Nocturnal and daytime stomatal conductance respond to root-zone temperature in ‘Shiraz’ grapevines

Suzy Y. Rogiers1,2,* and Simon J. Clarke1,3

1 National Wine and Grape Industry Centre, Wagga Wagga, NSW, Australia, 2 NSW Department of Primary Industries, Wagga Wagga, NSW, Australia and 3 School of Agriculture and Wine Science, Faculty of Science, Charles Sturt University, Wagga Wagga, NSW, Australia

* For correspondence. E-mails suzy.rogiers@industry.nsw.gov.au

INTRODUCTION

Rising global temperatures can be accompanied by smaller, but significant, changes in soil surface temperatures (van Gestel et al., 2011) and this has the potential to affect root physiology and root activity. In particular, a gradual rise in night-time air temperature over the past few decades (Vose et al., 2005) has probably resulted in an increase in soil temperature during the night and early morning, depending on soil depth. Root growth (Larson, 1970; Kasper and Bland, 1992), water uptake (Wan et al., 1999), nutrient uptake and availability (MacDonald et al., 1995; BassiriRad, 2000; Melillo et al., 2002; Pregitzer and King, 2005) and signal transduction (Zhang et al., 2008; Field et al., 2009) are all influenced by the temperature of the soil. These processes affect above-ground growth (Lopushinsky and Kaufmann, 1984; Dawes et al., 2011; Rogiers et al., 2011b) and productivity (He et al., 2001). As a result, analogous to air temperature, soil temperature can limit the geographical distribution of plants and crops (Fosaa et al., 2004).

Leaf gas exchange is particularly responsive to the root-zone environment. While there are many studies characterizing the consequences of soil moisture on leaf gas exchange, soil temperature has also been found to affect stomatal conductance and photosynthesis in perennials (Cai and Dang, 2002; Wan et al., 2004; Wu et al., 2012) and annuals (He and Lee, 2001; He et al., 2001; Zhang et al., 2008). Root-zone temperature can restrict photosynthesis through alterations in photosynthetic reactions (Cai and Dang, 2002; Zhou et al., 2004; Erice et al., 2006) or changes in stomatal conductance (Wan et al., 2004). For instance, boreal and alpine plants are often exposed to low soil temperature stress and in conifer species the maximum rate of carboxylation ($V_{\text{c,max}}$) and the maximum rate of electron transport ($J_{\text{max}}$) increased with soil temperature up to an optimum and then declined (Cai and Dang, 2002). Conversely, it was found that when Populus tremuloides was exposed to low temperatures soil net assimilation was limited by stomatal conductance (Wan et al., 1999). As a consequence, it was suggested that similar root-to-shoot signalling pathways may operate in plants subjected to drought and low root temperature (Wan et al., 2004). As such, it was found that roots of Cucurbitaceae species can regulate stomatal behaviour in response to root-zone temperature by...
modifying delivery of abscisic acid (ABA) to shoots and leaves (Zhang et al., 2008).

Those environmental parameters regulating stomatal conductance ($g$) and transpiration ($E$) during the day may also exert some control during the night. Stomata can remain partially open during the night and, although the function of night-time transpiration is yet to be resolved, this can result in substantial night-time transpiration if the vapour pressure difference between the leaf and air (VPD) is high. In some species and varieties, nocturnal transpiration can even cause disequilibrium in plant water status (Caird et al., 2007; Dawson et al., 2007; Fisher et al., 2007; Kavanagh et al., 2007). For instance, Vitis vinifera ‘Grenache’, an isohydric grapevine variety, has low $g$ both during the day and night. This is in contrast to ‘Semillon’, an anisohydric variety, with comparatively high $g$ throughout the diurnal cycle and as a result incomplete plant rehydration prior to dawn especially during warm, windy nights (Rogiers et al., 2009). Aside from inherent genetic factors, nocturnal $g$ appears to be influenced by abiotic factors such as VPD, wind, atmospheric CO$_2$ concentration and soil moisture (Ludwig et al., 2006; Howard and Donovan, 2007; Zeppel et al., 2010, 2012). Another key environmental factor which may regulate nocturnal $g$ is root-zone temperature. To date, the consequences of root-zone temperature on nocturnal stomatal conductance, to our knowledge, are unknown. It is therefore difficult to incorporate soil temperature into crop production models because there is little information available on how soil temperature affects daytime and especially night-time foliar gas exchange.

We assessed the foliar gas exchange response of ‘Shiraz’, an anisohydric grapevine variety (Schulz, 2003) originating from temperate Bordeaux, France, and grown widely in warm climates across southern Australia and Argentina. ‘Shiraz’ is grown across a broad range of latitudes, elevations and topographic conditions that expose this variety to a wide range in root-zone temperatures. Slope orientation and the extent of ground cover in the inter-row area by cover crops or weeds will also affect the temperature of the soil. Other factors such as rain patterns, irrigation and soil type influence rooting depth, and therefore root-zone temperature, and this will also affect plant response. The objective of this work was to clarify the role of root-zone temperature on both nocturnal and daytime $g$ in ‘Shiraz’. Using well-watered grapevines grown in three different root-zone temperatures for 2 months we assessed the response of $g$ to this below-ground parameter during both the day and the night. The three root-zone temperatures consisted of ambient, 5°C below or 5°C above ambient levels to encompass the natural variation that can occur across a vineyard site in spring.

MATERIALS AND METHODS

Plant material

Six-year-old ‘Shiraz’ grapevines ($n = 60$) on their own roots (Vitis vinifera L., clone 1654) were re-potted during dormancy into 40-litre pots containing a well-draining potting mix. The plants were placed outdoors in a bird-proof enclosure in a randomized block design surrounded on all sides by buffer plants. The root-zone temperature treatments were administered by circulating water at controlled temperatures through a 1:1-m long coil of 13-mm polyethylene irrigation tubing inserted within the pot and embedded through the root-zone to a depth of 30 cm. This tubing was attached to 50-mm DWV pipe connected to a recirculating water system (UPS 32-80 N 180; Grundfos, Bjerringbro, Denmark) and one of three temperature-controlled 1200-litre water tanks. The sides and bottom of the pots were insulated with blue 10-mm dense foam to minimize heat exchange between the soil and air or ground. At the time of re-potting, a soil temperature probe (DS18B20; Maxim Integrated Products, Sunnyvale, CA, USA) was inserted into the centre of the root mass of every vine. A TDR soil moisture probe (Trace; Soil Moisture Equipment Corp., Santa Barbara, CA, USA) was also inserted in the same location in nine pots per treatment. Both these probes were logged at 30-min intervals (Mini Trace data logger; Soil Moisture Equipment Corp.). A weather station, equipped with an air temperature probe (Interca HMP50; Vaisala, Hawthorn, VIC, Australia) and a quantum sensor (Apogee, SQ-110; Logan UT, USA) logging at half hourly intervals, was placed at canopy height within the trial. Ten weeks prior to bud-burst, the plants were pruned to two spurs, each carrying two buds. After bud-burst the plants were irrigated daily and excess water was allowed to drain from the bottom of the pot. Beginning 25 d after bud-burst plants were fertilized with 200 mL tap water containing 1 mL nutrient concentrate (Megamix Plus, equivalent to N/P/K 130 : 100 : 150 mg per plant) every 5 d until verison, then every 10 d thereafter.

Root-zone temperature treatments

Three root-zone temperature treatments were initiated at the onset of budburst (E-L Stage 4) and terminated at fruit-set (E-L stages 27–29). The root-zone temperatures were allowed to fluctuate diurnally, with the ambient treatment mimicking the nearby vineyard under-vine soil at a depth of 15 cm. Maximum root-zone temperatures over the 63-d treatment period averaged 16.9 ± 0.3°C for the cool, 22.6 ± 0.5°C for the ambient and 24.8 ± 0.4°C for the warm treatment, while minimum root-zone temperatures averaged 13.3 ± 0.3, 17.8 ± 0.5°C and 22.6 ± 0.2°C, respectively. Air temperature at the canopy level (approx. 1 m above the soil surface) was not altered by the treatments and ranged between an average minimum of 10-3°C and maximum of 28.5°C. VPD ranged between 1.97 and 0.17 kPa while daily maximum photosynthetically active radiation (PAR) averaged 1200 μmol m$^{-2}$ s$^{-1}$. Soil moisture over the 63-d treatment period averaged 21.9 ± 1.3% for the cool, 21.5 ± 1.4% for the ambient and 21.1 ± 1.4% for the warm treatment.

Plant measurements

Instantaneous net assimilation, stomatal conductance, transpiration and leaf intercellular CO$_2$ concentrations were measured using a portable photosynthesis system (LI-6400; LI-COR Biosciences Inc., Lincoln NE, USA). Midday measurements were carried out weekly from bud-burst to fruit-set. An artificial red–blue light source attached to the chamber head was used to illuminate the leaf at 1500 μmol m$^{-2}$ s$^{-1}$ PAR. The CO$_2$ concentration of the incoming air was maintained at 400 μmol mol$^{-1}$ and the block temperature was set.
at 25 °C. On each shoot (18 plants per treatment with four shoots per plant), the leaf opposite the basal inflorescence (most often located at the fourth or fifth node from the base) was measured. Nocturnal measurements (nine plants per treatment) were carried out every 2 weeks on the same leaves prior to dawn with the chamber light turned off, incoming CO₂ concentration set at 400 μmol mol⁻¹ and the block temperature set to 18 °C. Time-integrated values of transpiration were calculated based on a normal distribution of leaf stomatal transpiration (Rogiers et al., 2009), over a 15-h light period and constant E during the 9-h dark period. Light, temperature and VPD response curves were carried out at midday, 43–50 d after the onset of the root-zone temperature treatments, on four to six plants per treatment. VPD was not controlled in the temperature or light response curves.

Leaf chlorophyll was assessed non-destructively with a chlorophyll meter (SPAD-502; Minolta Co., Ltd, Tokyo, Japan) twice weekly from 30 d after bud-burst to fruit-set. The meter readings were converted to chlorophyll content using a calibration curve derived from paired meter and spectrophotometer readings. The spectrophotometer readings were converted to an estimate of chlorophyll content following the method of Steele et al. (2008). Measurements were carried out on the leaf opposite the basal inflorescence and all leaves opposite the basal tendril in the three-node repeating metamer pattern that occurs along V. vinifera shoots. Stomatal density was assessed on these leaves on six plants per treatment according to the method of Rogiers et al. (2011a).

A/Cᵢ responses to root-zone temperatures

Measurements of photosynthetic responses to cool and warm root-zone temperatures were carried out 50 d after onset of treatments on four plants per treatment, targeting fully expanded leaves opposite the basal inflorescence. The leaf respiration/internal CO₂ concentration (A/Cᵢ) response was measured according to Ainsworth et al. (2002). Photosynthesis was initially measured at 400 μmol mol⁻¹ CO₂ under saturating light (1500 μmol mol⁻¹ s⁻¹) and a block temperature of 25 °C, until A was steady-state. The CO₂ concentration surrounding the leaf (Cᵢ) was then reduced to 50 μmol mol⁻¹ over nine steps with A and Cᵢ recorded as soon as Cᵢ was stable. Cᵢ was then returned to 400 μmol mol⁻¹ and increased over eight steps to 2000 μmol mol⁻¹. Each A/Cᵢ curve was processed to obtain Jᵢₙₘₐₓ, the maximum rate of electron transport, Vₑₚ, the in vivo maximum rates of Rubisco activity, and Rₑ, the day respiration, according to the method of Greer and Weeden (2012) using SAS 9.1 (SAS Institute Inc., Cary, NC, USA).

Statistical analysis

SigmaPlot graphing and statistics software (version 12.3; SPSS Inc., Chicago, IL, USA) was used to fit linear or non-linear regressions of gas exchange parameters with soil temperature, air temperature, VPD and PAR. The three-dimensional mesh plots of nocturnal leaf stomatal conductance (gₛ) and nocturnal leaf stomatal conductance (Eₛ) with soil moisture and root-zone temperature were created with smoothed data calculated from running averages using SigmaPlot. An analysis of variance (GenStat release 15.0; VSN, Hertfordshire, UK) was used for comparison of treatment effects during the root-zone temperature treatments and least significant differences were calculated at 5 % significance. Results of the statistical analyses are presented in the tables and figures. Values presented in the text are means ± s.e.

RESULTS

Nocturnal gas exchange

Nocturnal leaf stomatal conductance, gₛ, (P < 0.001) and transpiration, Eₛ, (P < 0.001) responded to root-zone temperature (Table 1). In the cool root-zone treatment, gₛ was 14.5 % lower than in the ambient treatment and 20.7 % less than in the warm treatment. Similarly, compared with the ambient and warm root-zone treatments, Eₛ was 13.8 and 19.8 % lower, respectively, in the cool treatment. This decline was apparent without any treatment differences in soil moisture (P = 0.105) which averaged at 20.9 % at the time of measurement. A linear regression of gₛ with soil moisture at the time of the gas exchange measurements (P < 0.01) explained only 4 % of the variance in the data while a regression of this parameter with root-zone temperature (P < 0.002) accounted for 3 % of the variance. Further detailed examination of these two environmental parameters, however, showed that vines exposed to high root-zone temperatures combined with high soil moistures had highest gₛ and Eₛ values while those exposed to low temperatures and low moisture responded with low gₛ and Eₛ (Fig. 1). The combined factors of leaf age, leaf temperature, soil moisture and soil temperature accounted

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Root-zone temperature (°C)</th>
<th>Soil moisture (%)</th>
<th>A (μmol CO₂ m⁻² s⁻¹)</th>
<th>gₛ (mmol H₂O m⁻² s⁻¹)</th>
<th>Eₛ (mmol H₂O m⁻² s⁻¹)</th>
<th>Cᵢ (μmol mol⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool</td>
<td>14.8</td>
<td>21.2</td>
<td>-0.53</td>
<td>0.0314</td>
<td>0.275</td>
<td>455.2</td>
</tr>
<tr>
<td>Ambient</td>
<td>20.8</td>
<td>20.9</td>
<td>-0.45</td>
<td>0.0367</td>
<td>0.319</td>
<td>437.8</td>
</tr>
<tr>
<td>Warm</td>
<td>24.2</td>
<td>19.7</td>
<td>-0.48</td>
<td>0.0396</td>
<td>0.345</td>
<td>435.5</td>
</tr>
<tr>
<td>LSD</td>
<td>0.2</td>
<td>1.8</td>
<td>0.11</td>
<td>0.0034</td>
<td>0.025</td>
<td>11</td>
</tr>
<tr>
<td>F-test, P &lt;</td>
<td>0.001</td>
<td>0.179</td>
<td>0.199</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Values are means of three sampling dates over a 60-d treatment period (n = 9 on each sampling date). Root-zone temperatures and soil moistures represent the means at the time the gas exchange measurements were made. Means followed by different letters are significantly different at P < 0.05.
for 31% of the variance in $g_n$ ($P < 0.001$) and 58% of the variance in $E_n$ ($P < 0.002$).

Leaf respiration ($-A$) was not affected ($P = 0.20$) by root-zone temperatures and averaged 0.49 μmol CO$_2$ m$^{-2}$ s$^{-1}$ (Table 1). Internal CO$_2$ concentrations ($C_i$), were higher by about 20 μmol mol$^{-1}$ in cool root-zone temperatures compared with the other treatments ($P < 0.001$), although this was apparently not linked to $g_n$ because a linear regression of $C_i$ with $g_n$ was not significant ($P = 0.15$).

**Midday gas exchange**

As leaves matured over a 20-d period of rapid shoot growth, midday stomatal conductance ($g_d$) increased ($P < 0.001$) and had doubled by the time full lamina expansion had taken place. This occurred in all three treatments within 1 month after bud-burst (Fig. 2). On each measuring date, $g_d$ was substantially less in the cool root-zone as compared with the two other treatments. As the season progressed, air temperatures
rose, the soil temperatures of the ambient and the warm treatments converged, and so did leaf \( g_d \) of plants grown in those treatments.

Rates of CO\(_2\) assimilation (A) were highest in the warm and lowest in the cool root-zone temperatures (\( P < 0.001 \)), each diverging by about 5% from the ambient treatment (Table 2).

This was not the result of earlier bud-burst in the warm or later bud-burst in the cool treatment because bud-burst occurred at roughly the same time for all the treatments (\( P = 0.37 \)). Leaf development after bud-burst may have proceeded at a greater rate in the warm root-zone treatment, but even though leaves of plants grown in this treatment were larger (Table 4), lamina length and A were not correlated (\( P = 0.822 \)). Higher A was also not due to higher chlorophyll levels in warm plants because chlorophyll levels in the leaves from nodes 2 to 6 over this period were not different from each other in the cool and warm treatments (Table 3).

Despite no differences in soil moisture between the cool and the ambient treatments, midday \( g_d \) (\( P < 0.001 \)) and \( E_d \) (\( P < 0.001 \)) were lower by 22 and 17%, respectively, in the cool treatment (Table 2). While there were no differences in \( g_d \) or \( E_d \) between the ambient and warm treatments, regressions of \( g_d \) and \( E_d \) with root-zone temperature were highly \( (P < 0.001)\) significant (Fig. 3). During a 9-h period of darkness, total \( E_a \), amounted to 160 mL H\(_2\)O m\(^{-2}\) leaf area in the cool, 186 mL H\(_2\)O m\(^{-2}\) in the ambient and 200 mL H\(_2\)O m\(^{-2}\) in the warm treatment. During the 15-h light period, total \( E_d \) amounted to 1312 mL H\(_2\)O m\(^{-2}\) in the cool, 1584 mL H\(_2\)O m\(^{-2}\) in the ambient and 1580 mL H\(_2\)O m\(^{-2}\) in the warm treatment. Daily \( E_a \) as a proportion of \( E_d \) varied by only 1% between the treatments (12.2% for the cool treatment, 11.7% for the ambient treatment and 12.7% for the warm treatment).

Plants grown with cool root-zones had 15% greater transpiration efficiency (\( A/E \)) (\( P < 0.001 \)) and 23% greater intrinsic transpiration efficiency (\( A/g \)) (\( P < 0.001 \)) than plants grown in ambient soil (Table 2). Those grown in the warm soil also had somewhat higher \( A/g \) (6%) but this may have been an artefact of the slightly reduced soil moistures in this treatment. While there were no differences in \( A/E \) between the ambient and warm treatments (Table 2), the regression of \( A/E \) with soil temperature was significant due to the strong cool treatment effect (Fig. 3). Similar to \( g_d \), midday leaf \( C_i \) was somewhat less (7%) in the cool treatment, indicating depleted CO\(_2\) concentrations and a stomatal limitation to photosynthesis.

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**Table 2.** Midday leaf \( A \), \( g_d \), \( E_d \), \( A/g \), \( A/E \) and \( C_i \) of grapevines under cool, ambient or warm root-zone conditions

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Root-zone temperature (°C)</th>
<th>( A ) (( \mu \text{mol CO}_2 \text{ m}^{-2} \text{s}^{-1} ))</th>
<th>( g_d ) (( \mu \text{mol H}_2\text{O m}^{-2} \text{s}^{-1} ))</th>
<th>( E_d ) (( \mu \text{mol H}_2\text{O m}^{-2} \text{s}^{-1} ))</th>
<th>( A/g ) (( \mu \text{mol CO}_2 \text{ mol}^{-1} \text{H}_2\text{O} ))</th>
<th>( A/E ) (( \mu \text{mol CO}_2 \text{ mol}^{-1} \text{H}_2\text{O} ))</th>
<th>( C_i ) (( \mu \text{mol CO}_2 \text{ mol}^{-1} \text{air} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool</td>
<td>16.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8.83&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.155&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.70&lt;sup&gt;a&lt;/sup&gt;</td>
<td>62.0&lt;sup&gt;c&lt;/sup&gt;</td>
<td>3.74&lt;sup&gt;c&lt;/sup&gt;</td>
<td>262.3&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Ambient</td>
<td>23.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>9.17&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.198&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.26&lt;sup&gt;b&lt;/sup&gt;</td>
<td>50.5&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.24&lt;sup&gt;b&lt;/sup&gt;</td>
<td>280.0&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Warm</td>
<td>26.5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>9.60&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.201&lt;sup&gt;c&lt;/sup&gt;</td>
<td>3.25&lt;sup&gt;c&lt;/sup&gt;</td>
<td>53.8&lt;sup&gt;c&lt;/sup&gt;</td>
<td>3.35&lt;sup&gt;c&lt;/sup&gt;</td>
<td>275.4&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>LSD</td>
<td>0.3</td>
<td>0.30</td>
<td>0.006</td>
<td>0.09</td>
<td>2.7</td>
<td>0.13</td>
<td>5.0</td>
</tr>
<tr>
<td>F-test, ( P &lt; )</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Values are means of seven sampling dates over a 60-d treatment period (\( n = 18 \) on each sampling date). Root-zone temperatures represent the means at the time the gas exchange measurements were made. Means followed by different letters are significantly different at \( P < 0.05 \).
TABLE 3. Leaf chlorophyll concentrations and leaf photosynthetic characteristics derived from intercellular CO₂ response curves of mature leaves that emerged during the cool or warm rootzone treatments (n = 4)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Chlorophyll (mg m⁻²)</th>
<th>( J_{\text{max}} ) (µmol m⁻² s⁻¹)</th>
<th>( V_{\text{c,max}} ) (µmol m⁻² s⁻¹)</th>
<th>( R_{d} ) (µmol m⁻² s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool</td>
<td>424.4±2</td>
<td>91.0±1</td>
<td>34.8±4</td>
<td>0.29±0.01</td>
</tr>
<tr>
<td>Warm</td>
<td>424.9±2</td>
<td>97.1±1</td>
<td>33.0±4</td>
<td>0.58±0.01</td>
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<tr>
<td>LSD</td>
<td>0.756</td>
<td>0.442</td>
<td>0.655</td>
<td>0.18</td>
</tr>
<tr>
<td>F-test, P &lt;</td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( J_{\text{max}} \) is the maximum rate of electron transport, \( V_{\text{c,max}} \) is the in vivo maximum rates of Rubisco activity and \( R_{d} \) is the daytime respiration rate. Chlorophyll concentrations represent averages of nodes 2–6 of weekly measurements during the temperature treatments (n = 18 plants, four shoots per plant). Means followed by different letters are significantly different at P < 0.05.

Light, temperature and VPD response curves

Air temperature, light and VPD response curves (Figs 4–6) provide more extensive data of how leaf gas exchange was affected by root-zone temperatures. In both cool and warm root-zones, stomata were progressively more closed across an air temperature range of 18–38 °C (Fig. 4). VPD was not controlled over this temperature range and \( E_{d} \) increased linearly (P < 0.001) with air temperature in both root-zone temperature treatments. However, \( A \) did not change with this environmental parameter in either the cool (P = 0.38) or the warm (P = 0.73) root-zones. \( C_{i} \) followed similar trends to that of \( g_{d} \) with lower values in the cool root-zones.

There were similar trends in \( g_{d} \) and \( E_{d} \) with increasing VPD (Fig. 5). While \( g_{d} \) declined, \( E_{d} \) increased linearly across the VPD range of 1–4 kPa. Increases in \( E_{d} \) in the warm root-zones were double (slope 1.9 mmol H₂O m⁻² s⁻¹ kPa⁻¹) that in the cool root-zones (slope 0.86 mmol H₂O m⁻² s⁻¹ kPa⁻¹) (P < 0.001). Despite stomatal closure, \( A \) increased slightly with VPD in both root-zone treatments. \( C_{i} \) was lower in the cool root-zones and responded in a curvilinear manner to VPD, unlike in the warm root-zone treatment.

As with the air temperature and VPD curves, light response curves showed good separation between the root-zone treatments with higher values in the warm treatment as compared with the cool treatment (Fig. 6). Both \( g_{d} \) and \( E_{d} \) increases were curvilinear and did not plateau until the highest PAR value (2000 µmol m⁻² s⁻¹). \( A \) increased steeply in response to rising PAR and leaves from the warm root-zone reached a 15% higher plateau at 1000 µmol m⁻² s⁻¹ than in the cool root-zone. Conversely, \( C_{i} \) values declined with increasing PAR and above 1500 µmol m⁻² s⁻¹ \( C_{i} \) settled at 300 µmol mol⁻¹ in the warm and 260 µmol mol⁻¹ in the cool root-zone treatment.

FIG. 3. Midday leaf \( g_{d} \), \( E_{d} \), \( A/g \) and \( A/E \) as a function of root-zone temperature 48 d after the onset of treatments. Soil moisture was not different between the treatments (F-test, P = 0.72) and averaged 22.6 ± 14.5% at the time of measurement. F-test of linear regression for \( g \) = 0.001, \( E \) = 0.001, \( A/g \) = 0.001 and \( A/E \) = 0.001; variance accounted for in \( g \) = 0.47, \( E \) = 0.49, \( A/g \) = 0.34 and \( A/E \) = 0.19.
Leaf and photosynthetic characteristics

$A/C_i$ curves in response to root-zone temperatures are presented in Fig. 7. Further analyses of these curves indicate there were no differences in $J_{\text{max}}$ ($P = 0.44$) or $V_{\text{c,max}}$ ($P = 0.65$) between the treatments and they averaged 94.1 ± 7.5 and 33.0 ± 4.0 μmol m$^{-2}$s$^{-1}$, respectively (Table 3). Daytime dark respiration was also not different between the treatments ($P = 0.18$) and averaged 0.4 ± 0.2 μmol m$^{-2}$ s$^{-1}$. Furthermore, leaf chlorophyll concentrations did not differ ($P = 0.75$) and averaged 424.6 ± 1.3 mg m$^{-2}$.

One leaf characteristic that did differ between the treatments was stomatal density. Of those leaves that emerged during the treatments, stomatal density was 10% ($P < 0.05$) higher in the cool treatment as compared with the warm treatment (Table 4). Despite 8% larger leaves in the warm treatment as compared with the cool treatment (Table 4), there was no significant relationship between stomatal density and leaf area ($F$-test, $P = 0.10$ for a data set with combined treatments), and therefore other factors aside from leaf area appear to be involved. There were no differences in stomatal density of those leaves that emerged after the discontinuation of the treatments and they averaged 125.6 ± 5 stomata mm$^{-2}$. Note, however, that stomatal density of newly emerging leaves of plants grown in the warm treatment increased by 11% after that treatment had been removed. As averaged over 60 d following the termination of the treatments, leaf length remained 6% larger in the warm treatment than the cool treatment ($P < 0.001$).

Gas exchange after termination of the treatments

After discontinuation of the treatments the midday root-zone temperatures averaged at 20.6 ± 0.3 °C and varied by less than 4% (Table 5). Despite equal amounts of water applied, soil moisture was slightly (3%) higher in those plants that received the cool treatment as compared with the warm treatment. This is probably because the cool plants had less total leaf area (Table 4) and therefore less whole plant transpiration and lower rates of soil water utilization. Leaf $A$, $g_d$ and $E_d$ were no longer different between plants that had previously received the three treatments.

DISCUSSION

Nocturnal stomatal conductance

Our study confirms that daytime stomatal conductance of grapevines, like many other species, responds to root-zone temperature. Our present findings extend this observation to nocturnal stomatal conductance. There is very little experimental work on the interaction of root-zone temperatures with nocturnal gas exchange and we believe this is one of the first reports to characterize this. Cool root-zones resulted in a sustained suppression in $g$ and $E$ during both the day and the night and leaves transpired nearly 20% less than those grown in warm root-zones. Aside from the stomatal limitation evident in our data, others have shown that low $E$ can be the result of reductions in both soil and plant hydraulic conductance (Kramer and Boyer, 1995; Fennel and Markhart, 1998; Berndt et al., 1999) possibly through an increase in water viscosity (Muhsin and Zwiazek, 2002). After
discontinuation of the treatments, differences in leaf $g_d$ and $E_d$ were no longer apparent. This signifies that the root-zone temperature effect on gas exchange was not due to a permanent anatomical change but rather a transient physiological effect, perhaps relayed through signals targeted at the stomata.

Another study on aspen has demonstrated that low root-zone temperatures can reduce $g$ through pH, ion and ABA signals transported in the xylem sap (Wan et al., 2004). It would therefore be expected that these signals persist throughout the diurnal cycle, including the night. The role of such signals was not addressed in this study, however, and further work is required to verify their contribution to $g_d$ and $g_n$ in grapevines.

The resultant reduction in $g_n$ of plants growing in cool root-zones may thus be an after-effect of daytime changes, or it may offer a physiological advantage such as hastened plant rehydration through concomitant decreases in $E_n$. Nocturnal transpiration, assessed in this study under mild spring-time conditions, was generally about 12% of $E_d$. This is similar to other species grown in wetter environments (Caird et al., 2007; Dawson et al., 2007) and less than the 40–75% found in desert species (Ogle et al., 2012). Substantial night-time transpiration as a consequence of elevated $g_n$ in warm night-time root-zones may prevent complete plant rehydration prior to dawn (Kavanagh et al., 2007), resulting in greater water stress during the day as evaporative demand increases. Because our plants were well watered in all treatments with soil moistures not dropping below 20%, soil moisture was not a stressor. In grapevines, wilting tendrils at the shoot tips are the first signs of water stress (Winkler et al., 1974) and we did not observe this in any of our plants. In a field situation, however, under the absence of irrigation or under reduced water allocations, plants may experience daytime water stress due to elevated night-time soil temperatures, especially in warm, dry climates. It follows then that daily minimum soil temperature may be just as critical as daily maximum or average soil temperature in determining plant water relations.

Absence of acclimation

One of most significant findings of this study was that stomatal conductance remained low in the cool root-zones throughout the 2-month treatment period, with apparently no temperature acclimation. Sustained reduction in $g$ may be required over weeks if plants are to prevent dehydration, especially with rising midday and nocturnal VPD driving $E$ as the season progresses.

FIG. 5. Midday leaf $g_d, E_d, A$ and $C_i$ in response to VPD ($n = 4$) of vines grown in either cool or warm soil. At the time of measurement, root-zone temperature of the warm treatment was 20.3 ± 0.9 °C and of the cool treatment was 13.3 ± 0.7 °C ($P < 0.001$). Soil moisture was not different between the treatments ($F$-test, $P = 0.50$) and averaged 16.8 ± 0.5%. The intercepts and slopes of the regressions for the cool and warm cohorts are different from each other for $E_d$ ($P < 0.001$), but only the intercept for $g_d$ ($P < 0.001$) and $A$ ($P < 0.001$). A non-linear curve was fitted to the $C_i$ data of the cool root-zone temperature treatment ($P < 0.001$).
Because nocturnal gas exchange has not yet received the same depth of attention as daytime gas exchange, far less is known about the plasticity of nocturnal stomatal conductance to environmental factors. We found that aside from root-zone temperature, soil moisture was another variable that impinged on nocturnal stomatal conductance. Nocturnal stomatal conductance was found to decline with drying soil (Cavender-Bares et al., 2007; Howard and Donovan, 2007) and increasing VPD (Barbour and Buckley, 2007) in other studies. VPD did not explain any of the variance in \( g_n \) in our ‘Shiraz’ plants but this may be because the leaf chamber temperature was held constant and the resultant VPD range was fairly narrow.

**Other factors controlling nocturnal stomatal conductance**

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**Table 4. Stomatal density of leaves that emerged during the root-zone temperature treatments and of those leaves that emerged after the cessation of the treatments**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Stomatal density (stomata mm(^{-2}))</th>
<th>Lamina length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>During treatments</td>
<td>Following treatments</td>
</tr>
<tr>
<td>Cool</td>
<td>127.93(^{a})</td>
<td>127.04(^{a})</td>
</tr>
<tr>
<td>Ambient</td>
<td>123.15(^{ab})</td>
<td>120.08(^{a})</td>
</tr>
<tr>
<td>Warm</td>
<td>116.67(^{b})</td>
<td>129.70(^{a})</td>
</tr>
<tr>
<td>LSD</td>
<td>8.26</td>
<td>9.76</td>
</tr>
<tr>
<td>( F )-test, ( P &lt; )</td>
<td>0.018</td>
<td>0.127</td>
</tr>
</tbody>
</table>

Data during the treatments are the means of leaves up to and including node 6, where gas exchange measurements were made (\( n = 5 \) plants, four shoots per plant). Data of leaves that emerged after the treatments were discontinued up to node 27. Means followed by different letters are significantly different at \( P < 0.05 \).
Root-zone temperature regulates photosynthesis

Rates of CO₂ assimilation were highest in the warm and lowest in the cool root-zones, and this was apparent across a wide range in PAR, VPD and air temperatures. The decline in Cᵢ values under cool root-zone temperatures points to a stomatal limitation and therefore a curtailed CO₂ supply to photosynthesis under these conditions. There were no apparent limitations at the chloroplast level as chlorophyll content and synthesis under these conditions. There were no apparent limitations at the chloroplast level as chlorophyll content and synthesis under these conditions. 

The key point is that soil temperature did influence A, and furthermore A was more sensitive to soil temperature than to an air temperature range of 20–35 °C. Similarly, photosynthesis of red spruce saplings grown in a cold region was limited more by minimum soil temperature than minimum air temperature, especially in spring (Schwarz, 1997). If this is the case for grapevines grown in cool regions, it would be advantageous for the plant to direct root growth to a depth where diurnal temperature fluctuations are dampened. When field grapevines are drip irrigated, however, most of the roots can be found in the top layers (Stevens and Douglas, 1994) and therefore they are exposed to significant fluctuations in temperature. Natural daily cycling in temperature is often overlooked in root-zone studies (Pregitzer et al., 2000), but to mimic field conditions we allowed soil temperature to fluctuate diurnally by approximately 5 °C. Diurnal soil temperature fluctuations would also be relevant to newly established seedlings with small root systems as well as shallow-rooted species growing on impenetrable soils.

Transpiration efficiency responds to root-zone temperature

Despite greater A in warm root-zones, both A/g and A/E were inversely proportional to root-zone temperature. In other words, leaves of plants grown in the warmer root-zones lost greater amounts of water per unit of carbon gained. This is similar to the drop in transpiration efficiency of grapevine varieties grown in high VPD (Düring, 1987; Pou et al., 2008) or ample soil moisture (Cuevas et al., 2006). There is wide varietal diversity in transpiration efficiency of grapevines (Schultz, 1996; Bota et al., 2001; Gibberd et al., 2001; Rogiers et al., 2009). While the adoption of irrigation technology that confers water savings has improved water-use efficiency at the vineyard level, further gains can be made by planting inherently efficient varieties (Condón et al., 2004). Varietal selection therefore must not only take into consideration VPD and soil moisture responses but, as shown here, soil temperature as well.

Stomatal density responds to root-zone temperature

Stomatal density of concurrently formed leaves was lowest in the warm root-zone treatment and highest in the cool root treatment. It would seem intuitive that the high stomatal densities of the cold treatment might lead to higher gₛ and gₐ, but as is apparent here, there was no such relationship. The low g characteristic of the cool root-zone treatment is therefore not due to low stomatal density and must be related to stomatal aperture only.

In a previous study on ‘Chardonnay’ grapevines it was found that root-zone temperature and atmospheric carbon dioxide both impinged on stomatal density (Rogiers et al., 2011a). Because this leaf parameter was closely and inversely correlated with starch concentration in roots and trunks we suggested that the carbohydrate reserve status of the plant may be an important endogenous determinant of stomatal density. Depleted starch reserves, elicited by several weeks of high metabolism in the warm root-zones, would require...
replenishment and indeed we find that, in the current study, stomatal density of newly emerging leaves of grapevines grown in warm soil increased after the treatment had been removed.

Summary

We report that \( E_n \) of anisohydric grapevines can be a small (12 %) but significant part of daily transpiration. Similar to \( g_p \), \( g_n \) was responsive to root-zone temperature and thus those regulatory signals that are operative during the day also persist during the night. Removal of the cool or warm treatments brought \( g \) back to ambient levels, indicating the presence of a system that is able to react to environmental conditions. The limitation in photosynthesis induced by cool root-zones was the result of a stomatal limitation rather than limitations at the chloroplast level, and accompanying increases in stomatal density brought on by the cool root-zones were not able to offset this stomatal limitation. Intrinsic transpiration efficiency declined with increasing root-zone temperature. Therefore, it is likely that carbon assimilation will occur at the expense of a high water loss when anisohydric grapevines are grown in warm climates with warm soils.

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LITERATURE CITED


