Interactive effects of elevated CO\textsubscript{2} and drought on nocturnal water fluxes in \textit{Eucalyptus saligna}

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Nocturnal water flux has been observed in trees under a variety of environmental conditions and can be a significant contributor to diel canopy water flux. Elevated atmospheric CO\textsubscript{2} (elevated [CO\textsubscript{2}]) can have an important effect on day-time plant water fluxes, but it is not known whether it also affects nocturnal water fluxes. We examined the effects of elevated [CO\textsubscript{2}] on nocturnal water flux of field-grown \textit{Eucalyptus saligna} trees using sap flux through the tree stem expressed on a sapwood area ($J_s$) and leaf area ($E_l$) basis. After 19 months growth under well-watered conditions, drought was imposed by withholding water for 5 months in the summer, ending with a rain event that restored soil moisture. Reductions in $J_s$ and $E_l$ were observed during the severe drought period in the dry treatment under elevated [CO\textsubscript{2}], but not during moderate- and post-drought periods. Elevated [CO\textsubscript{2}] affected night-time sap flux density which included the stem recharge period, called ‘total night flux’ (19:00 to 05:00, $J_{sr}$), but not during the post-recharge period, which primarily consisted of canopy transpiration (23:00 to 05:00, $J_{sc}$). Elevated [CO\textsubscript{2}] wet (EW) trees exhibited higher $J_{sr}$ than ambient [CO\textsubscript{2}] wet trees (AW) indicating greater water flux in elevated [CO\textsubscript{2}] under well-watered conditions. However, under drought conditions, elevated [CO\textsubscript{2}] dry (ED) trees exhibited significantly lower $J_{sr}$ than ambient [CO\textsubscript{2}] dry trees (AD), indicating less water flux during stem recharge under elevated [CO\textsubscript{2}]. $J_{sc}$ did not differ between ambient and elevated [CO\textsubscript{2}]. Vapour pressure deficit ($D$) was clearly the major influence on night-time sap flux. $D$ was positively correlated with $J_{sr}$ and had its greatest impact on $J_{sr}$ at high $D$ in ambient [CO\textsubscript{2}]. Our results suggest that elevated [CO\textsubscript{2}] may reduce night-time water flux in \textit{E. saligna} when soil water content is low and $D$ is high. While elevated [CO\textsubscript{2}] affected $J_{sr}$, it did not affect day-time water flux in wet soil, suggesting that the responses of $J_{sr}$ to environmental factors cannot be directly inferred from day-time patterns. Changes in $J_{sr}$ are likely to influence pre-dawn leaf water potential, and plant responses to water stress. Nocturnal fluxes are clearly important for predicting effects of climate change on forest physiology and hydrology.

Keywords: drought, elevated CO\textsubscript{2}, nocturnal, sap flow, sap flux, transpiration.

Introduction

Nocturnal water flux is a widespread phenomenon that has been observed in a variety of ecosystems and plant functional groups (Snyder et al. 2003, Caird et al. 2007, Dawson et al. 2007), including trees (Daley and Phillips 2006, Fisher et al. 2007). Water flux at night may occur as nocturnal sap flow ($E_{n}$)
through the tree stem and as water loss through the leaf via stomatal and cuticular conductance (nocturnal leaf conductance, \( g_n \)). While it has been suggested that nocturnal water flux is primarily a function of stem refilling (i.e., recharge) (Caird et al. 2007), most studies indicate that water loss through the leaves is >50% of \( E_n \) (Caird et al. 2007, Zeppel et al. 2010). In turn, stomata account for the major proportion, and cuticular conductance for <10% of total leaf conductance at night (Phillips et al. 2010, Zeppel et al. 2010).

Nocturnal water flux can be a sizable component of whole-plant water use. In some arid ecosystems, \( E_n \) may reach 30–60% of day-time water flux (Snyder et al. 2003), but in most ecosystems it is rare for \( E_n \) to exceed 20% of day-time flux (Dawson et al. 2007). In *Eucalyptus*, \( E_n \) consistently averaged 5–8% of day-time flux across all seasons, occasionally reaching 20% of day-time flux on a single day (Phillips et al. 2010, Zeppel et al. 2010). \( E_n \) in eucalypts is strongly and positively correlated with higher vapour pressure deficit (\( D \)), such that water flux is largest on high-temperature, low-humidity nights (Phillips et al. 2010, Zeppel et al. 2010), as has been frequently observed in other species (Daley and Phillips 2006). \( E_n \) in eucalypts is also higher in wetter soils, but soil moisture is generally a weak predictor of \( E_n \) compared with \( D \) (Zeppel et al. 2010).

While the influence of \( D \) on nocturnal fluxes is well described, the effects of elevated \([\text{CO}_2]\) on nocturnal fluxes have not been studied. Trees commonly show reduced leaf-level day-time stomatal conductance (\( g_d \)) in elevated \([\text{CO}_2]\), due to partial stomatal closure, which reduces leaf-level water flux (Medlyn et al. 2001, Ainsworth and Rogers 2007). This change in leaf-level stomatal conductance can have significant consequences for whole-plant water use, soil moisture content and the impacts of drought stress (Field et al. 1995, Wullschleger et al. 2002). Droughts are widely predicted to increase in frequency and severity (IPCC 2007) in concert with rising \([\text{CO}_2]\) and there is a clear and obvious need to study their interactive effects on a range of plant water relations. At the whole-tree level, lower \( g_d \) may be partially or completely offset by larger leaf area production in elevated \([\text{CO}_2]\). Therefore, the net effect of elevated \([\text{CO}_2]\) on sap flux on a sapwood area basis (sap flux density, \( J_d \)) reflects combined effects of \( g_d \) and whole-canopy leaf area (Cech et al. 2003, Ainsworth et al. 2005, Uddling et al. 2008). However, the effects of \([\text{CO}_2]\) on nocturnal fluxes are not yet known, but have the potential to either strengthen or counteract effects on water balance through changes in day-time water flux, and therefore need to be quantified. In addition, both \([\text{CO}_2]\) and nocturnal fluxes influence the level of drought stress that a plant experiences (Howard et al. 2009).

While it is not known how rising \([\text{CO}_2]\) affects nocturnal water flux, there is some evidence that day-time and nocturnal water fluxes are correlated (Marks and Lechowicz 2007). Therefore, an initial hypothesis for the effect of elevated \([\text{CO}_2]\) on nocturnal fluxes would be that it would mimic the effect on day-time water flux; that is, if the day-time transpiration rate was reduced under elevated \([\text{CO}_2]\) then the night-time transpiration rate would also be reduced. However, there are key differences in the regulation of nocturnal and day-time water fluxes.

Day-time water flux is at least partially under active biological control through opening and closing of stomata. The reduction in stomatal conductance in elevated \([\text{CO}_2]\) reflects biological control balancing carbon uptake with water loss (Medlyn et al. 2011). In contrast, nocturnal water flux is primarily considered (at present) to be under physical control, particularly by \( D \) and soil moisture (Dawson et al. 2007, Phillips et al. 2010, Zeppel et al. 2010). If night-time sap flux is not under active biological control, it may be hypothesized that there would be no direct response to rising atmospheric \([\text{CO}_2]\). Hence, the major effect of rising \([\text{CO}_2]\) on night-time water flux might be via direct responses to changes in soil water content (SWC) which result from day-time sap flux. Lower day-time sap flux under high \([\text{CO}_2]\) might lead to improved stem water status, and therefore a reduced need to refill xylem, resulting in lower night-time sap flux. Consequently, we hypothesized that elevated \([\text{CO}_2]\) effects on night-time sap flux would follow changes in day-time sap flux.

This study is the first to address the interactive effects of elevated \([\text{CO}_2]\) and drought on nocturnal water flux. We studied *Eucalyptus saligna* Sm. saplings grown in closed-top, environmentally controlled whole-tree chambers (WTCs) in the field (Barton et al. 2010). Trees were exposed to either ambient or elevated \([\text{CO}_2]\) for a total of 24 months. In the final 5 months of the experiment, water was withheld from half of the experimental trees, resulting in four experimental treatments: (i) ambient \([\text{CO}_2]\), wet soils (AW); (ii) ambient \([\text{CO}_2]\), dry soils

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**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>( D )</td>
<td>Vapour pressure deficit (kPa)</td>
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<td>( E_n )</td>
<td>Nocturnal sap flux</td>
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<tr>
<td>( E_i )</td>
<td>Transpiration per leaf area (( \text{mm}^2 \text{ h}^{-1} \text{ m}^{-2} \text{ leaf area} ))</td>
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<tr>
<td>( E_{i,c} )</td>
<td>Transpiration per leaf area including recharge component or ‘total night transpiration’ (19:00 to 05:00)</td>
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<tr>
<td>( E_{i,c} )</td>
<td>Transpiration per leaf area with canopy transpiration only or ‘post-recharge transpiration’ (23:00 to 05:00)</td>
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<td>( g_n )</td>
<td>Nocturnal leaf conductance (sum of stomatal and cuticular conductance, ( \text{mmol m}^{-2} \text{ s}^{-1} ))</td>
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<tr>
<td>( g_d )</td>
<td>Day-time stomatal conductance (( \text{mmol m}^{-2} \text{ s}^{-1} ))</td>
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<td>( J_s )</td>
<td>Sap flux density (( \text{mm}^2 \text{ h}^{-1} \text{ mm}^{-2} ))</td>
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<tr>
<td>( J_{s,r} )</td>
<td>Nocturnal sap flux density including recharge component ‘total night flux’ (19:00 to 05:00)</td>
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<tr>
<td>( J_{s,c} )</td>
<td>Post-recharge flux density (23:00 to 05:00)</td>
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<tr>
<td>( \Psi_{pd} )</td>
<td>Pre-dawn leaf water potential (MPa)</td>
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<td>WTC</td>
<td>Whole tree chambers</td>
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</table>

Treatments as follows:

- AD: Ambient \([\text{CO}_2]\) and dry soil
- ED: Elevated \([\text{CO}_2]\) and dry soil
- AW: Ambient \([\text{CO}_2]\) and wet soil
- EW: Elevated \([\text{CO}_2]\) and wet soil
of 43.7 °C and a minimum temperature of 7.8 °C; precipitation
weather station (Richmond) of ~800 mm (1900–90). Over
temperate, with a long-term mean annual rainfall at the nearest
mean temperature was 22.7 °C with a maximum temperature
the measurement period (December 2008 to March 2009),
at elevation 25 m a.s.l. Site details are described in Barton

e-terns in response to elevated [CO 2].

Within each of the [CO 2] treatments, three WTCs
and six chambers were operated at elevated [CO 2] (ambi-
et al. (2010). Here, we report the effects of elevated [CO 2] on night-time sap
fluxes of saplings grown in wet or dry soils. We assessed the
impact of the [CO 2] and drought treatments during the night on
J s and transpiration per leaf area (E t, mm h⁻¹ m⁻²) as a function of
volumetric SWC, vapour pressure deficit (D) and pre-dawn
leaf water potential (Ψpd). Our goal was to assess whether J s
and E t would be affected by elevated [CO 2] or severe summer
drought, and whether night-time fluxes follow day-time pat-
terns in response to elevated [CO 2].

Specifically, we hypothesized that (i) elevated [CO 2] would
decrease J s and E t; (ii) drought would reduce J s and E t; and (iii)
elevated [CO 2] trees would be less drought stressed and
therefore the reduction in J s and E t due to drought would be
less under elevated [CO 2].

Materials and methods

Study site

Research was conducted at the Hawkesbury Forest Experiment
site in western Sydney (Australia) (33°36′44″S, 150°42′06″E)
at elevation 25 m a.s.l. Site details are described in Barton
et al. (2010). The local climate is considered to be warm and
temperate, with a long-term mean annual rainfall at the nearest
weather station (Richmond) of ~800 mm (1900–90). Over
the measurement period (December 2008 to March 2009),
mean temperature was 22.7 °C with a maximum temperature
of 43.7 °C and a minimum temperature of 7.8 °C; precipitation
was 254 mm. Trees were exposed to [CO 2] treatments from
April 2007 to March 2009. This experiment focuses on the
drought period during summer December 2008 to March 2009.
At the start of this period, the trees were ~6–9 m tall
with a diameter of 75–125 mm at ~1.10 m height.

Experimental design

Twelve WTCs were used to control atmospheric [CO 2] through-
out the experimental period; these are fully described in Barton
et al. (2010). Briefly, six WTCs were set to track ambient
[CO 2] and six chambers were operated at elevated [CO 2] (ambi-
ent + 240 ppm). All WTCs were maintained at ambient outside
temperature. Within each of the [CO 2] treatments, three WTCs
were irrigated every 3 days with 10 mm of water; due to hot
weather, irrigation was increased to 12 mm every 3 days from
15 January 2009 onward. In the remaining three WTCs in each
[CO 2] treatment, trees were irrigated as described above until
the drought treatment was initiated in October 2008 by a dry-
down in which water was completely withheld. Trees were
grown under the four [CO 2] x drought treatments under ambient
field temperature and light conditions for 5 months before
drought trees were re-watered. The post-drought period began
when heavy rains ended the drought in mid-February.

Soil moisture

The impact of the irrigation and drought treatments on soil mois-
ture was assessed using Sentek probes [Sentek TriSCAN® sen-
sors] inserted into an access tube, located ~0.8 m distance from
the base of the tree, and measured at soil depths of 0.25, 0.5, 0.75 and 1.0 m within each WTC plot. Data were calibrated using
field techniques outlined by Greacen et al. (1981). Soil moisture
data were corrected by calibrating data to 'field capacity' during
the days when flooding occurred (Duursma et al. 2011).

Leaf water potential

Bulk leaf water potential was measured pre-dawn (Ψpd, MPa)
each month on two fully expanded leaves per tree in each WTC
and control plot. Leaves were removed from the middle to upper-
 canopy and immediately sealed in a foil-laminate bag.
Measurements of Ψpd were conducted using a Scholander-style
pressure chamber (Model 600; PMS Instrument Company,
Corvallis, OR, USA).

Sap flux density

Sap velocity was measured using the heat ratio method
(HRM30, ICT International, Armidale, Australia) as described
by Burgess et al. (2001). One probe set (with two sensors per
tree) was inserted into each tree at ~1.3 m height. The radial
profile of sap velocity was examined in two nearby control
trees by inserting the probe set deeply into the sapwood, and
then withdrawing the unit 5 mm at 30-min intervals over the
entire width of the sapwood; these data were compared with
data from a probe set that remained in a single location
(Medhurst et al. 2002, Ford et al. 2004). Sap velocity was
measured at 15-min intervals throughout the experimental
period (December 2008 to March 2009). Heat ratio data were
converted to sap flux density (Jsv, mm² water mm⁻² sapwood
area h⁻¹) by correcting for the effects of wounding, radial vari-
ability in flow, sapwood area and volumetric fractions of water
and wood using algorithms described by Burgess et al. (2001).
Wound width may affect calculation of whole-tree water use, so
a different wound width was determined for each tree; wound
widths varied from 1.60 ± 0.02 to 1.95 ± 0.10 mm (Zeppel
et al. 2008a). Wood moisture content ((fresh weight−dry
weight)/dry weight) and density also affect sap flow calcula-
tions; however, there were no significant differences across
 treatments (P > 0.05). Variation in moisture content of sap-
wood across trees ranged from 63 to 66% (SE < 1.5%). Mean
(and SE) wood density was 4.1 ± 0.4 and 4.0 ± 0.3 g cm⁻³ for ED and AD treatments, respectively.

Heat ratio method data are accurate when sap flow values are low; however, they potentially under-predict sap flow during periods of very high water flux (>400 mm h⁻¹) (Madurapperuma et al. 2009) which may occur in E. saligna during the day-time. Therefore, sap flow at night was determined using HRM probes and day-time sap flow was calculated from WTC water flux measurements (Barton et al. 2010); HRM probes were calibrated against WTC data.

In order to account for differences in tree size, we normalized water flux on a sapwood area basis (i.e., sap flux density; J) and leaf area basis (i.e., Es, mm³ water m⁻² leaf area h⁻¹). We calculated two night-time sap flow terms.

(i) Total night flux, which is calculated as the total sap flow over the period when solar radiation was zero, ~19:00 until 05:00. This term includes stem water recharge and canopy transpiration and is denoted by Js,r. (ii) Post-recharge flux, which is calculated as the sap flow over the period from 23:00 to 05:00. This term reflects canopy transpiration only following Zeppel et al. (2010) and is denoted by Jc,c. These two definitions allowed an assessment of the impact of our [CO₂] and drought treatments on two different aspects of nocturnal water use.

**Zero-set of sap flow**

Accurate estimation of the zero-set of each sensor is important when using many types of heat-based sap flow system (Regalado and Ritter 2007), including the HRM. A sensitivity analysis was conducted on the effect of changing the zero offset on daily sap flow. When the zero offset was increased by 10, 20 and 50%, the hourly sap flux was decreased by 8, 9 and 23%, respectively. In this study, the zero-set of each sensor was determined using a modification of the technique of Ward et al. (2008), by using periods when WTC water fluxes were zero (between 24:00 and 05:00), and then within these periods, estimating the flow rates when D was zero (Ward et al. 2008).

**Statistical analyses**

Data were tested for normality and the homogeneity of variances by plotting residuals vs. predicted values. These tests indicated that the assumptions of normality and homogeneity of variances were met for all variables and no transformations were necessary. Statistically significant differences in soil water content within the dry treatments, compared with the wet treatments, became apparent from January 10 onward and were used to designate three distinct periods in this study, ‘moderate drought’ (5 December to 9 January 2009), ‘severe drought’ (January 10 to February 14 2009) and ‘post drought’ (February 15 to March 14 2009; Table 1), and then trees were harvested in mid-March 2009. Moderate and severe drought occur within the period defined as ‘late drought’ in Duursma et al. (2011). We used a repeated measures, two-way analysis of variance to examine the main and interactive effects of [CO₂] and water treatment on Js and Ec, Js, and Jc (19:00–05:00 and 23:00–05:00, respectively) and Ec, and Ec (transpiration per leaf area including recharge component between 19:00 and 05:00 and 23:00 and 05:00, respectively) were dependent variables, and [CO₂] and water treatment were fixed, categorical factors. Statistical significance was determined as P ≤ 0.05. Second-order polynomial regressions were used to assess the relationship between Js and Ec. Mean and error bars of ratios in Figure 3 are determined following previously described methods (Lewis et al. 2010). All statistical analyses were conducted using R version 2.11.1 (R Development Core Team 2010).

**Results**

*Environmental conditions*

Temperature at night was similar across the moderate-, severe- and post-drought periods, and ranged from a minimum of 8°C to a maximum of 25°C (Figure 1a). D averaged within the two night-time periods ranged from 0.05 to 0.9 kPa (Figure 1b). Minimal precipitation was received outside the chambers from December 15 until February 14; afterward, heavy rainfall occurred over a 10-day period (Figure 1c).

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**Table 1. Summary of three-way analysis of variance (CO₂ × water × drought period) on SWC and Ψpd measured on E. saligna grown at two [CO₂] (ambient and ambient +240 ppm) and two water treatments (well watered or dry) across three dry periods (moderate-, severe- or post-drought).**

| SWC—30 cm | n.s. | *** | *** | n.s. | n.s. | *** | n.s. |
| SWC—70 cm | n.s. | *** | *** | n.s. | + | ** | n.s. |
| SWC—110 cm | n.s. | n.s. | *** | n.s. | ** | * | n.s. |
| SWC—150 cm | n.s. | n.s. | *** | n.s. | *** | n.s. | n.s. |
| SWC—Total storage from 30 to 150 cm | n.s. | ** | *** | n.s. | n.s. | ** | n.s. |
| Ψpd | n.s. | ** | *** | n.s. | + | *** | ** |

SWC data were collected hourly from 1 December to 12 March and Ψpd data were collected approximately fortnightly during January and February. Significance levels are: n.s. = not significant (P > 0.10); *P < 0.1; **P < 0.05; ***P < 0.01; ****P < 0.001.
drought period, wet treatment chambers had consistently higher volumetric SWC at 0.30 and 0.70 m depths, and over the total soil volume, but not at 1.10 or 1.50 m depths, compared with the dry chambers (Figure 1d and e; Table 1). Soil water content gradually declined in both wet and dry chambers during the peak, hot summer period until heavy rains ended the drought in mid-February.

**Pre-dawn leaf water potential**

Water limitation was imposed by ceasing irrigation inside the WTCs in the dry treatments beginning in October 2008. [CO$_2$] had no significant effect on $\psi_{pd}$, whereas water treatment had a significant effect ($P < 0.05$) and there was an indication of an interaction with [CO$_2$] and water treatment during the severe drought ($P = 0.055$) (Figure 1f; Table 1). As the drought progressed, the $\psi_{pd}$ in the dry treatments declined to lower values than in the watered treatments in both [CO$_2$] treatments. There were no [CO$_2$] treatment effects on either the moderate-drought or post-drought $\psi_{pd}$.

### Table 2. Summary of two-way repeated measures analysis of variance (CO$_2 \times$ water) on sap flux density and transpiration for total night flux, between 19:00 and 05:00 ($J_{s,r}$, $E_{t,r}$) and post-recharge flux, between 23:00 and 05:00 ($J_{s,c}$, $J_{t,c}$) measured on E. saligna grown at two [CO$_2$] (ambient and ambient +240 ppm) and two water treatments (well watered or dry) during the severe drought period (10 January–14 February 2009).

<table>
<thead>
<tr>
<th>CO$_2$</th>
<th>Water</th>
<th>CO$_2 \times$ water</th>
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<tbody>
<tr>
<td>$J_{s,r}$</td>
<td>n.s.</td>
<td>*</td>
</tr>
<tr>
<td>$J_{s,c}$</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>$E_{t,r}$</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>$E_{t,c}$</td>
<td>n.s.</td>
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</table>

Significance levels are: n.s. = not significant ($P > 0.10$); *$P < 0.1$; **$P < 0.05$; ***$P < 0.01$; ****$P < 0.001$.
**Effects of tree size on sap flux density at night**

Tree size may affect tree water use, sap flux density ($J_s$) and transpiration ($E_t$) independently of [CO$_2$] or drought treatments (Zeppel and Eamus 2008). Therefore, we examined whether differences in water flux could be attributed to differences in tree size, specifically total leaf area and tree sapwood area. There was no significant relationship between $J_s$ and either leaf area or sapwood area for the [CO$_2$] and water treatments ($P > 0.10$). Similarly, there was no significant relationship for $E_t$ and either leaf area or sapwood area for any treatment.

**Interactive effects of elevated [CO$_2$] and water treatment on nocturnal sap flux density**

**Total night flux**

The effect of elevated [CO$_2$] on total night flux ($J_s$ and $E_t$) differed between wet and dry treatments. In the wet treatments, elevated [CO$_2$] caused total night flux (per leaf area) to significantly increase by 28% ($P < 0.05$). However, in the dry treatments, elevated [CO$_2$] caused total night flux (per leaf area) to decrease by 33% (Figure 2c and d). Total night sap flux density (per sapwood area) $J_{s,r}$ showed the same trends as transpiration per leaf area ($E_t$).

**Post-recharge flux**

Results were slightly different when only the post-recharge flux was considered. As for total night flux per unit sapwood area, there was a significant decrease in post-recharge night flux under elevated [CO$_2$] in the dry treatments. However, in the wet treatments, there was no significant difference between [CO$_2$] treatments (Figure 2e–h; Table 2). On a sapwood area basis, results were slightly different again. There was a significant [CO$_2$] × drought interaction under elevated [CO$_2$], post-recharge sap flux density was lower in the dry treatment than in the wet treatment (Figure 2f), but no such drought effect was observed under wet and dry ambient [CO$_2$] treatments (Figure 2e). There were no other significant differences among treatments for $J_{s,c}$. On a leaf area basis for $E_{t,c}$, AD was significantly higher than ED (Table 2).

**Comparison of day vs. night water fluxes**

As a result of the differential treatment effects of elevated [CO$_2$] on $J_{s,r}$ in the dry and wet treatments during recharge, elevated [CO$_2$] was associated with a 33% reduction in $J_{s,c}$ in the dry treatment but with a 28% increase in the wet treatment (Figure 3b); similar patterns were observed in $E_{t,c}$ (Figure 3e). Elevated [CO$_2$] did not significantly affect $J_{s,c}$ or $E_{t,c}$ in either watering treatment (Figure 3c and f). During the daytime, elevated [CO$_2$] did not strongly affect $E_t$ in the wet treatment; however, there was a reduction in the dry treatment (Figure 3a and d). $J_{s,c}$ and $E_t$ summed over the drought period were not significantly different among the four treatments (Figure 4). However, $J_{s,r}$ was significantly lower in ED compared with AD, whereas there was no significant difference between $J_{s,r}$ of AW and EW ($P < 0.05$).

**Environmental regulation of sap flux density**

Both soil moisture content and $D$ exerted strong control over night-time fluxes (Figures 5 and 6). There were positive correlations between night-time fluxes and $D$ but those relationships differed with [CO$_2$] and soil moisture availability. In wet soil, total night transpiration was higher at elevated [CO$_2$] compared with ambient [CO$_2$] at a given $D$ (Figure 5c). In contrast, in dry treatments, total night transpiration and post-recharge flux were higher at ambient [CO$_2$] compared with elevated [CO$_2$] for any given $D$, particularly when $D$ was > 0.25 kPa (Figure 5a and b). Wind speed ($U$) inside each chamber was high, with visibly fluttering leaves, thereby reducing the leaf boundary layer, and comparable across all treatments (Barton, unpublished data). Therefore, the relationship between $E_t$ and $U$, and the product of $U$ and $D$ was not analysed (see Phillips et al. 2010, Zeppel et al. 2010).

As drought progressed and soil moisture decreased, $J_{s,r}$ decreased in both AD and ED treatments (Figure 6). For a given $D$, $J_{s,r}$ was higher in the moderate drought period compared with the severe drought period in both AD (Figure 6a) and ED (Figure 6b) treatments. Towards the end of the drought, and when $D$ was not high, nocturnal sap flux was occasionally negative. Negative flow rates have been previously reported under dry conditions using the HRM, which is accurate under low flow rates (Burgess et al. 1998, 2001). Soil moisture thus has an important effect on night-time fluxes, in that sap flux at a given $D$ is reduced as soil moisture availability declines. The physical control of night-time fluxes increased as soil moisture declined, as demonstrated by a much stronger correlation between sap flux and $D$ in dry soil treatments than in well-watered treatments (Figure 5).

**Discussion**

This study was the first to quantify the effect of elevated [CO$_2$] on nocturnal water fluxes. We hypothesized that: (i) elevated [CO$_2$] would decrease $J_s$ and $E_t$, which was confirmed for dry soil but not for wet soil; (ii) drought would reduce $J_s$ and $E_t$, which was confirmed; and (iii) elevated [CO$_2$] trees would be less drought stressed and therefore the reduction in $J_s$ and $E_t$ due to drought would be less under elevated [CO$_2$], which was rejected. Elevated [CO$_2$] significantly reduced $J_{s,c}$ in trees in the dry treatment, but increased $J_{s,c}$ in trees in the wet treatment, compared with plants grown in ambient [CO$_2$]. In contrast, elevated [CO$_2$] did not alter $J_{s,c}$ or water fluxes for wet treatment plants during the day-time, compared with wet treatment plants grown in ambient [CO$_2$]. The primary driver of $J_{s,r}$ was $D$, which was positively correlated with $J_{s,r}$ and had a proportionately greater impact on $J_{s,r}$ at high $D$ in AD trees compared with
Figure 2. [CO₂] effects on night-time water use. Total night flux \( J_s,r \) (mm³ night⁻¹ mm² sapwood area) in wet soil treatments (a) and dry soil treatments (b). Total night transpiration \( E_t,r \) (10³ mm³ night⁻¹ m⁻² leaf area) in (c) wet soil treatments and (d) dry soil treatments. Post-recharge flux \( J_c,c \) (mm³ night⁻¹ mm² sapwood area) of wet soil treatments (e) and dry soil treatments (f). Post-recharge transpiration \( E_c,c \) (10³ mm³ night⁻¹ m⁻² leaf area) for (g) wet soil treatments and (h) dry soil treatments. Data points represent mean (± SE) of each treatment (for clarity, representative SE bars are only shown on initial data points). Night is defined here as the hours between 19:00 and 05:00. Treatments are elevated [CO₂] and wet soil (EW); ambient [CO₂] and wet soil (AW); elevated [CO₂] and dry soil (ED); and ambient [CO₂] and dry soil (AD). Dotted lines represent the zero line.
ED trees. This study suggests that elevated [CO$_2$] may reduce $J_s,r$ in _E. saligna_ when SWC is low and $D$ is high, which often occurs during temperate summers (Zeppel et al. 2008b).

Our results found contradictory changes in water flux under elevated [CO$_2$] with increased transpiration per leaf area $E_{t,r}$ under elevated [CO$_2$] in the wet treatment, but decreased $E_{t,r}$ in the dry treatment. In previous studies conducted during the day, [CO$_2$] and drought interactions have been observed. For example, in a free air CO$_2$ enrichment experiment, _Pinus taeda_ transpired less water per unit of leaf area only when drought was severe (Schäfer et al. 2002). _Liquidambar styraciflua_, the other major species in the forest, used progressively less water, resulting in a 25% reduction in sap flux density after 3.5 years under elevated [CO$_2$] (Schäfer et al. 2002). In contrast, cherry and peach seedlings grown in environmentally controlled conditions did not exhibit a [CO$_2$] × drought interaction, partly because increased leaf area under elevated [CO$_2$] compensated for lower water use per leaf area (Centritto et al. 1999). Similarly, other [CO$_2$] studies have failed to provide evidence that the effect of elevated [CO$_2$] on sap flow is enhanced during dry conditions (Hymus et al. 2003, Bobich et al. 2010).

Although reductions in sap flow under elevated [CO$_2$] during the day have been observed in trees (Schäfer et al. 2002), experimental evidence remains equivocal. For example, after an initial increase in annual day-time sap flow of 14% in the first year of elevated [CO$_2$] treatment, annual sap flow in subsequent years was reduced by 13–16% (Wang et al. 2005). It is important to note that elevated [CO$_2$] often substantially increases total tree leaf area, such that decreased $E_t$ due to elevated [CO$_2$] may not fully compensate for greater tree leaf area; subsequently, total water use per tree (L day$^{-1}$) may still be increased (Tognetti et al. 1999, Uddling et al. 2008, Bobich et al. 2010). Ultimately, whole-tree water flux in elevated [CO$_2$] will be dependent on both $J_s$ and tree leaf area production.

**Why are nocturnal fluxes differentially affected by elevated [CO$_2$] under wet and dry conditions?**

In order to determine why $J_s$ and $E_t$ are differentially influenced by elevated [CO$_2$] in wet and dry conditions, we examined the suite of environmental variables that affect water fluxes during the day, including $D$, $U$, SWC, wood density and wood moisture. Radiation, which is clearly a strong driver of...
water fluxes during the day, was not examined because it was zero after 19:00. There were no significant differences in wood density or wood moisture content. Wind speed was similar in all chambers due to the continually blowing fans. Analyses of \( J_{s,r} \) at the same \( D \) (Figure 5a) showed a marked decrease in \( J_{s,r} \) in the ED treatment at the same value of \( D \); therefore, \( D \) was not the main driver of differences in \( J_{s,r} \) under elevated \([\text{CO}_2]\) compared with ambient \([\text{CO}_2]\).

The decrease in total night sap flux in ED compared with AD may be the result of biological processes during the day. Less water was transpired in ED compared with AD, and \( E/A \) was lower in the dry treatment (Figure 3a). In the dry treatment, low day-time fluxes followed the same reduction under elevated \([\text{CO}_2]\) as low night-time fluxes. Although the exact nature of the relationship between day-time and night-time fluxes is not clear in \( E. \text{saligna} \), previous studies have also shown that day-time fluxes are linked to night-time fluxes (Marks and Lechowicz 2007). Less refilling of the tree trunk may occur because it requires less water to fill, as a result of the lower volume of water transpired during the day compared with AD, and therefore less capacitance is available. Or perhaps, the tree uses less water during the day because the volume of water refilled the previous night was smaller in ED than in AD. Regardless of which of these two processes is dominant, the volume of water required to recharge the tree at night clearly influences \( \psi_{pd} \), which is a strong indicator of plant water stress and a strong driver of water fluxes during the day.

Higher values of total night sap flux in EW compared with AW may be explained by two possible mechanisms. First, flushing leaves have higher nocturnal water fluxes than older leaves (Phillips et al. 2010). Elevated \([\text{CO}_2]\) is known to influence leaf phenology (Lewis et al. 2003), and the combination of wet soil and high \([\text{CO}_2]\) may have led to plants in EW containing a higher proportion of newly flushed leaves, despite a smaller leaf area, than in AW. Second, the role of nutrient transport has been raised as a mechanism explaining nocturnal water fluxes, although the evidence is equivocal (Howard and Donovan 2007, 2010, Scholz et al. 2007). Nutrient transport would be more likely to occur in wet soil compared with dry soil because water facilitates the transport of nutrients. Further, there is evidence that leaves grown under elevated \([\text{CO}_2]\) have reduced nutrient concentrations compared with ambient \([\text{CO}_2]\) (Lewis et al. 2002, 2010), thereby requiring greater nutrient transport.

**Impact of elevated \([\text{CO}_2]\) on soil water status**

In the present study, a lower (more negative) \( \psi_{pd} \) for the ED trees compared with AD during the severe drought period (Figure 1) treatment was counter-intuitive, particularly as the ED trees had lower leaf area. However, higher water stress (more negative \( \psi_{pd} \) under elevated \([\text{CO}_2]\)) was similar to previous studies that reported lower \( \psi_{pd} \) in plants that had higher leaf area under elevated \([\text{CO}_2]\) (Centritto et al. 1999). Similarly, Atwell et al. (2009) reported greater water stress during drought for eucalypts in elevated \([\text{CO}_2]\) compared with ambient \([\text{CO}_2]\) due to shallow rooting under elevated \([\text{CO}_2]\). This suggests that some plants, and in particular eucalypts, grown under elevated \([\text{CO}_2]\) may experience more water stress, because roots are more concentrated at shallower depths, which leaves them vulnerable to drought stress when soil moisture declines in shallow soil (Atwell et al. 2009, Duursma et al. 2011). Our findings generally contradicted the ‘water savings’ paradigm associated with growth in elevated \([\text{CO}_2]\) (Wullschleger et al. 2002). A second explanation for greater water stress under elevated \([\text{CO}_2]\) was that recharge of tree stems was lower under elevated \([\text{CO}_2]\) than ambient \([\text{CO}_2]\) (Figure 2b). This lower volume of recharge may lead to a
reduced degree of refilling of tree stems under elevated [CO$_2$], generating a more negative $\Psi_{pd}$ (Figure 1). In any case, we found no evidence of amelioration of drought stress under elevated [CO$_2$].

The response of $E_n$ to $D$ in elevated [CO$_2$]

Our results are similar to those indicating that the impact of elevated [CO$_2$] on water fluxes depends strongly on environmental conditions (Kellomaki and Wang 1998) and that the impact is higher at high $D$ (Kellomaki and Wang 2000). The present study demonstrates that these patterns hold for some weather conditions (dry soil or high night-time $D$) but not others (wet soil or low night-time $D$). Wang et al. (2005) reported that, similar to the current study, at high $D$, differences between sap flux density under ambient and elevated [CO$_2$] were higher compared with low $D$ (presumably also because there is more ‘signal’ and less ‘noise’ in sap flow when $D$ is high). Similarly, Wullschleger and Norby (2001) found that stand transpiration during the day was significantly lower under elevated [CO$_2$] only when $D$ was >1.0 kPa and

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**Figure 5.** Transpirational water loss as a function of mean night $D$ in the wet treatments as (a) total night flux, and (b) post-recharge flux, and in the dry treatments as (c) total night flux and (d) post-recharge flux. Mean night $D$ was calculated during the period 19:00 – 5:00 for total night and from 23:00 – 5:00 for post-recharge. Elevated [CO$_2$] treatments are represented as closed symbols and ambient [CO$_2$] treatments as open symbols. Dotted lines represent the zero line.

**Figure 6.** The relationship between total night flux (normalized by sapwood area, $J_{sn}$) for each night (19:00–05:00) as a function of $D$ within each chamber in the (a) ambient [CO$_2$] and dry (AD) treatment and the (b) elevated [CO$_2$] and dry (ED) treatment. ‘Early severe drought’ (closed symbols) is defined as January 10–January 23, and ‘late severe drought’ (open symbols) is defined as January 24–February 14, based on distinct $\Psi_{pd}$ in Figure 1. Dotted lines represent the zero line.
radiation was >400 J m\(^{-1}\) s\(^{-1}\). It is important to note that our findings apply to nocturnal water fluxes under elevated [CO\(_2\)], while previous studies have only examined the impact of [CO\(_2\)] on day-time water fluxes.

**Stomatal conductance at night**

Meta-analyses have reported that \(g_s\) generally declines under elevated [CO\(_2\)] (Medlyn et al. 2001). Many studies have quantified \(g_s\) (see review by Caird et al. 2007), and both Phillips et al. (2010) and Zeppel et al. (2010) demonstrated that \(g_s\) in eucalypts was primarily due to stomatal rather than cuticular conductance, which was 5.6 mmol m\(^{-2}\) s\(^{-1}\) in *E. saligna* (Phillips et al. 2010). A reduction in \(g_s\) of 20% in January \((P = 0.095)\) occurred during the summer months, but not during wetter months before irrigation was withheld (February, March, May, June, July, September, November and December; \(P > 0.10\)). Water limitation may decrease \(g_s\) (Dawson et al. 2007, Howard and Donovan 2007), although \(g_s\) is not always reduced under water-limited conditions. In fact, \(g_s\) was observed to be >20% of \(g_s\) even during drought conditions, in 10 different species in four deserts in North America (Tissue, unpublished data).

Benefits of \(J_{sr}\) or \(g_s\) are suggested to include the refilling of xylem embolism at night to prevent hydraulic failure (Bucci et al. 2004), the transport of nutrients (Dawson et al. 2007, Scholz et al. 2007) (but see Howard and Donovan 2010) and refilling of stem capacitance (Wang et al. 2008), which will prevent or minimize water stress (Caird et al. 2007). However, hydraulic redistribution, which ameliorates water stress in plants in xeric environments (Brooks et al. 2002), is reduced under nocturnal transpiration (Howard et al. 2009). Subsequently, if nocturnal fluxes are reduced and therefore hydraulic redistribution is increased, water stress may be alleviated. Furthermore, global circulation models predict that temperatures will rise, and in many areas precipitation may decrease, leading to greater declines in water availability. Thus, the role of nocturnal fluxes and water stress of plants under a changing climate is complex and requires further investigation.

**Conclusions**

This study on large trees, grown in water-limited conditions for extended periods, reported the first results of the impact of elevated [CO\(_2\)] on nocturnal fluxes. During an extended drought period, *E. saligna* saplings experienced reductions in \(J_{sr}\) in elevated [CO\(_2\)] (by 32%), but increased \(J_{sr}\) by 28% under well-watered conditions. Furthermore, as \(D\) increased, the reduction in \(J_{sr}\) under elevated [CO\(_2\)] was higher than at low \(D\). That is, although elevated [CO\(_2\)] reduced \(E_n\) during drought, these reductions are likely to become greater at high night-time \(D\) (over 0.5 kPa), and that \(E_n\) decreases as drought progresses. Contrary to our initial hypothesis, elevated [CO\(_2\)] trees did not experience less drought stress compared with ambient [CO\(_2\)] trees. Nocturnal water fluxes were significantly lower in the ED treatment compared with the AD treatment, suggesting that drought was not ameliorated by elevated [CO\(_2\)] in the dry treatment. As atmospheric [CO\(_2\)] levels are elevated, nocturnal sap flow which refills tree stems may be reduced, thereby increasing tree water stress and vulnerability to drought in future climates. These findings will enable improved predictions of diel water fluxes and should be incorporated into ecophysiological models to more accurately represent water and carbon fluxes under global climate change.

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**References**


