

# Assessing the impact of large-scale water table modifications on riparian trees: a case study from Australia

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## ABSTRACT

Mining below groundwater tables is increasing globally, yet little is known of how associated large-scale modification of water tables impact functioning of surrounding ecosystems. We used measurements of foliage density ( $\rho_F$ ) and sapwood-related sap flow ( $Q_S$ ) to assess effects of depth to groundwater on *Eucalyptus victrix*, a tree species that is common in riparian zones in central and northern parts of Australia.

Foliage density ( $\rho_F$ ) varied with season and among sites. Of itself,  $\rho_F$  provided a partial indicator of how trees responded to falling (more than 10 m) and rising (more than 9 m) water tables. Assessment of  $Q_S$  was highly informative. Across all sites,  $Q_S$  was least ( $90\text{--}130\text{ l m}^{-2}$  sapwood  $\text{h}^{-1}$ ) where groundwater was naturally deep (30 m) or had fallen substantially over the past 4 years (from 8 to 19 m). Fastest rates of  $Q_S$  ( $>245\text{ l m}^{-2}$  sapwood  $\text{h}^{-1}$ ) were recorded where groundwater had risen to a depth similar to a site where depth to groundwater remained stable at 6–7 m. Our analyses of daytime and night-time  $Q_S$  emphasize that water use by *E. victrix* is highly plastic and opportunistic. We discuss how empirical analysis of  $Q_S$ , coupled with a sound understanding of local hydrogeology, can help assess responses in ecosystem function to large-scale modification of groundwater levels – an important issue globally, as well as in Australia. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS tree water use; water abstraction; riparian; phreatophyte; rising water table

Received 14 January 2014; Revised 3 June 2014; Accepted 26 June 2014

## INTRODUCTION

Open-cut mining below the water table for industrial minerals, mineral fuels, and metals requires lowering of the groundwater level ('drawdown') in order to prevent flooding of mine pits. There is a well-established and long-standing appreciation of the scale of the drawdown required to prevent groundwater from entering such mine pits and its dependence on local hydrogeology. A useful summary of the approach, including the creation of 'cone(s) of depression' around abstraction bores (usually located close to mine sites), is found in Alley *et al.* (1999). Spatial extent and base slope of such cones of depression vary because of a range of factors, including the following: volume of aquifer(s); transmissivity of soil and bedrock; amplitude of direct and indirect recharge; volume and duration of water displacement; and borefield design (Alley *et al.*, 1999). Effects of

drawdown on surrounding ecosystems are thus spatially limited but expected to be greatest immediately adjacent to the bores. In addition, there are very few completed studies (refer to Naumburg *et al.*, 2005) of the effects of discharge of abstracted water. Overall, the combined phenomena of abstraction, discharge, and local changes in water tables is fundamentally different to irrigated agriculture where regional and larger-scale falls in water tables result from widespread (e.g. hundreds of bores) water abstraction. The latter situation affects streamflow and aquifer dynamics in many regions of the world (MacKay, 2006).

In the Pilbara, a mining region in the north of Western Australia, high-grade channel iron deposits (CIDs) are increasingly sourced from below water tables as deposits above water tables become exhausted. These operations require abstraction of considerable quantities of groundwater (ranging up to  $>100\text{ ml day}^{-1}$  per borefield). By 2030, the total amounts of water abstracted and discharged across the whole region will have tripled (Department of Water, 2010) as a result of an increasing number of mines, with a high frequency of below water table operation. These predictions emphasize the need to greatly increase the currently limited understanding of the effects of local drawdown

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(and discharge) on surrounding dependent terrestrial ecosystems (Froend and Sommer, 2010).

The Pilbara is characterized by ephemeral streams and creeks where depth to groundwater is often shallow but varies widely according to underlying geology, evapotranspirative water losses, and rates of recharge. The riparian vegetation of major watercourses is dominated by *Eucalyptus victrix* L.A.S. Johnson & K.D. Hill, sometimes interspersed with *Eucalyptus camaldulensis* Dehnh. and *Melaleuca argentea* W. Fitzg. Research across semiarid landscapes of Australia and elsewhere has shown that most riparian eucalypts qualify as facultative phreatophytes (Busch *et al.*, 1992; Mensforth *et al.*, 1994; Smith *et al.*, 1998; Lamontagne *et al.*, 2005; Holland *et al.*, 2006; Costelloe *et al.*, 2008). Here, we define facultative phreatophytes as species that are dependent on access to groundwater or water from the capillary fringe, when soil water originating from surface recharge becomes limited. Studies elsewhere suggest that falls in groundwater and associated capillary fringe affect species composition and productivity of dependent ecosystems (Laine *et al.*, 1995; Murphy *et al.*, 2009; Sommer and Froend, 2011) and may cause declining tree health (Murray *et al.*, 2003) or even tree death (Horton *et al.*, 2001; Eamus and Froend, 2006). Negative effects on ecosystem function are usually attributed to the limited drought tolerance of riparian trees (Naumburg *et al.*, 2005; Orellana *et al.*, 2012).

Establishing effects of falling groundwater on facultative phreatophytes requires both consideration of rates of drawdown and antecedent groundwater levels (Shafroth *et al.*, 2000). For example, trees accessing shallow groundwater may be more sensitive to drawdown compared with trees growing above groundwater at greater depth. The net result is a range in dependence on groundwater by trees across a landscape and variable responses to water availability (Murray *et al.*, 2003). Water use of phreatophytes is intimately linked to soil water availability. Under conditions where tree water use (transpiration) generates increasingly negative water potentials inside the plant, signals from roots and/or the atmosphere serve to reduce stomatal conductance ( $g_s$ ), effectively reducing water loss (e.g. Porporato *et al.*, 2002). Examples of the links among declining soil water availability, reduced  $g_s$ , and declining rates of sap flow in tree stems are provided by Whitehead and Beadle (2004) and Bovard *et al.* (2005). Trees can limit water losses by abscission of foliage (Bréda *et al.*, 2006), and for eucalypts, abscission of foliage has long been linked to acute water shortages at the end of summer (Attiwill and Adams, 1996). There is also evidence from riparian poplars of reductions in  $g_s$  and abscission of leaves as a result of falling water tables (refer to Amlin and Rood, 2003 and references therein), but there is little evidence for other riparian tree species, including eucalypts.

For the borefield associated with the study reported here, hydrological modelling suggests that by 2030, the

groundwater level at the centre of the cone of depression will have fallen by as much as 180 m (Johnson and Wright, 2001), with much smaller falls at greater distance from the centre. As groundwater is being abstracted and depth to groundwater is increasing, there is a prerogative for mine managers to carefully consider how this water is used. Clearly, in addition to water for dust suppression and other industrial procedures, a high priority must be given to the use of abstracted water to prevent a decline in ecosystem functioning in the area affected by drawdown. Of particular concern is maintaining surface flow where that existed before the commissioning of the mine. For this purpose, a series of spurs were installed that release groundwater to areas upstream and downstream of a major surface expression, known locally as a 'spring'.

Here, we report on the following: (i) a 4-year study of foliage density ( $\rho_F$ , a measure of leaf area per unit canopy space) and (ii) a short-term study of tree water use (using sapwood-related sap flow ( $Q_S$ ) as a surrogate), in the initial stages of the mining and borefield operations.

Water availability dictates ecosystem processes, including plant water uptake (Porporato *et al.*, 2002). For the short-term (91 days) study, we specifically targeted the dry season when soil water becomes progressively limiting and forces phreatophytes to increase dependence on water from deeper sources (Lamontagne *et al.*, 2005). We specifically tested the following hypotheses related to the plasticity of *E. victrix* for surviving a broad range of environmental conditions: (i) A fall in groundwater from moderate to deep depths would result in trees becoming increasingly water limited similar to trees with a life history of accessing deep water sources; (ii) a rise in groundwater from deep to moderate levels would result in increased water use by trees compared with those that have a life history of access to water sources at moderate depth.

## MATERIALS AND METHODS

### *Study area*

A detailed description of the hydrogeological characteristics of the study area along Weeli Wolli Creek is provided as *Supplementary Information*. Briefly, the tree vegetation within the riparian zone of the Weeli Wolli Creek consists variously of the following: (i) narrow belts on banks and elevated locations within the channel and (ii) widely spaced woodlands on low-lying areas adjacent to the channel. Trees are irregularly distributed and do not form a continuous canopy (refer to Figure S3–S5). These characteristics make hydrological scaling of water fluxes problematic. We focused on characterizing the effects of changing water tables on tree health (as measured by leaf density) and physiological performance (as measured by sap velocity).

Four research sites were established along a 30-km section of the upper and midsection of the creek where at least five trees could be accessed within a reasonable area. Two sites were established, termed 'control<sub>29</sub>' (−23.04°lat, 119.18°long; 608 m a.s.l.) and 'control<sub>6</sub>' (−22.93°lat, 119.19°long; 577 m a.s.l.) where depth to groundwater was stable. Location of control<sub>29</sub> was outside the cone of depression, and the groundwater level was naturally deep (around 29 m; Figure 1, Table I). Depth to groundwater at control<sub>6</sub> was less (6 m) and was artificially maintained by discharge from a series of 'spurs' from a major water pipeline (Figure 1 and S1, Table I). A third site, termed 'drawdown' (−22.94°lat, 119.17°long; 583 m a.s.l.), was selected immediately above the cone of depression where depth to groundwater had dropped from 8.3 to 19.2 m since commencement of drawdown (Figure 1 and S1, Table I). The fourth site, termed 'surplus' (−22.81°lat, 119.29°long; 496 m a.s.l.) was established in the midsection of the creek,

15 km downstream of control<sub>6</sub>. Discharge of excess groundwater further upstream had lifted the water table at this site from 16 to 7 m (Table I). All measured trees were within 5–10 m of the main channel of Weeli Wollie Creek. Nominally, all sample trees were *E. victrix*. Distinguishing this species from *E. camaldulensis* in the field is difficult, relying on characteristics of seed capsules that are not always present.

#### Regional climate

Climate of the Pilbara is bimodal and generally hot (refer to Pfautsch *et al.*, 2011). In the central Pilbara, near the town of Newman, annual mean maximum air temperature is 32 °C (1996–2012) and annual precipitation is 315 mm (1971–2012; Bureau of Meteorology, 2012). Large proportions of annual precipitation can fall in a single event (up to 200 mm or more) originating from decaying summer

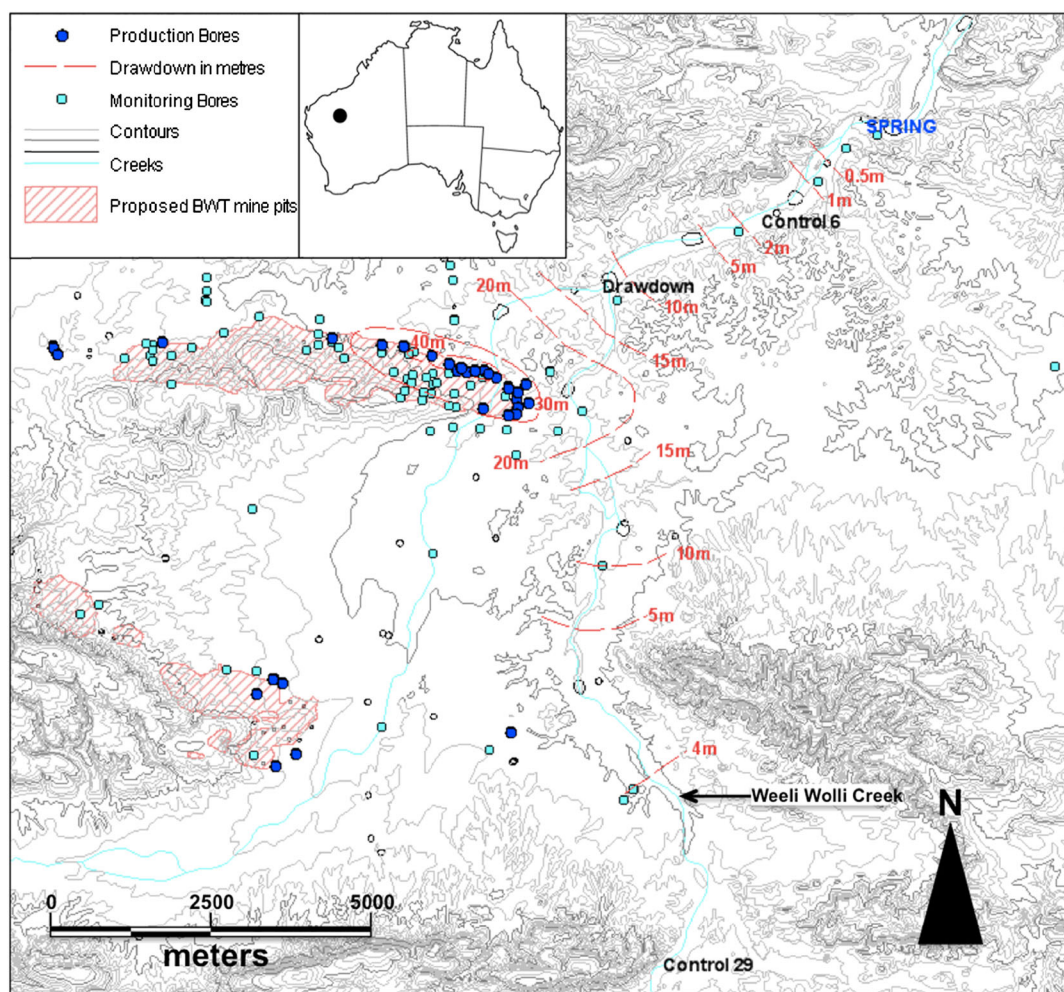


Figure 1. Location of research sites along the upper section of Weeli Wollie Creek (control<sub>29</sub>, drawdown, and Control<sub>6</sub>) in relation to proposed below water table (BWT) mine pits. Contour lines indicate extent and depth of drawdown at the end of Nov 2010 compared with pre-mining groundwater levels. Because of reasons of scale, the map does not show the location of the surplus site (12 km NE of spring site).

Table I. Depth to groundwater for research sites.

Site name	Pre-management (m)	Current (m)	Change current to pre-management (m)	Change within study period (m)
Control <sub>29</sub>	28.74 (0.03)	29.40 (0.02)	−0.66	−0.42
Drawdown	8.28 (0.22)	19.23 (0.13)	−10.95	−0.87
Control <sub>6</sub>	6.33 (0.32)	6.23 (<0.01)	+0.10	−0.07
Surplus	16.33 (0.04)	7.05 (<0.01)	+9.28	−0.22

Pre-management depths represent average depth-to-groundwater between 1998 and 2007. Current depth-to-groundwater was averaged from fortnightly data spanning from 30 June to 27 Nov 2010. Variance ( $s^2$ ) is shown in parentheses.

cyclones. Droughts are frequent during which annual rainfall can be less than 40 mm year<sup>−1</sup>. Study sites were all located in the same broad valley system and subject to the same general climate (i.e. identical vapour pressure deficit ( $D$ ) and temperatures within 1–2 °C at any given time). Rainfall during the wet season preceding that of our study was low (126 mm between November 2009 and April 2010) relative to long-term records and insignificant during the first half of the preceding dry season (20 mm between May and August 2010). Annual potential evapotranspiration (PET) in the central Pilbara can reach up to 3700 mm (Luke *et al.*, 1987). A weather station established close to our drawdown site recorded air temperature ( $T_{air}$ , °C) and relative humidity (rH, %; HMP43A, Vaisala, Finland), rainfall (mm; TB3/0.2, Hydrological Services America, USA), solar radiation (EQ08-E, Middleton Solar, Australia), and wind speed and direction (Model 05103–5, RM Young Company, USA) at 10-min intervals. PET (mm) was calculated from these measurements using a modified Penman–Monteith equation. Vapour pressure deficit was calculated using average  $T_{air}$  and rH according to Snyder and Shaw (1984):

$$D = \left( 0.6108 \times \left( \frac{\exp(17.27 \times T_{air})}{T_{air} + 237.3} \right) \right) \times \left( 1 - \frac{rH}{100} \right) \quad (1)$$

#### Canopy monitoring

Long-term patterns of tree health were monitored at all sites over a 4-year period (2006–2010), except at control<sub>29</sub> (2009–2010). Canopy monitoring at the latter site was delayed because of access restrictions. A single sample point was established and permanently marked underneath 10 tree canopies at three research sites and 12 canopies at surplus to monitor changes in  $\rho_F$ . Digital images with an approximately 15° field of view were collected at each point up to four times a year. Foliage cover ( $C_F$ ) and crown cover ( $C_C$ ) were calculated according to Macfarlane *et al.* (2007). An estimate of  $\rho_F$  within crowns was calculated as  $C_F:C_C$ . This sampling strategy does not provide an average measurement of cover across whole stands because only individual canopies were sampled, omitting gaps between widely spaced individuals. The measurement objective was to detect changes in  $\rho_F$  of tree canopies rather than quantify

stand averages. We used a gap-filling approach to account for missing images. This approach used the average relative change in  $C_F$  and  $C_C$  among all trees at the relevant site between two consecutive sample periods to estimate missing data (<4% of all images were missing from a total of 1200).

#### Sap velocity measurements

We recorded heat velocity ( $V_h$ ) in stems of five *E. victrix* at all sites for 91 days (1 September to 30 November 2010) except at control<sub>6</sub> where data were recorded for 71 days (1 September to 11 November) using probes that operate on the principle of the heat ratio method (HRM, Burgess *et al.*, 2001). All measured trees were located within 10 m of the riverbank. Physical characteristics of measured trees are given in Table S1. Additional measurements and procedures (refer to Pfautsch *et al.*, 2010) allowed conversion of  $V_h$  to sapwood-related sap flow ( $Q_S$ , l (unit sapwood area)<sup>−1</sup> (unit time)<sup>−1</sup>). At each site, we installed four probe sets in one tree in four hemispherical directions to detect any circumferential variation of sap velocity. One probe set was installed at the southern side of four additional trees. Probe sets, data loggers, and auxiliary equipment were acquired from ICT International (Armidale, Australia), and probes were shielded to reduce thermal load. At the end of sap flow measurements, we extracted two blocks of sapwood from opposite sides of three measured trees at each site. Sapwood was immediately analysed for fresh weight and volume (immersion technique). Once returned to the lab, blocks were dried for 72 h at 105 °C before recording their dry weight. Sapwood density was calculated as mass per unit volume (g cm<sup>−3</sup>). In addition, we extracted wood cores from each of four cardinal positions from each tree equipped with sap flow sensors for a detailed analysis of sapwood depth ( $D_S$ ) using light microscopy as outlined in Pfautsch *et al.* (2012).

Initial measurements collected across a radial gradient of  $D_S$  indicated that maximum  $Q_S$  was concentrated in outer sapwood. This section of sapwood supports transpiration of the sunlit canopy and is a strong indicator of availability and use of water by trees (Fiora and Cescatti, 2005). Given our focus on effects of drawdown on tree health and physiological function and the irregular distribution of these riparian stands, we focused on characterizing patterns

of  $Q_S$  rather than total volumetric water use on a stand basis. Consequently, thermistors were positioned at 7 mm  $D_S$  in all trees ensuring comparability among trees and sites. According to the conductive properties of stainless steel probes (Swanson, 1983),  $Q_S$  reported here represents an integral of velocities at  $D_S$  2–12 mm.

### Statistical analyses

One-way analysis of variance (ANOVA) was used to assess if sapwood density and moisture content varied significantly between sites. Trends in mean monthly peak  $Q_S$  ( $Q_{Sp}$ ) were established relative to the period where  $Q_S$  at control<sub>6</sub> (i.e. 'benchmark site' where trees grow at continuously high groundwater level) was more or less constant (1000–1800 h). As shown previously for this species (Pfautsch *et al.*, 2011), the relation of  $Q_S$  to  $D$  differs markedly between daytime and night-time. Hence, we used 6-h windows to assess this relation when average  $D$  was at its maximum ( $Q_{SDmax}$ , 1100–1600 h) and minimum ( $Q_{SDmin}$ , 0100–0600 h) for each site. For these tests, we applied repeated measures (RM) ANOVA to mean  $Q_S$  ( $n$  = five trees) for each hour of the identified time window ( $n$  = 6) and used Fisher's LSD post hoc test to examine between-subject (month to month) variation. RM-ANOVA was also used to evaluate if  $\rho_F$  differed significantly among sites. ANOVA was used to test if  $\rho_F$  at individual sites changed significantly from September 2010 to December 2010. Significance of all tests was given if  $P < 0.05$ . AABEL3 (Gigawiz, Tulsa, USA) was used for statistical tests.

## RESULTS

### Foliage density in tree canopies

Long-term monitoring (October 2006–December 2010) indicated significant intra-site variation of  $\rho_F$ , with variation being greatest at surplus (Table II). Amongst all sampling intervals and sites,  $\rho_F$  was largest in February 2007 following a pronounced wet season. In contrast,  $\rho_F$  decreased in the wet season of 2009/2010 where rainfall was below long-term

averages (refer to 'Regional climate'). Average  $\rho_F$  was lowest at control<sub>29</sub> ( $0.65 \pm 0.08$  (mean  $\pm 1$  standard deviation (SD))). Trees at all other sites showed  $\rho_F$  of 0.69–0.70 (overall  $\pm 0.09$ ). Changes in depth to groundwater (refer to Table I) had no measurable long-term effect on  $\rho_F$  at drawdown or surplus. Analyses of data collected in September and December 2010 showed a tendency of declining  $\rho_F$  across all sites, albeit this decline was only significant (0.75 to 0.63,  $P < 0.001$ ) at drawdown (Figure 2).

### Weather conditions

From September to November 2010, the weather became generally hotter and drier. Average maximum  $T_{air}$  rose from 25 °C in September to 35 °C in November while at the same time, rH declined from 22 to 10%.  $D$  increased accordingly to reach 7.3 kPa during the hottest day ( $>41$  °C) in November and remained high during night-time where it

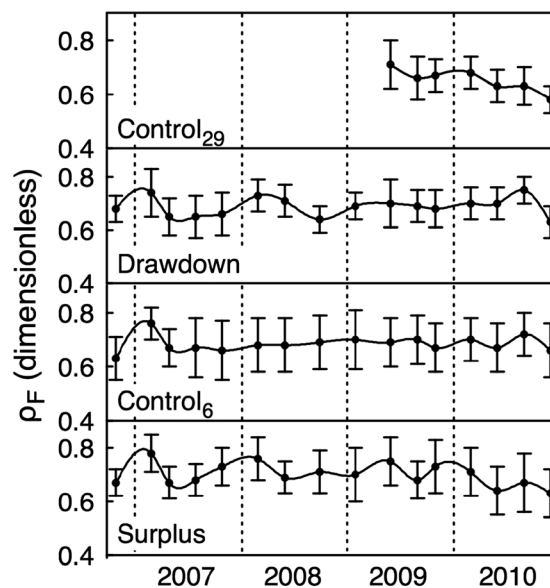


Figure 2. Variation of foliage density ( $\rho_F$ ) in canopies of *Eucalyptus victrix* ( $n = 20$  site<sup>-1</sup>) between October 2006 and December 2010. Solid lines show smoothed averages; error bars show SD.

Table II. Statistics for RM-ANOVA (including Bonferroni–Dunn post hoc) testing differences in foliage density ( $\rho_F$ ) of *Eucalyptus victrix*.

Site name	DF $\rho_F$	SI	Residual	MS $\rho_F$	SI	$F$ -ratio $\rho_F$	SI	Partial $\omega^2$ for SI	Post hoc		
									score total	score Sep–Nov	Adjusted $\alpha$ level
Control <sub>29</sub>	18	6	108	0.02	0.03	4.69	10.12	0.29	6	No	0.0024
Drawdown	14	15	210	0.02	0.02	5.53	4.82	0.19	10	Yes	0.0004
Control <sub>6</sub>	16	15	240	0.08	0.01	22.05	3.53	0.12	11	No	0.0004
Surplus	18	15	270	0.06	0.03	19.12	9.14	0.29	31	No	0.0004

All RM-ANOVA indicated that  $\rho_F$  differed significantly among SI ( $P < 0.001$ ). Post hoc scores denote number of significant differences among all possible combinations of SI per site. Significant differences in  $\rho_F$  during study period are shown separately. DF, degrees of freedom; MS, mean squares; SI, number of sampling intervals.

regularly exceeded 2 kPa. Maximum  $D$  during night-time was 3.9 kPa. During our study, PET totalled close to 600 mm.

### Sap flow

Average sapwood density of *E. victrix* was  $0.695 \text{ g cm}^{-3}$  ( $\pm 0.056$ ). Moisture content of sapwood ranged from 32 to 39%. Both parameters did not vary significantly among sites.

Sap flow within the outer band of sapwood varied considerably with tree size, ranging from an average of 22 to  $2241 \text{ m}^{-2} \text{ h}^{-1}$  ( $\pm 52$ , Figure S2). We calculated mean monthly diel courses of  $Q_S$  for all sites. One similarity among sites was that  $Q_S$  never approached zero. Another was a doubling of  $Q_S$  from minimum rates within 2 h of early daylight (Figure 3a–d). Overall, trees at sites where groundwater was deep (control<sub>29</sub> and drawdown) used less water compared with trees that grew at sites where groundwater was closer to the surface (control<sub>6</sub> and surplus).

Diel courses of  $Q_S$  varied greatly among sites. For the sites where the water table was at greatest depth (control<sub>29</sub> and drawdown),  $Q_S$  increased rapidly with the onset of daylight, in September reaching  $Q_{Sp}$  around midday (control<sub>29</sub>,  $1331 \text{ m}^{-2} \text{ h}^{-1}$ ; drawdown,  $1481 \text{ m}^{-2} \text{ h}^{-1}$ ). As the dry season progressed,  $Q_{Sp}$  declined (in November: control<sub>29</sub>,  $101 \text{ m}^{-2} \text{ h}^{-1}$ ; drawdown,  $1111 \text{ m}^{-2} \text{ h}^{-1}$ ) and was reached earlier each day (e.g. by 0800 h in November).  $Q_S$  slowed during daytime, and its relation to  $D$  became gradually linear with increasingly negative slopes (refer to Figure 3a and b, Table III). For sites where groundwater was closer to the surface (control<sub>6</sub> and

Table III. Slope, intercept, and regression coefficient for relation between peak sap flow ( $Q_{Sp}$ ,  $\text{m}^{-2} \text{ h}^{-1}$ ) and daytime hours (10:00–18:00) in *Eucalyptus victrix*.

Site name	Month	Slope	y-intercept	$R^2$
Control <sub>29</sub>	Sep	−2.41	136.28	0.40
	Oct	−3.00	125.32	0.89
	Nov	−3.34	103.53	0.97
Drawdown	Sep	−3.71	154.00	0.59
	Oct	−4.50	143.78	0.84
	Nov	−4.57	121.03	0.91
Control <sub>6</sub>	Sep	−1.75	209.80	0.34
	Oct	−0.56	204.35	0.31
	Nov	−0.32	198.83	0.09
Surplus	Sep	−1.94	243.50	0.58
	Oct	0.34	241.52	0.23
	Nov	−0.15	234.20	0.03

Data were averaged for the months of Sep, Oct, and Nov 2010.

surplus), daytime  $Q_S$  was consistently faster throughout the research period (Figure 3c and d). For these sites, and following an early and steep increase in  $Q_S$  after dawn,  $Q_{Sp}$  was reached between 1000 and 1100 h where it remained with little change for the entire day. On average,  $Q_{Sp}$  was  $2121 \text{ m}^{-2} \text{ h}^{-1}$  at control<sub>6</sub> and  $>2401 \text{ m}^{-2} \text{ h}^{-1}$  at surplus (Figure 3c and d). There was negligible variation in  $Q_{Sp}$  from September to November for these sites (Table III).

Hysteresis in  $D$  versus  $Q_S$  relationships is shown in Figure 3e–h. Notably, differences in  $Q_S$  between morning

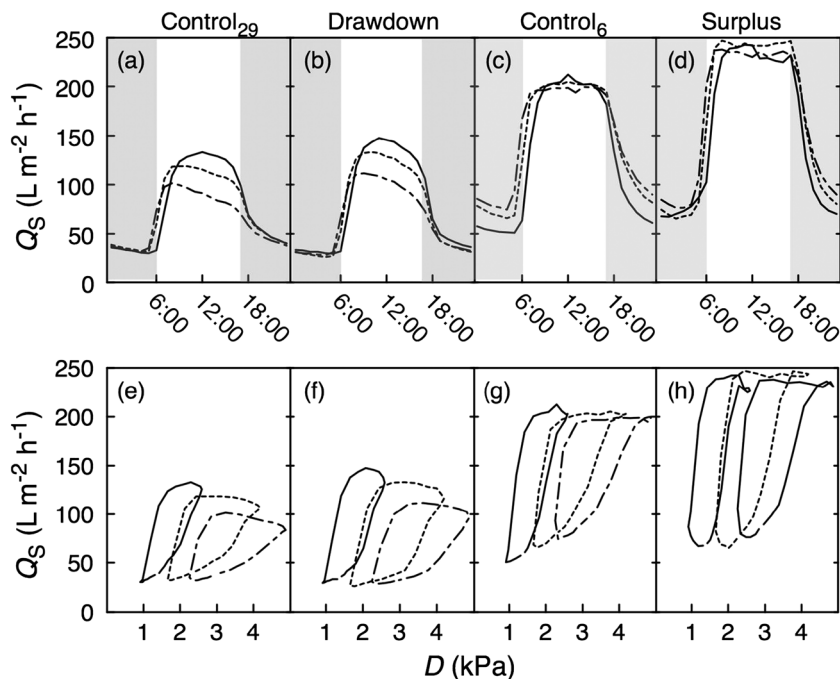


Figure 3. Diel profiles of sapwood-related sap flow ( $Q_S$ , panel a–d) and the relation of  $Q_S$  to vapour pressure deficit ( $D$ , panel e–h) in *Eucalyptus victrix* ( $n=5 \text{ site}^{-1}$ ). Data were averaged for Sep 2010 (solid line), Oct 2010 (dotted line), and Nov 2010 (dash-dotted line). Circular arrow in (h) indicates direction of hysteresis.

and afternoon for a given  $D$  were greater for trees at control<sub>6</sub> and surplus than for trees at control<sub>29</sub> and drawdown (Figure 3e–h), suggesting greater flexibility in stomatal opening when water tables are higher. The lower overall  $Q_S$  and reducing difference (for a given  $D$ ) between morning and afternoon at control<sub>29</sub> and drawdown suggest that within-tree water deficits may be reducing overall stomatal opening. When water tables were closer to the surface (control<sub>6</sub> and surplus), maintenance of faster  $Q_{Sp}$  till late each day (e.g. 1800 h), as signified by the horizontal ‘beak’ at the upper end of the hysteresis loop (Figure 3g and h), reflects weaker control by  $D$ .

$Q_{SDmax}$  at control<sub>29</sub> and drawdown declined by around 30% from September to November (control<sub>29</sub>: 128 to 86  $l\ m^{-2}\ h^{-1}$ ; drawdown: 139 to 98  $l\ m^{-2}\ h^{-1}$ ; Table IVa) but remained more or less constant at control<sub>6</sub> and surplus (Table IVa). Changes in  $Q_{SDmax}$  across the research period were significant only for control<sub>29</sub> and drawdown (Table IVb).

In clear contrast to varying responses in  $Q_{SDmax}$  among sites,  $Q_{SDmin}$  increased significantly in trees at all sites (Table IVa and b). Increasing  $Q_{SDmin}$  was most pronounced at control<sub>6</sub> (+76%) and surplus (+30%), followed by control<sub>29</sub> (+24%) and drawdown (+14%; Table IVa). Mean  $D$  during this interval increased from 1.0 kPa (September,  $\pm 0.7$ ) to 2.5 kPa (November,  $\pm 0.7$ ).  $Q_{SDmin}$  was the main driver for increased tree water use from September to November at control<sub>6</sub> and surplus, while decreasing  $Q_{SDmax}$  caused the opposite at control<sub>29</sub> and drawdown.

DISCUSSION

Our research from semiarid Australia offers insights into how falling or rising groundwater levels influence water use of facultative phreatophytes. There are no comparable studies in the published literature, as far as we can ascertain, of the effects of high rates of abstraction (here  $>96\ ml\ day^{-1}$ ) and a fast and sustained fall in groundwater level (here  $>1\ cm\ day^{-1}$  over 4 years) on tree water use and health.

Digital photography (Macfarlane *et al.*, 2007) and visual assessment of tree crowns (Souter *et al.*, 2010) have both been used elsewhere to assess leaf density or projected area and, *inter alia*, can serve as indices of tree health. Both techniques have their limitations when assessing widely spaced riparian stands. Estimation of a leaf area index cannot fully capture declining health of individual tree canopies when trees are sparse, while visual assessment depends on assessor experience and consistency. Using  $\rho_F$  is more likely to capture changes in canopy condition of widely spaced trees as it repeatedly assesses the same section of a canopy.

Over the 4-year period of study,  $\rho_F$  varied within moderately small ranges, despite variations in annual rainfall of  $>50\%$  from the long-term annual mean. Variation in  $\rho_F$  did not reflect depth or access to groundwater, and equal variability in  $\rho_F$  was evident across all sites albeit not during September and December 2010. Although the decline of  $\rho_F$  recorded between September

Table IV. (a) Average monthly sapwood-related sap flow ( $Q_S$ ,  $l\ m^{-2}\ h^{-1}$ ) in *Eucalyptus victrix* ( $n=5$ ); (b) related statistical analyses.

(a)		$Q_s\ (l\ m^{-2}\ h^{-1})$			
		Sep	Oct	Nov	Nov – Sep
Control <sub>29</sub>	$Q_{SDmax}$	127.78 (29.61)	110.54 (12.67)	85.90 (11.86)	–41.88
Drawdown	$Q_{SDmax}$	138.65 (34.79)	122.16 (16.53)	98.18 (13.43)	–40.41
Control <sub>6</sub>	$Q_{SDmax}$	203.94 (43.95)	202.46 (5.54)	198.10 (5.13)	–4.62
Surplus	$Q_{SDmax}$	232.32 (57.44)	242.98 (16.11)	233.19 (13.98)	+0.87
Control <sub>29</sub>	$Q_{SDmin}$	32.42 (8.69)	38.23 (12.72)	40.28 (17.45)	+7.86
Drawdown	$Q_{SDmin}$	31.21 (8.54)	31.75 (11.26)	35.56 (14.89)	+4.35
Control <sub>6</sub>	$Q_{SDmin}$	54.18 (19.02)	78.15 (24.90)	95.28 (34.37)	+41.10
Surplus	$Q_{SDmin}$	79.55 (30.63)	85.73 (41.38)	103.31 (49.95)	+23.76
(b)		RM-ANOVA			
Site name		DF	F-ratio	P	P (Nov – Sep only)
Control <sub>29</sub>	$Q_{SDmax}$	179	1.40	<0.01	<0.01
Drawdown	$Q_{SDmax}$	179	1.35	0.01	<0.01
Control <sub>6</sub>	$Q_{SDmax}$	59	0.97	>0.50	<0.01
Surplus	$Q_{SDmax}$	179	1.04	0.37	>0.50
Control <sub>29</sub>	$Q_{SDmin}$	179	1.99	<0.01	<0.01
Drawdown	$Q_{SDmin}$	179	2.30	<0.01	<0.01
Control <sub>6</sub>	$Q_{SDmin}$	59	2.29	<0.01	<0.01
Surplus	$Q_{SDmin}$	179	3.26	<0.01	<0.01

$Q_S$  was recorded 1 Sep–30 Nov 2010 and is presented separately for 6-h windows where vapour pressure deficit of the atmosphere was at maximum ( $Q_{SDmax}$ , 11:00–16:00) and minimum ( $Q_{SDmin}$ , 1:00–6:00); SD is shown in parenthesis; ‘Nov–Sep’ in (a) indicates change in  $Q_S$  from Sep to Nov. Results of RM-ANOVA denote between-subject statistics, including degrees of freedom (DF), test statistic ( $F$ -ratio), and significance probability ( $P$ ); ‘Nov–Sep’ in (b) shows  $P$  according to Fisher’s LSD test. Significance was given at  $P < 0.05$  for all tests.

and November 2010 in trees at the drawdown was significant, ongoing monitoring suggests that trees recovered completely in the following wet season (data not presented). Additional information, say as provided by  $Q_S$ , is critical to assessing the effects of water availability for riparian ecosystems as studied here.

The control<sub>6</sub> site provides a clear example of water use dynamics of *E. victrix* with more or less unlimited access to water. The dynamics were similar to those reported recently by Pfautsch *et al.* (2011) for sites where depth to groundwater was around 1–2 m. Similar patterns (i.e. a steep increase during early morning, followed by a plateau during most of the day and rapid decline with nightfall) have been reported from other semiarid environments (e.g. Meinzer *et al.*, 1999; Bucci *et al.*, 2008; O'Grady *et al.*, 2009). Under well-watered conditions, this pattern remains stable regardless of season (O'Grady *et al.*, 1999; Eamus *et al.*, 2000; Pfautsch *et al.*, 2011) and is indicative of a dominant effect of  $D$  (Scott *et al.*, 2004; Huang *et al.*, 2009). Limitation of  $g_s$  as  $D$  increases reduces risks of damage (e.g. via cavitation) to vascular systems. Our data not only from control<sub>6</sub> but also from surplus support this regulatory mechanism. Stomatal limitation of transpiration during daytime with increasing  $D$ , and looser regulation during night-time when  $Q_S$  tracks  $D$ , has been reported for *E. victrix* (Pfautsch *et al.*, 2011) and other eucalypts under natural conditions (Buckley *et al.*, 2011) as well as in common gardens (Phillips *et al.*, 2010).

Groundwater at moderate depth (6–7 m) resulted in stable  $Q_{SDmax}$ . Where groundwater was deep,  $Q_{SDmax}$  declined significantly during the dry season (by  $30 \pm 2\%$ ). On the other hand,  $Q_{SDmin}$  increased during this period across all sites, albeit to a smaller degree at control<sub>29</sub> (24%) and drawdown (14%) when compared with surplus (30%) and control<sub>6</sub> (76%). This observation is in line with previous description of relations between stomatal regulation and  $D$ . During daytime,  $Q_{SDmax}$  declines when soil water availability becomes limiting and remains constant when sufficient soil moisture can be accessed. As  $D$  increased steadily throughout the research period, including at night, increasing  $Q_{SDmin}$  is likely a result of increasing night-time transpiration where the magnitude of increasing  $Q_{SDmin}$  reflects the availability of soil moisture.

Superficially, trees functioned similarly at sites with deep groundwater, irrespective of abstraction effects. Differences between these sites in rates of sap flow were consistently small and arguably not significant. However, this observation is in broad agreement with the 'life history concept of roots', which states that the impact of groundwater drawdown will affect trees growing over historically shallow groundwater will more negatively compared with trees that had developed over historically deeper levels of groundwater (Scott *et al.*, 1999; Shafroth *et al.*, 2000).  $Q_{SDmin}$  was consistently less at drawdown compared with

control<sub>29</sub>. At the other extreme, where groundwater had risen as the result of discharge (surplus), *E. victrix* transpired at faster rates compared with a site where depth to groundwater remained at 6 m (control<sub>6</sub>). Taken together, our observations support both of our hypotheses and underline the capacity of *E. victrix* to survive a wide range of ecohydrological settings.

It is unclear if roots of *E. victrix* access groundwater as deep as 29 m. Across biomes, average maximum rooting depth of trees is around  $7 \pm 1.2$  m (Canadell *et al.*, 1996). However, tree species from semiarid environments have been shown to access groundwater at depths below 30 m (Zencich *et al.*, 2002), and tap roots of *Eucalyptus marginata* have been found at depths beyond that (Dell *et al.*, 1983). Generally, dimorphic root systems, as well as capacity to reach water sources deep in soil profiles or the regolith, are well described for phreatophytes (Ehleringer *et al.*, 1991; Dawson and Pate, 1996). Even so, factors such as low oxygen concentrations in deep soil layers, impeding soil layers, and increasing resistance to water transport in roots often severely limit transport of large volumes of water over long path lengths (Tyree and Ewers, 1991; Canadell *et al.*, 1996). The capacity of root growth to match rates at which groundwater levels fall can also severely constrain tree water access (Zencich *et al.*, 2002). However, the capacity of another Australian phreatophyte (*Banksia* spp.) to adjust growth dynamics of roots in accordance to fluctuation of groundwater tables has been documented recently (Canham *et al.*, 2012). Nevertheless, some reports of maximum rates of root growth of  $3\text{--}15 \text{ mm day}^{-1}$  by arid zone species (reviewed in Naumburg *et al.*, 2005) do not take account of soil depth (i.e. can trees grow roots as quickly at 20 m depth as at 1 m depth?), and maximum rates for riparian species in semiarid environments are unknown. Large investments of carbon needed for root growth at great depth may not be available because of low  $g_s$  imposed on trees by water limitation (Reich, 2002; Naumburg *et al.*, 2005). Then again, falling groundwater levels increase the volume in soil available for storage of precipitation and capillary rise, which has been shown to increase water use of some plants (Jackson *et al.*, 2000). This advantage may be of limited use for plants growing in semiarid environments where annual precipitation is low.

Where groundwater had risen from 16 to 7 m depth (surplus),  $Q_S$  was generally faster compared with where groundwater remained at 6 m (control<sub>6</sub>). Previous research suggests that plant productivity might increase with rising groundwater (assuming no anoxia; e.g. Groeneveld and Crowley, 1988; Naumburg *et al.*, 2005). Anoxic conditions were not a factor for trees at surplus, as many metres of soil remained unsaturated. If rising groundwater tables lead to increasing productivity in *E. victrix* remains a question for future research.



*E. victrix* displayed opportunistic physiognomy in using water, a strategy also reported for facultative phreatophytes from the wet tropics of Australia (O'Grady *et al.*, 2006) and the USA (Hultine *et al.*, 2010) but not for some other species (Amlin and Rood, 2003). In a global context, riparian ecosystems have emerged as 'intense political, economic, social and ecological battlegrounds over limited water resources' (*sensu* Cleverly *et al.*, 2006). Here, we have shown how anthropogenic modification of water tables can affect water use of eucalypts that dominate these zones. We demonstrated a remarkable capacity of *E. victrix* to sustain a significant short-term decline in depth to groundwater. Similar investigations will be required in other semiarid environments where open-cut mining affects groundwater and dependent tree species. Our results suggest repeated (even if intermittent) monitoring of selected parameters like tree water use will be required.

We agree with MacKay (2006) that negative impacts of dewatering can only be minimized once sound understanding of local hydrogeology is developed. Models describing plant responses to either rising or falling water tables have been developed (Shafroth *et al.*, 2000; Naumburg *et al.*, 2005). To date, these models do not consider situations common to open-cut mining where water tables may drop significantly over short time spans. Improving our understanding of how dewatering and associated discharge impact nearby ecosystems is now a pressing issue, as open-cut mining below water tables is increasing in Australia and elsewhere.

#### ACKNOWLEDGEMENTS

This research was funded by the Australian Research Council Linkage Project 0776626, which included support by Rio Tinto Iron Ore (RTIO). The authors would like to thank Pauline Grierson (University of Western Australia), Nicole Gregory (RTIO), Shawan Dogramaci (RTIO), Craig Macfarlane (Commonwealth Scientific and Industrial Research Organisation) and Neil Murdoch (University of Sydney) for their assistance during the project.

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