). This suggests that the effects of water deficit on flowering dates were mostly the result of delayed budburst.

4. Much delayed veraison under panels with an opposite effect of water deficit

Overall, the treatments had much more pronounced effects on veraison than on budburst or flowering date (Figure 4 and Table 1). For FS WW plants (considered as the control), veraison occurred with only slight (although significant, $p < 0.001$) differences between years, varying from DOY 202 in 2020 to DOY 208 in 2019.

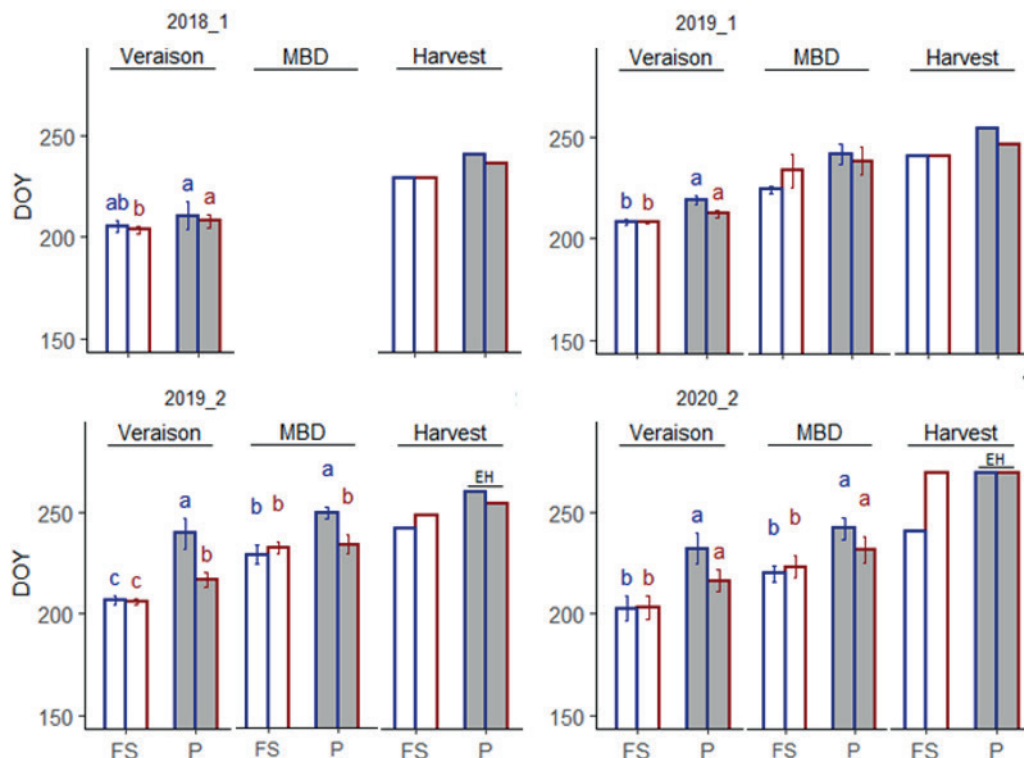


FIGURE 4. Effect of shading and watering treatments on veraison date, time to reach maximum berry diameter and harvest date of potted vines (first batch in left plots, second batch in right plots) during their first year (2018_1, 2019_1, upper plots) and second year of treatments (2019_2, 2020_2, lower plots). Full sun conditions (FS, non-shaded bars) or shading with panels (P, shaded bars) were applied during two plant cycles and were combined with well-watered (WW, blue) or water deficit (WD, red) conditions applied from veraison to harvest on each year. Same legend as in Figure 3 for statistics. EH; early harvest (21°Brix not reached).

For these control plants, GDD from budburst to veraison was mostly conserved with a mean of 1185 °Cd and less than 3 % difference between years.

In the first year of treatment, the panels significantly delayed veraison for P WW plants compared to FS WW ones by 5.5 (2018_1) and 12 (2019_1) days (Figure 4). Since the panels hardly modified the temperature within the canopy, their effect on delayed veraison was also observed when expressed in GDD per treatment, corresponding to a 7 % (2018_1) and 18 % (2019_1) increase in GDD from budburst to veraison under panels compared to unshaded conditions (Table 1). Strikingly, the delay in veraison caused by panels over P WW plants further increased in the second year of shading - as much as 33 (2019_2) and 29.5 (2020_2) days after the veraison of FS WW plants (Figure 4). These delays due to panel influence for two years corresponded to a 35 % (2019_2) and 29 % increase in GDD from budburst to veraison.

The panels also delayed veraison in the plants submitted to WD, although to a lesser extent than WW plants (Figure 4). In the first year of treatment (2018_1 and 2019_1), veraison occurred 4 days later in P WD than FS WD plants (Figure 4, upper plots). In the second year of treatment, this delay increased by up to 10.5 (2019_2) and 14 days (2020_2), which was approximately half the delay caused by panels after 2 years in WW conditions (Figure 4, lower plots). This observed shorter delay for WD than for WW plants is consistent with the well-known triggering effect of WD on veraison. Compared to WW conditions and considering

only shaded plants, water deficit significantly advanced veraison by 23 (2019_2) and 16 days (2020_2), thereby partly counteracting the delay to veraison caused by the panels. Water deficit had no significant influence on veraison in FS plants, since it was applied to them just as veraison began. Interestingly, the treatments had similar effects on veraison date and veraison rate, which was determined as the daily progression rate of percent of coloured berries per cluster (Figure 5). In WW conditions, the panels once again slowed down veraison rate more markedly in the second year of treatment. WD enhanced the veraison rate to its highest levels for both FS and P treatments, suggesting that a threshold rate was reached and making panel effects hardly detectable. As observed for veraison date, the panels had the opposite effects on veraison rate to those of water deficit. In spite of the substantial differences in terms of period when veraison occurred between all treatments and years, the mean temperature within the canopy during this period varied only slightly (from 25.3 to 26.5 °C). The differences in veraison rate can therefore be associated with the treatments, without the confounding effect of temperature.

5. More time to reach maximum berry diameter under panels in the second year of treatment and under well-watered but not water deficit conditions

Berry growth was monitored by measuring berry diameter until harvest, beginning just after veraison in 2019 and as from the pea-size stage in 2020. The double berry growth pattern can be clearly seen in 2020 (Figure 6), while only the

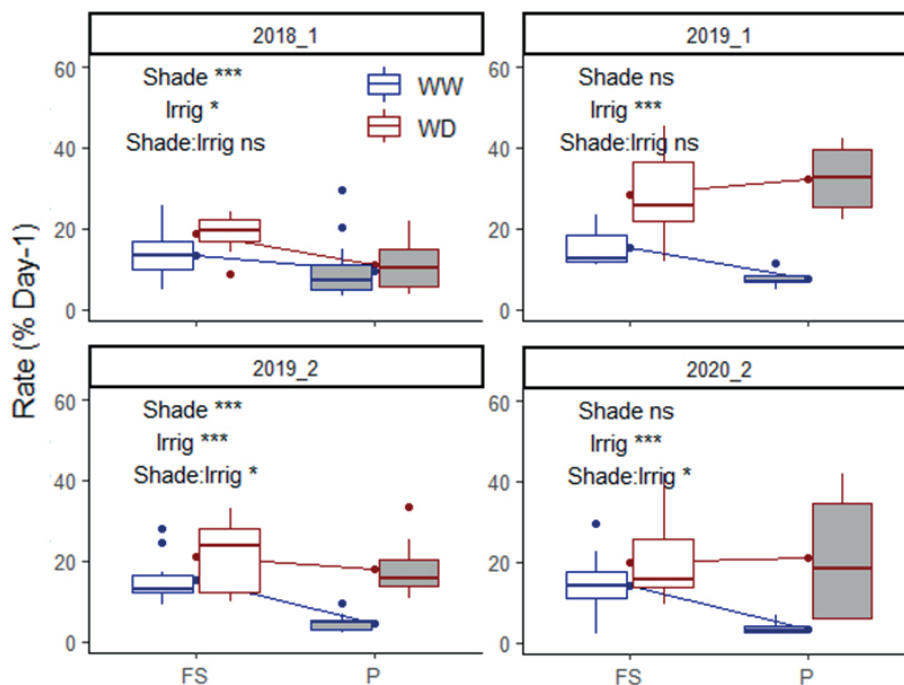


FIGURE 5. Rate of veraison, calculated as the daily percent change of colour within clusters.

Effects of shading (Shade) treatment (FS = full sun, open boxes; P = panels, shaded boxes), watering (Irrig) regime (blue = well-watered condition; red = water deficit) and interaction (Shade: Irrig) were tested by two-way Anova (***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$). Boxplots for both batches of plants (first batch in left plots, second batch in right plots) experimented on in their first year (2018_1, 2019_1, upper plots) and second year of treatment (2019_2, 2020_2, lower plots). Lines join the means of each watering regime to highlight the effect of panels.

second phase corresponding to ripening could be observed in 2019. The panels delayed the onset of the second growth phase, regardless of watering regime and year of treatment (Figure 6).

The DOY of when maximum berry diameter was reached, which is indicative of the end of sugar loading in berries and considered as physiological maturity (Shahood, 2017), was determined for each cluster as an average of three measured berries. Consistent with the delayed onset of the second phase of berry growth under the panels, the maximum diameter was reached significantly later under panels than in full sun

conditions ($p < 0.05$). For WW plants, the delay in reaching maximum berry diameter caused by panels was substantial in the first year (17 days later in P than in FS conditions in 2019_1, not determined in 2018_1) and further increased in the second year of treatment (20 days in 2019_2 and 22 days in 2020_2). WD largely countered the delay in reaching maximum berry diameter caused by the panels, with a difference of 5 days between FS and P treatments in 2019_1, 2 days in 2019_2 and 8 days in 2020_2. These opposing influences of the panels and water deficit, which had already been observed at veraison, continued to reduce the phenological differences between FS WD and P WD plants at maximum berry diameter.

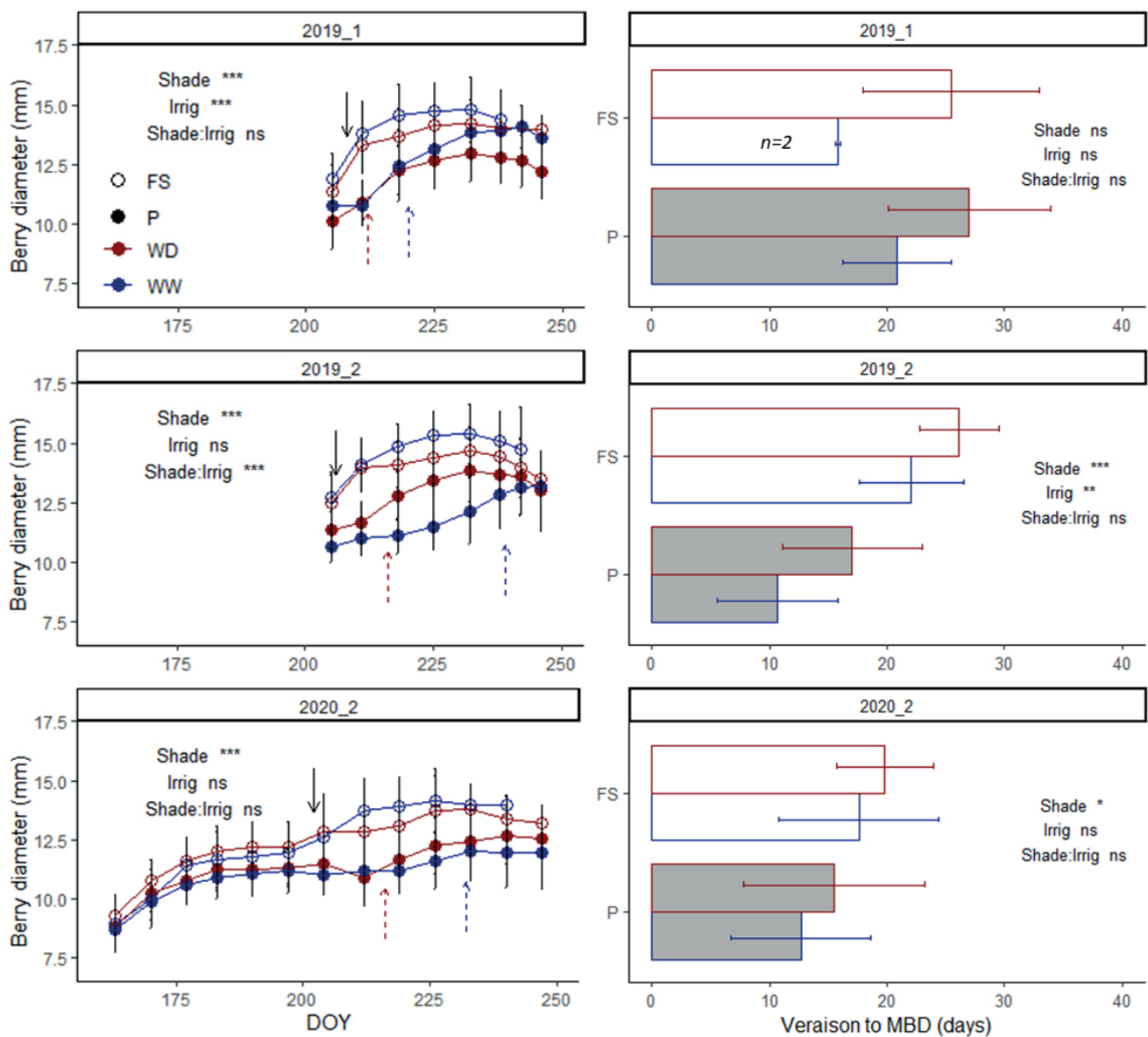


FIGURE 6. Response of berry diameter to the different treatments.

Berry diameter evolution as function of the day of year (DOY, left plots) and length of time between veraison and the DOY when maximum berry diameter (MBD) was reached (right plots) for one batch of plants in the first year of treatment (2019_1, not determined in 2018_1) and both batches of plants in the second year of treatment (2019_2, 2020_2). Shading (Shade) treatment (FS = Full sun, non-filled symbols; P = panels, filled symbols), watering (Irrig) regime (blue: well-watered condition; red: water deficit) and interaction (Shade:Irrig) were tested by two-way Anova (***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$; ns : not significant). Arrows in left-hand plots indicate veraison dates for FS WW (solid black, same date for FS WD), P WW (blue dotted) and P WD (red dotted) treated plants. Means \pm sd for $n > 6$.

The influence of the panels on the period between veraison and maximum berry diameter was examined in more detail (Figure 6). Overall, the major significant effect was a shortening of this period under the panels compared to FS conditions in the second year but not in the first year of treatment. By contrast, WD increased the length of time between veraison and maximum berry diameter in the second year of treatment for both batches of plants, but this was only significant for 2019_2. In the first year of treatment (2019_1), the duration of this period tended to increase by about 5 days under the panels for WW plants, while it was mostly conserved for WD plants. Berry diameter was not monitored on the first batch of plants (2018_1) to confirm this lengthening of the period between veraison and maximum berry diameter in the first year under the panels. The shortening of the period from veraison to maximum berry diameter caused by two years of shading contrasted with the delay caused by panels in terms of all the other phenological traits. Nevertheless, the opposing influences of the panels and water deficit was conserved. All the changes caused by panels to the length of time between

veraison and maximum berry diameter were much greater than the corresponding changes in GDD over that period. This makes it unlikely that there was any simple influence of temperature difference between P and FS conditions, whether due to shading or a shift in the ripening period.

The highest value for maximum berry diameter in each year was observed in the control (FS WW) conditions (Figure 6). Compared to this control, the panels reduced the maximum berry diameter, regardless of the water regime and year, albeit to different extents. Compared to FS conditions, the reduction in maximum berry diameter due to the panels was more marked in 2020_2 (-17 %, $p < 0.001$) and 2019_2 (-15 %, $p < 0.05$) than in 2019_1 (-8 %, $p < 0.01$), once again indicating a more pronounced effect of the panels over plants in their second year of treatment. Water deficit had variable impacts on maximum berry diameter depending on the shading conditions and year of treatment. Under FS conditions in all years, water deficit reduced maximum berry diameter as expected. Under panels with water deficit, this reduction was observed in the first year of treatment (2019_1), but,

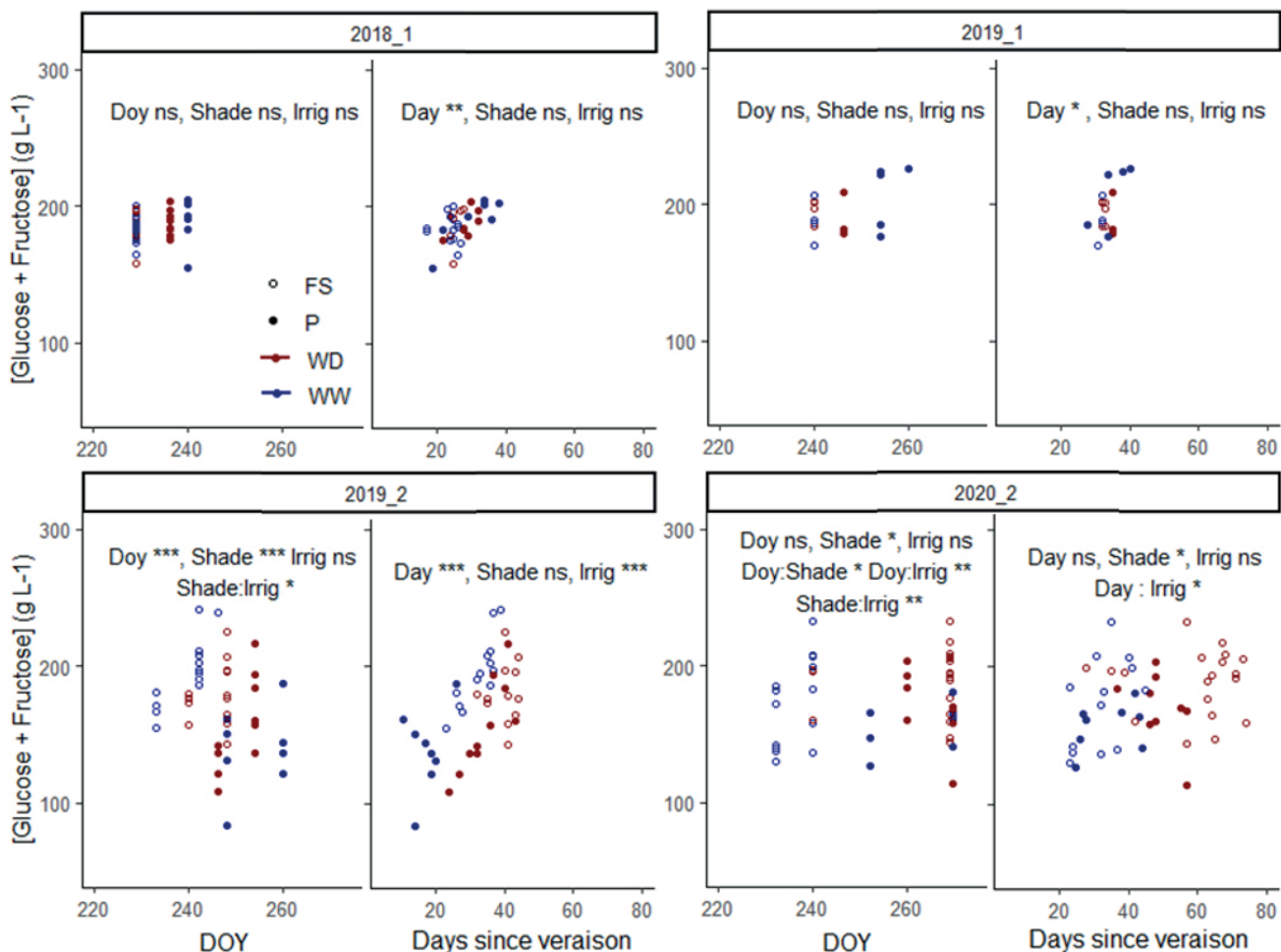


FIGURE 7. Evolution of sugar concentration at harvest in response to shading and watering treatments.

Results for individual clusters are shown for plants in full sun conditions (non-filled symbols) or shaded by panels (filled symbols) and either well-watered (blue) or submitted to water deficit (red), in the first (2018_1, 2019_1, upper plots) and second year of treatment (2019_2, 2020_2, lower plots) for a first (left plots) and second batch of plants (right plots). Covariance analyses were performed with day of year (DOY) or days since veraison as covariables and shading (Shade) or watering treatment (Irrig) and their interactions as factors (***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$; ns, not significant).

TABLE 2. Harvest dates and characteristics of berries and clusters at harvest for the different light conditions and watering regimes. When possible, harvest was performed targeting 21°Brix and not later than 17 September in 2019 and 25 September in 2020. Total soluble solids (TSS), number of berries per cluster (BpC), percentage of green berries per cluster (%GB), cluster weight (CW), mean berry weight (BW), sugar (glucose and fructose) concentration ([G+F]) and sugar content per berry (G+F) are shown as means for each treatment and each batch of plant in their first year (2018_1, 2019_1) or second year of treatment (2019_2, 2020_2). Part 1/2.

Batch and year	Treatment	Harvest (day/month)	TSS (°Brix)	Berries per cluster	% Green berries	Cluster weight (g)
2018_1	FS WW	17/08	20.9 ± 1.1 a	106.4 ± 57.5 a	5.0 ± 9.4 a	115.1 ± 57.8 a
	FS WD	17/08	20.9 ± 1.4 a	103.5 ± 62.9 a	0.8 ± 1.4 a	104.1 ± 46.2 a
	P WW	28/08	21.6 ± 1 a	106.1 ± 41.2 a	13.2 ± 12.3 a	110.1 ± 44 a
	P WD	24/08	21.1 ± 1.1 a	78.4 ± 44.8 a	3.4 ± 4.6 a	69.6 ± 43.1 a
2019_1	FS WW	28/08	20.7 ± 0.6 a	91 ± 46 a	1.7 ± 2 a	150.4 ± 55.7 a
	FS WD	28/08	21.6 ± 0.6 a	143.2 ± 92.7 a	0 ± 0 a	190.5 ± 92.2 a
	P WW	11/09	21.6 ± 2.3 a	96.3 ± 19.3 a	7.3 ± 6.4 a	147 ± 31.8 a
	P WD	03/09	21.3 ± 1.4 a	106.7 ± 54.4 a	0 ± 0 a	140.8 ± 74 a
2019_2	FS WW	30/08	22 ± 1.8 a	135.7 ± 48.1 a	4.4 ± 7 b	228.9 ± 86 a
	FS WD	05/09	21.1 ± 2.2 a	98.2 ± 56 a	0 ± 0 b	145.4 ± 71.3 b
	P WW	17/09	17.6 ± 2.6 a	120 ± 21.4 a	23.6 ± 17 a	127.4 ± 42 b
	P WD	11/09	19.4 ± 2.8 a	126.8 ± 37.6 a	0.2 ± 1 b	182.3 ± 49.2 ab
2020_2	FS WW	27/08	21.1 ± 1.9 a	120.9 ± 49.6 a	1.8 ± 4 ab	176.6 ± 73.2 a
	FS WD	25/09	20.3 ± 3.1 a	109.3 ± 72.4 a	0 ± 0 b	119.1 ± 65.7 ab
	P WW	25/09	16.7 ± 3.1 a	96.7 ± 46.7 a	9.4 ± 12 a	111.9 ± 53.7 ab
	P WD	25/09	18.3 ± 2 a	74 ± 22.9 a	0 ± 0 b	61.8 ± 14.8 b
Batch and year	Treatment	Harvest (day/month)	Berry weight (g)	[Glucose] + [Fructose] (g L ⁻¹)	Glucose + Fructose (mg berry ⁻¹)	n
2018_1	FS WW	17/08	1.14 ± 0.17 a	184.9 ± 9.4 a	185 ± 35.6 a	≥ 14
	FS WD	17/08	1.11 ± 0.26 a	184.9 ± 17.1 a	188.3 ± 46.6 a	≥ 7
	P WW	28/08	1.07 ± 0.17 a	190 ± 17.2 a	160.5 ± 32.9 a	≥ 8
	P WD	24/08	0.9 ± 0.2 a	187.1 ± 9.7 a	160 ± 41.7 a	≥ 8
2019_1	FS WW	28/08	1.78 ± 0.38 a	187.7 ± 15.1 a	313.6 ± 59.9 a	4
	FS WD	28/08	1.49 ± 0.35 a	194.5 ± 8.8 a	265.5 ± 55.6 a	4
	P WW	11/09	1.53 ± 0.08 a	203.1 ± 19.7 a	286.1 ± 38.3 a	3
	P WD	03/09	1.3 ± 0.11 a	189.5 ± 16.9 a	226.6 ± 9.2 a	3
2019_2	FS WW	30/08	1.68 ± 0.18 a	203.8 ± 17.2 a	315.1 ± 47.7 a	8
	FS WD	05/09	1.52 ± 0.14 ab	186.8 ± 24.2 ab	263.3 ± 41.7 ab	≥ 8
	P WW	17/09	1.05 ± 0.27 b	153.4 ± 30.6 b	155.6 ± 70 b	3
	P WD	11/09	1.45 ± 0.12 ab	174.4 ± 29 ab	237.4 ± 57.4 ab	6
2020_2	FS WW	27/08	1.45 ± 0.15 a	188 ± 30.7 a	250.2 ± 33.4 a	8
	FS WD	25/09	1.18 ± 0.25 a	187.9 ± 20.7 a	205.5 ± 49.3 b	≥ 11
	P WW	25/09	1.16 ± 0.09 ab	164 ± 13.6 a	177.3 ± 17.2 bc	≥ 3
	P WD	25/09	0.87 ± 0.2 b	158 ± 26.1 a	125.4 ± 12.8 c	5

Same legend as Table 1 for statistics.

TABLE 2. Harvest dates and characteristics of berries and clusters at harvest for the different light conditions and watering regimes. When possible, harvest was performed targeting 21 °Brix and not later than 17 September in 2019 and 25 September in 2020. Total soluble solids (TSS), number of berries per cluster (BpC), percentage of green berries per cluster (%GB), cluster weight (CW), mean berry weight (BW), sugar (glucose and fructose) concentration ([G+F]) and sugar content per berry (G+F) are shown as means for each treatment and each batch of plant in their first year (2018_1, 2019_1) or second year of treatment (2019_2, 2020_2). Part 2/2.

		Factor	TSS	BpC	%GB	CW	BW	[G+F]	G+F
Anova p-values main factors	All experiments	Shade	**	ns	***	**	***	**	***
		Irrig	ns	ns	***	**	***	ns	*
		Year	*	ns	ns	***	***	ns	***
		Rep	**	ns	ns	**	**	0.062	0.063
Anova p-values interactions	All experiments	Shade:Irrig	ns	ns	**	ns	ns	ns	ns
		Shade:Year	**	ns	ns	ns	ns	*	0.052
		Irrig:Year	ns	ns	ns	ns	0.083	ns	*
		Shade:Rep	***	ns	ns	ns	ns	***	ns
		Irrig:Rep	ns	ns	ns	ns	ns	ns	ns
Batch and year									
Anova p-values per batch and year	2018_1	Shade	ns	ns	*	ns	*	ns	0.079
		Irrig	ns	ns	*	0.097	ns	ns	ns
		Shade:Irrig	ns	ns	ns	ns	ns	ns	ns
	2019_1	Shade	ns	ns	ns	ns	ns	ns	ns
		Irrig	ns	ns	ns	ns	ns	ns	ns
		Shade:Irrig	*	ns	ns	ns	ns	*	ns
	2019_2	Shade	**	ns	*	ns	***	*	**
		Irrig	ns	ns	***	ns	ns	ns	ns
		Shade:Irrig	ns	ns	**	*	***	0.084	**
	2020_2	Shade	*	ns	0.089	*	***	**	***
		Irrig	ns	ns	*	*	***	ns	**
		Shade:Irrig	ns	ns	0.085	ns	ns	ns	ns

Same legend as Table 1 for statistics.

intriguingly, not in the second year of treatment (2019_2 and 2020_2). Maximum berry diameter in the second year under panels was even higher for WD than WW plants, notably in 2019_2 and to a much lower extent in 2020_2. In 2020_2, the lower berry diameter of plants under panels than in full sun was observed at an early stage of berry development during the first period of growth before veraison (Figure 6).

6. Delayed maturity after one year of shading with panels and even more after two years, with opposite influence of water deficit

In the first year of treatment, the 21 °Brix target for harvest was reached regardless of the treatment (Table 2), but again with a substantial delay caused by the panels (Figure 4). The harvest date for P plants occurred later than that of FS plants by: 11 days in 2018_1 and 13 days in 2019_1 under WW conditions and by 7 days in 2018_1 and 5 days in 2019_1 WD conditions. The harvest date was not influenced by the watering regime in FS conditions, but it was 4 (2018_1) to 8 days (2019_1) earlier in WD conditions compared to WW conditions under the panels (Figure 4).

Shading by the panels for two consecutive years further delayed the harvest date compared to one year of treatment, which was associated with a significant decrease in TSS ($p < 0.05$; Table 2). Under the WW regime, the increase in TSS was so late under the panels that it only reached 17.6 ± 2.6 °Brix on 17 September 2019 and 16.7 ± 3.1 °Brix on 25 September 2020 at harvest, which was 18 days later than the harvest date of FS WW plants in 2019_2, and 29 days later in 2020_2. Under the WD regime, the panels also lengthened the time to reach high TSS, but to a lesser extent than under WW conditions. The plants submitted to WD only reached 19.4 ± 2.8 °Brix in 2019_2 and 18.3 ± 2.0 °Brix in 2020_2, in spite of the late harvest in all these cases.

To determine whether the panels had a specific influence on the phase between veraison and harvest (when 21 °Brix was expected), the corresponding time interval was calculated. Overall, in the first year of treatment, this latter phase was longer under panels, meaning that the delay caused by the panels that was already observed at veraison slightly increased at harvest. In this first year of treatment, under the WW regime, the time interval between veraison and

harvest increased from 24.0 ± 2.8 (FS) to 29.5 ± 6.7 days (P) in 2018_1 and from 31.7 ± 2.8 (FS) to 35.3 ± 2.1 days (P) in 2019_1. The panels also lengthened this last phase of ripening under the WD regime, although to a lesser extent than in WW conditions and not significantly, with less than 3 days difference between FS and P conditions in the time interval between veraison and harvest. This analysis was not possible for the second year of treatment, since the targeted TSS was not always reached.

To better determine the effect of the panels in the first and second year of treatment during the last phase of ripening, the sugar concentration in the harvested berries was plotted as a function of DOY or days after veraison for each plant (Figure 7). In the first year of treatment, only slight differences in sugar concentration were observed among treatments and plants (Table 2), consistent with the quite stable TSS at harvest. Slight variations in TSS correlated with the time interval between veraison and harvest, as was expected, with a progressive accumulation of sugars (Figure 7, upper plots). In the second year of treatment, the sugar concentration largely varied between treatments and plants (Figure 7, lower plots) as did TSS at harvest (Table 2). The relationship between sugar concentration the length of time as from veraison was not as clear as in the first year of treatment. In 2019_2, the lower sugar concentration under panels compared to FS in both water regimes was largely due to the shorter time interval after veraison. In addition, the water deficit delayed sugar accumulation in both P and FS conditions. In 2020_2, the panels also decreased the sugar concentration when considering both watering regimes together ($p < 0.05$). This was observed even with a substantial time interval as from veraison. Interestingly, since the panels postponed and lengthened the berry ripening period towards late summer, the mean temperature during that period decreased for P plants. Consequently, the average GDD calculated from veraison to harvest was 19 % lower for P than for FS conditions (Supplementary table 2). This was very close to the 13 % lower sugar concentration observed at harvest for P compared to FS plants (Table 2). This suggests that the effect of panels on sugar concentration may be due to the lower temperature during the delayed ripening.

All the yield components excepting fertility, which was highly variable in these young graftings, were examined. In the first year of treatment (2018_1 and 2019_1) under panels, a small and generally not significant reduction was observed in cluster weight, number of berries per cluster, and hence mean berry weight, compared to FS conditions, regardless of the watering regime (Table 2). The sugar concentration was quite stable between treatments for this first year of treatment. A small reduction in berry weight under panels was therefore also observed for amount of sugar per berry (Table 2).

The reductions in yield components observed in the first year of treatment under panels were amplified in the second year, leading to significant differences between P and FS plants (Table 2). Compared to WD, the results were clearer for plants in the WW regime, where the panels significantly decreased cluster weight, mean berry weight and sugar concentration.

Therefore, the panels in the WW regime significantly decreased the amount of sugar per berry compared to FS WW for both 2019_2 (-51 %) and 2020_2 (-29 %). In addition, the P WW treatment significantly increased the proportion of green berries compared to FS WW. In WD conditions, the results slightly diverged between the two batches of plants (2019_2 and 2020_2). For 2019_2, the panels in the WD regime did not impact cluster weight and berry weight compared to FS WD. Although the differences were not significant, the sugar concentration tended to be lower in P WD than in FS WD plants, resulting in slightly lower sugar content per berry in P WD plants. For the second batch of plants (2020_2) in the WD regime, these decreases due to panels became significant. As a result, the panels in the WD regime significantly decreased berry sugar content compared to FS WD in 2020_2, in spite of the period between veraison and harvest being longer in 2020_2 than in 2019_2.

DISCUSSION

1. Panels strongly delayed phenological development from veraison to harvest, but not at flowering: a trophic hypothesis

In this study on potted grapevines, the panels caused a significant phenological delay compared to full sun conditions, with a shift in veraison of up to 33 days that was partly maintained at harvest. This delay in veraison was longer when shading was repeated for two years in well-watered conditions (about 30 days) than for one year (between 4 and 12 days) or in water deficit conditions (between 4 to 13 days). Delayed veraison and a slower rate of berry colouring caused by shading have been reported in other studies that used nets to permanently shade the whole plant (Bureau *et al.*, 2000; Cartechini and Palliotti, 1995). However, shading did not delay veraison by more than 10 days in all previous studies (Abeysinghe *et al.*, 2019; Guan *et al.*, 2015; Lu *et al.*, 2021), which is much lower than in the present study. The different results in the studies may be due to differences in the shading conditions or the watering regime.

Interestingly, the shading of only the clusters without altering the light conditions for the rest of the canopy has also been found to delay veraison, albeit to a moderate extent (Dokoozlian and Kliewer, 1996; Guan *et al.*, 2015; Koyama and Goto-Yamamoto, 2008). The longer delay that was observed when shading the whole plant, like in the present study, may therefore result from two mechanisms: the local influence of reduced light on the clusters (Garrido *et al.*, 2021) and reduced carbon assimilation by the canopy. In line with the latter mechanism, blocking carbon assimilation by leaf removal has also been found to delay grapevine phenology (Ollat and Gaudillere, 1998). Dependence on carbon resource is particularly critical when berries start to grow and accumulate sugar (Bennett, 2002; Lebon *et al.*, 2008); in the present study, the marked influence of shading started between flowering and veraison, which corresponds to this phase of high carbon dependency. Further supporting the role of carbon supply in mediating shading response, the developmental delay in veraison caused by the panels was

much longer in the second year of treatment than in the first. This may be related to the progressive depletion of carbon stored in the perennial parts of the vine when shading the canopy for several years (Vaillant-Gaveau *et al.*, 2014), which may have limited carbon availability and hindered the phenological development.

Intriguingly, the influence of heavy whole-plant shading on reproductive development has been reported to be far less in previous studies (Cartechini and Palliotti, 1995) than in the present one. Here, the daily alternation of shade and sun conditions produced by fixed panels over the plants resulted in an averaged shading ratio of 55 %. Similar or heavier shading has been applied without causing more than a 10-day delay in veraison (Abeyasinghe *et al.*, 2019). This indicates that conditions other than the reduction in radiation availability at plant level would need to be examined in order to explain the long delay observed in the present study.

2. Water deficit countered the phenological delay caused by panels: a possible explanation for the short delay reported under shading in field studies

The present experiments showed that the panels had a much lower effect on vine phenology when combined with a water deficit. Water stress is known to trigger berry colouring and ripening by enhancing abscisic acid biosynthesis (Cantín *et al.*, 2007; Pilati *et al.*, 2017). Even a moderate water deficit accelerates ripening (Castellarin *et al.*, 2007). Here, among all the conditions applied to potted grapevines, the latest veraison was observed when the vines were abundantly watered several times a day and shaded with panels. Shading itself decreases water stress by lowering evapotranspiration (Caravia *et al.*, 2016). The combination of well-irrigated and shaded conditions can therefore be considered to release any water stress and block abscisic acid production, which is required to trigger veraison. The substantial proportion of green berries observed in clusters of well-irrigated potted plants, whether shaded or not, may be related to this absence of water stress. Field conditions, even when irrigated, generally contrast with the well-watered conditions studied in the present report. The leaf water potential of field cultivated vines in full sun conditions typically drops to -0.3 MPa at predawn and below -1.0 MPa at midday on sunny days (Cataldo *et al.*, 2022), which is much lower than the values observed here on well-irrigated potted vines and closer to those measured under water deficit. The shorter delay in veraison caused by shading field grown plants compared to the long delay caused here by panels over well-watered potted vines, may therefore be due to the water deficit that typically develops, even moderately, with aged plants under usual, cultivated conditions (Lu *et al.*, 2021).

3. Panels only slightly affected air temperature within the canopy

Temperature is the most important driver of phenological development in plants. Accordingly, GDD, which is the sum of mean daily temperatures exceeding a threshold of 10 °C for grapevine, has been shown to correlate with the duration

of phenophases like budburst to flowering (Martínez-Lüscher *et al.*, 2016; Ruml *et al.*, 2016), and has been widely used to compare grapevine phenology in different locations and years (Caffarra *et al.*, 2011; Wang *et al.*, 2020). By using shading devices, one of the original expectations was that temperature would decrease and plant development would slow down. Here, shading modified the daily pattern of air temperature under the panels compared to full sun conditions, but did not significantly affect GDD; overall, the temperature within the canopy could not explain the delay in reproductive development caused by the fixed panels. In other studies, cloth shading decreased GDD mainly as a result of a drop in daytime temperature in the shade (Caravia *et al.*, 2016; Lu *et al.*, 2021). The type of shading may explain this discrepancy between studies. While a slight drop in daytime temperature under the fixed panels compared to full sun conditions was observed in the present study, a slightly higher nighttime temperature was observed, which compensated for the daytime effect. It can be postulated that, during the night, the horizontal position of the panels directly over the plants may have favoured the conservation of radiative losses in contrast to shading nets.

It should be noted that organ temperature, not air temperature, actually drives plant development. Shading with panels could have modified organ temperature in the daytime to a larger extent than air temperature within the canopy as a result of the dramatic reduction in radiation intercepted by the shaded plant (Abeyasinghe *et al.*, 2019). Organ temperature was not taken into account in the present study, because it is heterogeneous and difficult to record throughout grapevine development. It cannot be ruled out that part of the observed delay in vine phenology under the panels was likely due to a substantial reduction in the temperature of growing organs. However, the temperature difference between shaded and unshaded plants cannot explain the much stronger effects observed after two years of treatment than in the first year. Reduced carbon assimilation and depletion of carbon reserves in plants under panels remains the most likely explanation in that respect.

4. Panels delayed maturity and limited berry growth with two possible mechanisms

The experiment reported here showed that shading led to a delay in and a slowdown of cluster colouring and sugar loading, with a sharp reduction in berry size at harvest. These effects were much stronger in the second year than in the first year of treatment, especially in the well-irrigated regime. Overall, these results can be linked to the role of carbon reserves in mediating the response to shading. High demand for carbon starts during the first herbaceous phase of berry growth when cells actively divide (Li *et al.*, 2021). Any mismatch between limited carbon offer and high carbon demand during this phase will result in reduced berry size before veraison, which is maintained throughout the second growth phase (Ollat and Gaudillère, 1998; Niculcea *et al.*, 2014; Ojeda *et al.*, 2001). This reduction was particularly clear in the present study when comparing panels and full sun conditions during the second year of the experiment. The water deficit slightly

compensated for this reduction in the second year, which can be explained by the well-known acceleration of berry ripening under water deficit (Castellarin *et al.*, 2007).

Limited berry growth has also been observed with the localised shading of clusters (Dokoozlian and Kliewer, 1996; Guan *et al.*, 2015; Koyama and Goto-Yamamoto, 2008), although not systematically (Downey *et al.*, 2004).

This suggests that a second mechanism independent of the whole plant carbon status may mediate the effect of shading, including when shading is applied to the whole plant as in the present study. Finally, both cluster and canopy shading may have contributed to the reduction in berry size in this study as observed in a previous one (Rojas-Lara and Morrison, 1989).

Interestingly, the panels affected the time interval from veraison to maximal berry diameter more than any other phenological period. The shorter time interval may simply be due to the smaller final berry size under the panels, which required less time to be reached given that the growth rate was hardly affected.

5. Shading with panels as a promising solution for the adaptation of viticulture to climate change

Due to the delay in the ripening phase caused by the panels in this study, the mean temperature during the ripening of the shaded plants decreased by 2.5 °C (2019_2) to 3.0 °C (2020_2). Similar results have been observed with other technical practices, such as kaolin spraying (Cataldo *et al.*, 2022) and shading nets (Cataldo *et al.*, 2022; Lu *et al.*, 2021) used to mitigate the effects of excessive radiation and temperature. These practices have been proved to be effective for controlling sugar accumulation and decreasing the sugar to acid ratio at harvest (Cataldo *et al.*, 2022; Lu *et al.*, 2021). Our results regarding sugar concentration also confirm the potential for intermittent shading to decrease alcohol level in wine. A cooler ripening period could also have positive consequences for grape, in particular by preserving berry acidity and anthocyanin content, as both are known to decrease under high temperature (Arrizabalaga *et al.*, 2018; Kuhn *et al.*, 2014; Sweetman *et al.*, 2014). These characteristics should also be studied under the conditions of intermittent shading produced by panels.

The extrapolation of this study from young plants to various vineyard conditions has several limitations. Repeating the shading treatment for more than 2 years could amplify undesired effects, like millerandage, reduction in berry size and, in turn, very low sugar content in berries, as observed in this study, resulting in unacceptable production. It should also be noted that this study focused on the responses of plants in pots to one large strip of shade provided by panels. Different results could be obtained in a vineyard with mature plants and other cultivars in different soil and climatic conditions. It may be possible to observe different plant growth adaptations depending on the timing, intensity and duration of the shade provided by panels (Valle *et al.*, 2017). Lastly, the phenological delay in ripening caused by the panels is quite limited under water deficit conditions; thus the benefit would likely only concern vineyards not submitted

to water deficit. It can therefore be assumed that the main benefit of the panels in arid areas is not the modification of the phenological cycle, but the water saved as a result of the shading.

CONCLUSION

It can be concluded from the present study that intermittent shading produced by panels can shift ripening into a cooler period compared to unshaded plants. The panels only slightly affected the budburst and flowering stages, while the most marked phenological changes were observed between flowering and veraison, at the beginning of berry formation and onwards until harvest. A substantial delay was observed when the plant water status was preserved by heavy shading and well-watered soil. However, this was associated with a sharp decrease in berry sugar content at harvest due to both a decrease in berry diameter and a blockage of sugar loading at cluster level. All these trends were amplified in the second year of treatment, highlighting the negative cumulative effects. The water deficit shortened the delay caused by the panels, thus partly cancelling out the expected benefits of a cooler period, but it helped maintain the yield components and sugar load by triggering an earlier veraison. Finally, the shading ratio would need to be finely tuned to evaporative and soil water conditions in order to be able to benefit from the phenological delay caused by panels, without altering production in the long term. In this way, the use of tiltable panels, like those used in dynamic agrivoltaics (Valle *et al.*, 2017), is a promising tool for adaptive shading strategies.

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