Prediction of Grape Berry Temperature Using Wireless Dataloggers Contained Within a Grape Mimic

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KEYWORDS. ‘Camminare noir’, fruit exposure, leaf removal, solar radiation, Vitis sp.

ABSTRACT. Fruit zone leaf removal effects on grapevine (Vitis sp.) productivity and fruit quality have been widely researched. Many fruit zone leaf removal studies state that grape temperature influences grape composition; however, few studies have quantified grape berry temperature fluctuations over time, likely because of technical challenges. An efficient, simple, and economical way to estimate grape berry temperature would be valuable for researchers and industry. Consistent quantification of grape temperature would allow researchers to compare the effects of leaf removal on grape composition across varying climates and regions. A cost-effective means to quantify berry temperature would also provide industry members site-specific information on berry temperature patterns and guide leaf removal practice. Our goals were to develop a method and model to estimate berry temperature based on air temperature and berry mimics, thereby precluding the need to measure solar radiation or obtain expensive equipment. We evaluated the ability of wireless temperature sensors, submerged in various volumes of water within black or white balloons, to predict berry temperature. Treatments included 0-, 10-, 30-, 50-, and 70-mL volumes of deionized water in black and white balloons and a clear plastic bag with no water. Regression analysis was used to determine the relationship between sensor-logged temperatures and ‘Camminare noir’ berry temperatures recorded with hypodermic thermocouples. Nighttime berry temperatures were close to air temperature in all treatments. Using a piecewise regression model, the 30-mL white- and 30-mL black-balloon treatments predicted berry temperature with the greatest accuracy ($R^2 = 0.98$ and 0.96, respectively). However, during daytime hours only, the 30-mL white-balloon treatment ($R^2 = 0.91$) was more effective at estimating temperature than the 30-mL black-balloon treatment ($R^2 = 0.78$). Housing temperature sensors in balloons proved to be an accurate, practical, and cost-effective solution to estimate berry temperature. Further refinement of this method in different regions, row orientations, training systems, and cultivars is necessary to determine applicability of this approach under a wide range of conditions.

Leaf removal alters grape metabolites via changes in berry temperature (Bergqvist et al. 2001; Hickey and Wolf 2018; Spayd et al. 2002; Tarara et al. 2008), but treatment effects can only be attributed to berry temperature if it is quantified. Grape berry temperature models have been published (Cola et al. 2009), but such methods are likely to be more precise in regions characterized by predictable sky conditions (e.g., arid climates). Meteorological modeling may not be reliable across all grape-growing regions (Faust and Logan 2018). For example, cloud coverage is highly variable in the humid climates of the eastern United States, making it difficult to predict the temperatures of objects in such conditions. Therefore, a simple method to quantify berry temperature would facilitate comparisons between studies conducted in similar and divergent climates and advance our understanding of how leaf removal affects berry temperature and subsequent grape metabolite profiles. To our knowledge, only four studies have recorded berry temperature over time during the course of fruit development from veraison (commencement of grape sugar accumulation) to harvest (Bergqvist et al. 2001; Hickey and Wolf 2018; Spayd et al. 2002; Tarara et al. 2008). The studies used handheld thermometers or dataloggers to record temperatures with hypodermic thermocouples inserted beneath the skin of grape berries. Where the handheld thermometers were used, berry temperatures had to be manually recorded throughout the day on multiple dates. Although the use of data-loggers reduces time spent manually recording data, semipermanent thermocouples inserted in berries require regular monitoring to ensure the thermocouple is still in the berry. These current methods to measure berry temperature over time are costly and require the technical skill to wire and program dataloggers.

Units

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<th>SI unit</th>
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<td>°F</td>
<td>°C</td>
<td>(°C × 1.8) + 32</td>
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</table>

Fruit zone leaf removal in grape (Vitis sp.) production is a vineyard management practice that can reduce fungal rots (English et al. 1989; Hed et al. 2009; Hickey et al. 2018; Vogel et al. 2020; Wolf et al. 1986) and allow growers to manipulate primary and secondary berry metabolite concentrations (Crupi et al. 2010; Hunter et al. 1991; Jackson and Lombard 1993; Lee et al. 2005; Ryona et al. 2008). Leaf removal changes the fruit zone microclimate, such that solar radiation and temperature are greater than those in shaded fruit zones (Bledsoe et al. 1988; Guidoni et al. 2008; Ristic et al. 2007; VanderWeide et al. 2018; Zoecklein et al. 1992). High temperatures over an extended period can reduce grape anthocyanin content and limit color development (Bergqvist et al. 2001; Spayd et al. 2002; Tarara et al. 2008). However, variable cloud cover may moderate radiant heating of berries, relative to conditions experienced in arid, less cloudy growing regions (Faust and Logan 2018), resulting in maintained or increased grape anthocyanins in highly exposed grapes (Hickey and Wolf 2019).
Easy, reliable, and cost-effective means of estimating berry temperature would likely increase the frequency of berry temperature quantification in future canopy management studies across climates. In addition, industry practitioners may benefit from evaluating berry temperature patterns in commercial vineyards to determine optimal leaf removal practices on a sitespecific basis.

Factors that are likely to affect berry temperature include volume and color of a berry, cluster morphology, ambient air temperature, solar radiation, and wind speed; the latter two metrics are perhaps less commonly measured than air temperature. Because several parameters are important in determining grape temperature, we sought to account for them in our study by developing a berry mimic that might resemble a grape. The goals of the study were to 1) accurately estimate the actual temperature of grape berries using an air temperature–based model, and 2) identify a berry mimic that resembles the physical properties of grapes within a cluster and most accurately predicts grape berry temperature. We evaluated if small temperature loggers submerged in various volumes of water inside black or white balloons could be used to accurately predict grape berry temperature. Black and white balloons were used because they were expected to respond differently to radiative heating.

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Materials and methods

Experimental vineyard. The experiment was conducted at University of Georgia’s Durham Horticulture Farm in Watkinsville, GA, USA. ‘Camminaire noir’ grape was planted in Spring 2018 with 60-ft vine × 12-ft row spacing in north-south oriented rows. Vines were intended to be trained to a single canopy, vertical-shoot-positioned (VSP) system with low, bilateral cordons, but the age of the vineyard precluded full canopy establishment. Experimental vines had bilateral canes, and shade cloth (Green-Tek 80% Black 26 ft Wide Shadecloth; Green-Tek, Baldwin, GA, USA) was positioned around the middle and top catch wire to uniformly represent an above-head canopy in the canopy-sparse vines that were in their second growing season at the time of the study. The fruit zone was cleared of all leaves on 9 Aug 2019 when berries were at modified Eichhorn-Lorenz (EL) stage 36 (berries with intermediate sugar values) (Dry and Coombe 2004). The first experimental period was 10 Aug 2019 at 0800 HR to 23 Aug 2019 at 0730 HR, and the second was 24 Aug 2019 at 0700 HR to 6 Sep 2019 at 0730 HR. Data from both periods were combined for analysis.

Two vines were used in the experiment. The project was set up as a randomized complete block with four blocks, each of which consisted of one arm (cane) of a vine. Because of block proximity and therefore similar environmental conditions, there was little variability in berry mimic temperature among blocks (Fig. 1); they were thus treated as experimental replicates. Four clusters with no surrounding leaf layers, one from each cane, were chosen for berry temperature recording.

“Logged” berry temperature, ambient temperature, and ambient solar radiation. During the first experimental period, from 10 to 23 Aug 2019, each cluster had four thermocouples (HYPI-30-1/2-T-G-60-SMP-M; OMEGA, Norwalk, CT, USA) inserted into four berries (two on the east and two on the west sides of clusters) per cluster, totaling 16 thermocouples across the four experimental replicates. In the second experimental period, from 24 Aug to 6 Sep 2019, two more thermocouples were added to each cluster, resulting in six thermocouples inserted into six berries (three on the east and three on the west sides of clusters) per cluster, totaling 24 thermocouples across the four experimental replicates. East and west thermocouple temperatures were ultimately averaged for model development. On occasion, thermocouples were removed from berries that lost turgidity and placed in turgid berries in the same experimental replicate. The thermocouples were connected to a thermocouple multiplexer (AM25T; Campbell Scientific, Logan, UT, USA). The needle probe ends of the thermocouples were inserted ~3 mm into grape berries at approximately EL stage 36 (berries with intermediate sugar values) for the first experimental period and at approximately EL stage 37 (berries not quite harvest ripe) for the second experimental period (Dry and Coombe 2004). The multiplexer was connected to a datalogger (CR1000, Campbell Scientific), which measured the thermocouples and logged the data. Ambient total solar radiation was measured with a pyranometer (SP-110-SS; Apogee Instruments, Logan, UT, USA) and ambient air temperature was measured with a thermistor (ST-110-SS, Apogee Instruments) housed in an aspirated radiation shield (TS-110-SS, Apogee Instruments). The shielded thermistor was mounted at the height of the top catch wire, 5 ft from the ground, between the two vines used for the experiment. Both the pyranometer and thermistor data were logged with the above-mentioned datalogger. Berry temperatures and ambient conditions were logged every 10 min as a sample (i.e., one measurement not the average over the 10-min period) to mirror the wireless temperature sensor logging method (see the next section).

Berry mimic temperature measured by wireless temperature sensors. White and black 12-inch, latex balloons (Way To Celebrate Latex Balloons 12” Plain Black and White; Walmart Apollo, LLC, Bentonville, AR, USA) were filled with five different volumes of deionized water. Wireless temperature sensors (WTS) (DS1921G#F Thermochron, 4K; Maxim Integrated, San Jose, CA, USA), were programmed to log temperatures as a sample (not average) every 10 min during the two experimental periods mentioned previously. After programming, the WTS were placed into clear, miniature zipper-sealable plastic bags (1.5 inches × 1.5 inches, 2 mils) and randomly assigned to
treatments. The treatments were as follows: one WTS in a clear plastic bag (C), a WTS in a clear plastic bag, placed into a black balloon filled with 0, 10, 30, 50, or 70 mL of water (0 Black, 10 Black, 30 Black, 50 Black, and 70 Black, respectively), and a WTS in a clear plastic bag, placed into a white balloon filled with 0, 10, 30, 50, or 70 mL of water (0 White, 10 White, 30 White, 50 White, and 70 White, respectively).

These berry mimics were randomly placed along the fruit zone within each replicate (cane) and attached to the catch wire using nylon cable fasteners so that they hung in the open fruit zone, directly above the grape clusters from which berry temperature was being measured, and directly under the above-head shadecloth. Each replicate contained 11 WTS, one of each treatment.

**DATA COLLECTION.** After each 2-week experimental period, the WTS data were downloaded onto a computer using a driver (DS1402D-DR8 iButton Reader, Maxim Integrated) with adapter (DS9490R# USB 1-Wire Adapter, Maxim Integrated) and software (ExpressThermo; Eclo Solutions, Leiria, Portugal). The WTS were then re-programmed for the second experimental period. In the same manner mentioned previously, the WTS were placed in new clear plastic bags and randomly assigned to treatments before being randomized within each replicate. During the experiment, berry temperature, solar radiation, and ambient temperature data were downloaded weekly from the datalogger.

**BERRY DIAMETER AND WEIGHT.** A random sample of 100 total ‘Camminare noir’ berries was taken across all four experimental replicates on 6 Sep 2019; individual berry weight was measured, and berry diameter was measured using digital calipers. Only 83 of the sampled berries were measured; 17 berries incurred damage during sample transportation to the laboratory. Diameters were also measured on the “logged berries” on the same day. To report the estimated weight of the berries with thermocouples, an equation representing the relationship between weight and diameter was developed using a linear regression (Fig. 2). The equation allowed for the estimation of the average weights of the thermocouple-logged berries (Table 1). Temperature was recorded only on turgid berries throughout the experiment.

**STATISTICAL ANALYSIS AND MODEL DEVELOPMENT.** Statistical computation was performed using statistical software (JMP Pro ver. 15; SAS Institute Inc., Cary, NC, USA). Exploratory data analysis was conducted to determine the best method to model grape temperature. Multiple simple linear regressions were run to evaluate the relationship between berry temperature and WTS temperatures in the different treatments (Table 2). Between-block variation was analyzed to ensure homogeneity (Fig. 1); because this variation was low, blocks were treated as replicates. A piecewise model was used to develop separate models for day and night because the variance in nighttime temperatures was lower than that of daytime temperatures. Preliminary analysis indicated that the optimal breakpoints between day and night were 2000 and 1000 HR. To prevent the night period from being broken into two separate periods (2000 to 2400 HR and 2400 to 1000 HR), we used the number of hours starting at 2000 HR for the regressions:

\[
y = \beta_0 + \beta_1 x_1 + \beta_2 x_2\]

where \( y \) = estimated berry temperature (degrees Celsius), \( \beta_0, \beta_1, \) and \( \beta_2 \) are regression parameters, \( x_1 \) is the temperature of the berry mimic, and \( x_2 \) is the number of hours starting at 2000 HR.

![Fig. 1. Between-block variation in grape berry mimic temperature from treatments 30 Black and 30 White [wireless temperature sensors with 30 mL (1.014 fl oz) water in black and white balloons, respectively] to illustrate that median, interquartile range, and variation of each block in both treatments is similar and not statistically different so that blocks can be treated as replicates. Analysis of variance performed to evaluate variance \((n = 4)\); \((1.8 \times ^\circ C) + 32 = ^\circ F\).
Fig. 2. The relationship between grape berry weight and diameter of ‘Camminare noir’ grapes on 6 Aug 2019. This relationship shows the typical size of ‘Camminare noir’ grapes and allows for weight estimation of in-field “logged berries” (those on which temperature was measured continuously throughout the experimental period) \( n = 83 \); 1 mm = 0.0394 inch, 1 g = 0.0353 oz.

Training set to create the prediction models, and data from replicates three were used as an independent test data set for evaluation of model performance. Model performance was evaluated based on the correlation between measured and modeled berry temperature and root mean square error (RMSE). RMSE is the standard deviation of residuals, how far from the regression line sample values fall. Residuals had a normal distribution, suggesting consistent over- and under-estimation; therefore, regressions were not forced through 0. Models with the lowest RMSE were chosen.

**Results and discussion**

**Ambient temperature and solar radiation.** Ambient temperature and solar radiation varied diurnally, as expected (Fig. 3). During the night, when solar radiation was lowest, ambient temperature was between 15.4 and 26.5°C. Ambient temperature was highest from 1200 to 1900 HR when it ranged from 21.8 to 35.6°C. Diurnal solar radiation trends were bell shaped, but with substantial variability because of clouds. The highest ambient solar radiation occurred between 1000 and 1600 HR and ranged from 79.6 to 1039 W·m\(^{-2}\) during that timeframe. Berry temperature is generally higher as ambient temperature and incident solar radiation increases (Hickey and Wolf 2019; Tarara et al. 2008). Exposed grape clusters will be subjected to higher solar radiation compared with shaded clusters, and therefore, internal berry temperature increases throughout the day in exposed clusters (Hickey and Wolf 2019). Exposure to high ambient temperature and solar radiation, most common between 1000 and 1900 HR, may increase berry temperature to the critical threshold for grape anthocyanin accumulation, which is thought to be between 30 and 35°C (Spayd et al. 2002; Tarara et al. 2008). Based on the diurnal ambient temperature and solar radiation patterns in Fig. 3, measuring grape berry temperature between 1200 and 2000 HR would provide the best opportunity to determine if critical berry temperature thresholds are being reached or exceeded under our experimental conditions. Measuring point-in-time berry temperature between 1200 and 2000 HR may help industry members determine if critical temperature thresholds are being met and thus guide best leaf removal practices at their site. However, training system, row orientation, and growing region will change the time of day when the greatest solar radiation within the fruit zone is experienced (Campos et al. 2017; Hunter et al. 2020).

**Berry diameter and weight.** Across the experimental replicates, berry weights ranged from 1.25 to 4.29 g, and berry diameter ranged from 12.2 to 20.0 mm (data not shown). The average diameter and weight of ‘Camminare noir’ grapes were 16.8 mm and 2.86 g, respectively (data not shown). When a regression equation was calculated, the results indicated a positive correlation \( r = 0.97 \) between berry weight and berry diameter (Fig. 2). Berry volume and physical properties are likely to affect the heating and cooling dynamics of grapes. Thus, even under the same experimental conditions (e.g., row orientation, training, exposure), differences in grape size, color, and cluster morphology are likely to be differentially heated and cooled by air temperature.

Table 1. Average estimated grape berry weight calculated by diameter measurement. Estimates determined from regression equation presented in Fig. 2.

<table>
<thead>
<tr>
<th>Replicate no.</th>
<th>Berry diam (mm)</th>
<th>Berry wt (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.49</td>
<td>2.72</td>
</tr>
<tr>
<td>2</td>
<td>16.81</td>
<td>2.86</td>
</tr>
<tr>
<td>3</td>
<td>17.02</td>
<td>2.96</td>
</tr>
<tr>
<td>4</td>
<td>16.95</td>
<td>2.92</td>
</tr>
</tbody>
</table>

\(^1\)Replicates consist of six berries, three on east canopy side and east on west canopy side, which were averaged to compare values.

\(^2\)Diameters were measured on the “logged berries” in field to characterize those in which thermistors were inserted; 1 mm = 0.0394 inch.

\(^3\)Weights were estimations determined using the equation from the linear regression (Fig. 2): weight (grams) = \(-4.4456 + 0.4347 \times \text{diameter (millimeters)}\); 1 g = 0.0353 oz.
and solar radiation. Hunter et al. (2021) found that even among berries within the same row, vine, and cluster, berry heating occurred at different rates based on position, radiant heating, and berry size. A grape cultivar with unique physical berry properties and cluster architecture may require a different model and berry mimic to optimally predict berry temperature.

Regression analysis between treatments and berry temperature. Both east and west side berry temperatures were closely and positively correlated with ambient air temperature throughout the experimental period \( R^2 = 0.894 \) and \( 0.911 \), respectively (Fig. 4). However, solar radiant heating throughout the day can change this relationship (Hickey and Wolf 2019; Tarara et al. 2008). Thus, berry temperature estimation methods that simultaneously account for ambient temperature and time of day would be desirable, such as the water-filled balloons with WTS that were anticipated to mimic/estimate berry physical properties. The correlation between berry and WTS temperatures tended to be stronger than that between berry and air temperature when compared over the course of day and night (Table 2, Fig. 4). For example, over the entire 24-h period, the relationship between treatment and average berry temperature produced \( R^2 \) values were at least 0.889; the \( R^2 \) values for 0 White, 10 White, and 30 White were 0.964, 0.963, and 0.956, respectively. The temperatures of black balloons tended to not be as closely correlated to berry temperature as those of white balloons, but 30 Black had an \( R^2 \) value of 0.956 across all hours. When night temperatures were removed, the correlations between berry temperature on the east and west canopy sides and ambient temperature were reduced (\( R^2 = 0.670 \) and 0.727, respectively). Again, the relationship between the WTS treatments and berry temperature were stronger than those between ambient air temperature and berry temperature with nighttime temperatures removed (Table 2). In the daytime hours, all WTS treatments had an \( R^2 \) value range of 0.650 to 0.854.

During nighttime hours, \( R^2 \) values were higher, and the variation of \( R^2 \) values was lower when compared with daytime. For example, the temperature sensor in a plastic bag explained 92.9% of the temperature variance at night, whereas the 30 White and 30 Black explained 91.7% and 96.2%, respectively. During the day, however, the temperature

### Table 2. \( R^2 \) values of the correlation between treatment temperature and grape berry temperature during daytime hours, nighttime hours, and the combination of both.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>1000–2000 HR</th>
<th>2000–1000 HR</th>
<th>0000–2400 HR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 White</td>
<td>0.854</td>
<td>0.942</td>
<td>0.964</td>
</tr>
<tr>
<td>10 White</td>
<td>0.829</td>
<td>0.950</td>
<td>0.963</td>
</tr>
<tr>
<td>30 White</td>
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<tr>
<td>50 White</td>
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<td>0.944</td>
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<tr>
<td>70 White</td>
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</tr>
<tr>
<td>0 Black</td>
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<td>0.882</td>
<td>0.937</td>
</tr>
<tr>
<td>10 Black</td>
<td>0.650</td>
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<tr>
<td>30 Black</td>
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<td>0.956</td>
</tr>
<tr>
<td>50 Black</td>
<td>0.749</td>
<td>0.938</td>
<td>0.939</td>
</tr>
<tr>
<td>70 Black</td>
<td>0.709</td>
<td>0.932</td>
<td>0.942</td>
</tr>
<tr>
<td>Control</td>
<td>0.746</td>
<td>0.929</td>
<td>0.939</td>
</tr>
<tr>
<td>Ambient</td>
<td>0.785</td>
<td>0.836</td>
<td>0.927</td>
</tr>
</tbody>
</table>

* Treatment names consist of volume of water (milliliters) followed by color of balloon. Control was a clear plastic bag with no water added. Ambient temperature was measured with a thermistor at the height of the top catch wire, 5 ft (1.52 m) from the ground; 1 mL = 0.0338 fl oz, \((1.8 \times ^\circ C) + 32 = ^\circ F\).  

* Daytime is considered the hours between 1000 and 2000 HR; nighttime is considered hours between 2000 and 1000 HR.
Table 3. Equations for the grape berry temperature prediction models developed for 30 White and 30 Black treatments. Estimated (Est) berry temperature \([\text{temp (degrees Celsius)}] = b_0 + b_1 \times \text{wireless temperature sensor (WTS) temp} + b_2 \times \text{hour (starting at 2000 HR as 0 h and 1000 HR as 14 h). Daytime is between 1000 and 2000 HR. Nighttime is between 2000 and 1000 HR.}^1

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Model Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 White Daytime (14–0 h)</td>
<td>Est berry temp = 3.07 + 1.11 × WTS temp – 0.30 × h</td>
</tr>
<tr>
<td>30 White Nighttime (0–14 h)</td>
<td>Est berry temp = –4.00 + 1.11 × WTS temp + 0.18 × h</td>
</tr>
<tr>
<td>30 Black Daytime (14–0 h)</td>
<td>Est berry temp = 8.57 + 0.86 × WTS temp – 0.33 × h</td>
</tr>
<tr>
<td>30 Black Nighttime (0–14 h)</td>
<td>Est berry temp = 1.86 + 0.87 × WTS temp + 0.02 × h</td>
</tr>
</tbody>
</table>

¹ 30 White and 30 Black = [WTS with 30 mL (1.014 fl oz) water in white and black balloons, respectively]; \((1.8 \times ^\circ C) + 32 = ^\circ F\). Values of regression coefficients determined using statistical software (JMP Pro ver. 15; SAS Institute Inc., Cary, NC, USA).

in the plastic bag explained only 74.6% of the variance, whereas 30 White and 30 Black explained 83.0% and 76.4% of the variance, respectively. A piecewise model was used to optimize berry temperature prediction by accounting for time of day separations determined by hours with highest solar radiation and effects of the berry mimics; the linear regressions used to develop the data in Table 2 only accounted for time of day.

**Statistical insights and the berry temperature prediction model.** During exploratory analysis, the AICc model selection indicated that treatments 30 White and 30 Black had the lowest error and, therefore, the best fit for berry temperature prediction. The regression coefficients for 30 White and 30 Black were based on the training data from three of the four replicates, resulting in the berry temperature prediction models (Table 3).

Once the models were created, they were evaluated for accuracy using data from the replicate that was not used for model development to determine how the predicted temperatures from the 30 White and 30 Black treatments compared with actual berry temperatures measured with thermocouples (Fig. 5). Evaluation of daytime regressions showed that 30 White had a RMSE of 1.217 °C and 30 Black had a RMSE of 1.865 °C. The \(R^2\) values for daytime regressions between predicted and measured berry temperatures in the 30 White and 30 Black were treatments 0.90 and 0.77, respectively. The residuals for both model regressions were normally distributed. Based on these findings, the treatment with the best model fit was 30 White.

The models developed here may be suitable for grapes grown in Watkinsville, GA, USA, and proximate locations as climates vary on a latitudinal and longitudinal basis. There were experimental limitations. ‘Camminare noir’ vines were 2 years old at the time of the experiment and were loosely trained to a VSP trellis system, which was oriented in rows that were planted north-south. The experiment was only conducted during two periods within one growing season. The models were based on time of day and temperature of berry mimics; solar radiation was not a factor for model development. It is likely that berry temperature prediction models will vary across cultivars, training systems, row orientations, locations, and growing seasons (as environmental conditions and vine growth varies). The developed model may thus not be suitable for all vineyards, but a similar approach to the one described here could be used to develop site-specific berry temperature models, in addition to an easier, cost-effective way to predict berry temperature over time. This work serves as proof-of-concept that grape berry temperature models can be developed using low-cost temperature loggers placed inside balloons partly with water.

**Conclusions**

New, simple methods for estimating grape berry temperatures in field

![Fig. 4. The relationship between ambient temperature and “logged” grape berry temperature on the east canopy side (A) and west canopy side (B); \(R^2 = 0.894\) and 0.911, respectively. Data recorded in three berries on each canopy side from one experimental replicate over the entire experimental period, 10 to 22 Aug 2019 and 24 Aug to 5 Sep 2019 (n = 12); \((1.8 \times ^\circ C) + 32 = ^\circ F\).](image-url)
research are essential for quantifying how temperature affects grape metabolites. All treatments could estimate berry temperature accurately at night. During the day, when solar radiation was a factor, the increased variation in models and lowest error in estimated temperature narrowed the best treatment to 30 White.

Using the developed model, a WTS can effectively report berry temperature and its relationship with berry physiology. Although a solution was explored and validated on a case-specific basis by parties interested in implementation, the increased variation in models and lowest error in estimated temperature narrowed the best treatment to 30 White.

Fig. 5. The relationship between measured grape berry temperature and modeled temperature, based on wireless temperature sensor (WTS) temperatures and time of day, for the 30 Black and 30 White treatments [WTS with 30 mL (1.014 fl oz) water in black and white balloons, respectively] during the daytime, nighttime, and combination (n = 24); (1.8 × °C) + 32 = °F.

References


