CSIRO PUBLISHING

RESEARCH PAPER
https://doi.org/10.1071/BT21002

Australian Journal of BOTANY

Nutritional traits of riverine eucalypts across lowland catchments in southeastern Australia

Denise R. Fernando[A], Fiona Dyer[B], Susan Gehrig[C], Sam Capon[D], Anthony E. Fernando[E], Amy George[D], Cherie Campbell[F], Alica Tschierschke[B], Gary Palmer[D], Micah Davies[G], Andrew S. Kinsela[H], Richard N. Collins[H], Martin Nolan[G] and Tanya Doody[G,*]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
Tanya Doody
CSIRO Land and Water, Glen Osmond, SA 5064, Australia
Email: tanya.doody@csiro.au

Handling Editor:
Susanna Venn

ABSTRACT

Eucalyptus (Myrtaceae) trees are ubiquitous in riparian–floodplain zones of Australia's south-eastern river catchments, where natural ecosystems continue to be affected. In the Murray–Darling Basin (MDB), provision of environmental flows to mitigate tree decline is informed by past field studies. However, broadscale empirical field data on tree nutrition and response to external changes remain scarce. This is the first study to gather soil and plant data across a large area of catchment lowlands to generate a low-resolution regional snapshot of tree nutrition and soil chemistry. Leaves and soils were sampled across and adjacent to the MDB; from and beneath mature trees of three key riverine eucalypts, *Eucalyptus largiflorens*, *E. camaldulensis*, and *E. coolabah*. Foliar sodium concentrations ranged from ~500 mg kg^{-1} for *E. coolabah* up to ~4500 mg kg^{-1} for *E. largiflorens*, with highest values at the River Murray sites. The results suggest *E. largiflorens* is highly salt tolerant by foliage accumulation given all trees sampled were in good condition. Further research into these species is needed to determine toxicity thresholds for elements such as sodium to aid early diagnosis of potential tree stress, which could provide an additional line of evidence for when environmental water is required to mitigate decline.

Keywords: environmental flows, eucalypt nutrition, *Eucalyptus camaldulensis*, *Eucalyptus coolabah*, *Eucalyptus largiflorens*, floodplain–riparian environments, Lake Eyre Basin, Murray–Darling Basin, Murray River, natural waterflows, plant biogeochemistry, salinity, water extraction.

Introduction

The condition of native trees reliant on natural waterflows within some of Australia's key river basin systems such as the Murray–Darling Basin (MDB; Fig. 1) continues to be variously affected by diminishing environmental conditions, primarily attributed to climate change and water extraction (Pittock and Finlayson 2011; Swirepik *et al.* 2016; Grafton *et al.* 2018). The agriculturally productive MDB represents over a million square kilometres, incorporating a variety of ecosystems, from aquatic to riparian to floodplain. Trees native to these habitats are highly represented by the southern hemisphere genus *Eucalyptus* (Myrtaceae); mostly *E. largiflorens* Muell. (Black Box), *E. camaldulensis* Dehnh. (River Red Gum), and *E. coolabah* Blakely and Jacobs (Coolabah) (Fig. 2) (Overton *et al.* 2009; Roberts and Marston 2011; Doody *et al.* 2014; https://avh.chah.org.au/).

Disjunct studies undertaken over past decades have offered useful insights (Treloar 1959; Stone and Bacon 1995; Akeroyd *et al.* 1998; Bramley *et al.* 2003; Jensen *et al.* 2008; Doody *et al.* 2009, 2015; Rahimi-Nasrabadi *et al.* 2013); however, their collective geographic coverage has historically focused on the southwest corner of the MDB, in South Australia. It is difficult to resolve causes and effects related to stress response in mature trees given the complexities of, (a) underlying interrelated drivers such as soil chemistry, climate, water flows and plant genetics (Fernando and Lynch 2015; Fernando *et al.* 2018), and, (b) resolving time lags between specific causes and their detectable

Received: 2 January 2021
Accepted: 21 July 2021
Published: 28 October 2021

Cite this:
Fernando DR *et al.* (2021)
Australian Journal of Botany, **69**(8), 565–584.
doi:10.1071/BT21002

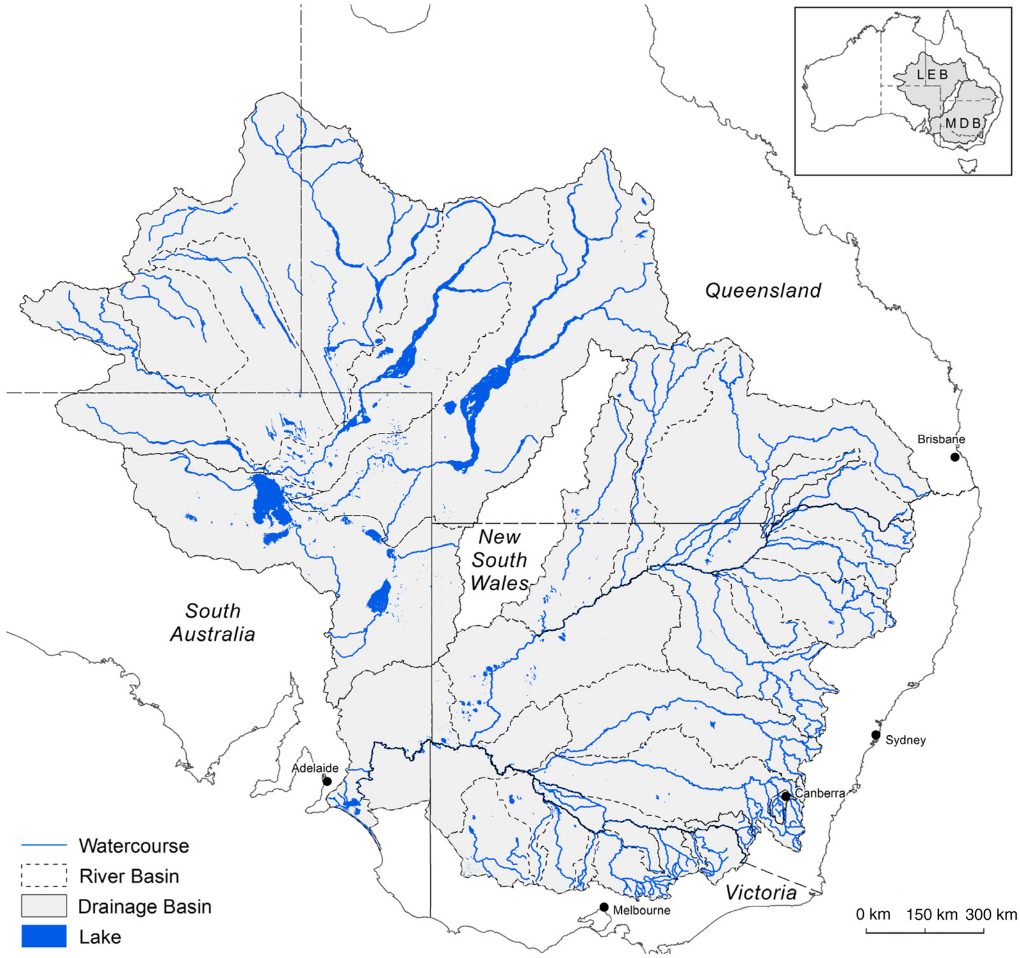

Fig. 1. The Murray–Darling Basin (MDB) and the Lake Eyre Basin (LEB), and their major watercourses (from Geoscience Australia, 1997, Australia's River Basins: https://data.gov.au/data/dataset/d4561e86-2d13-4dcb-bf9e-aae75ba4850c).

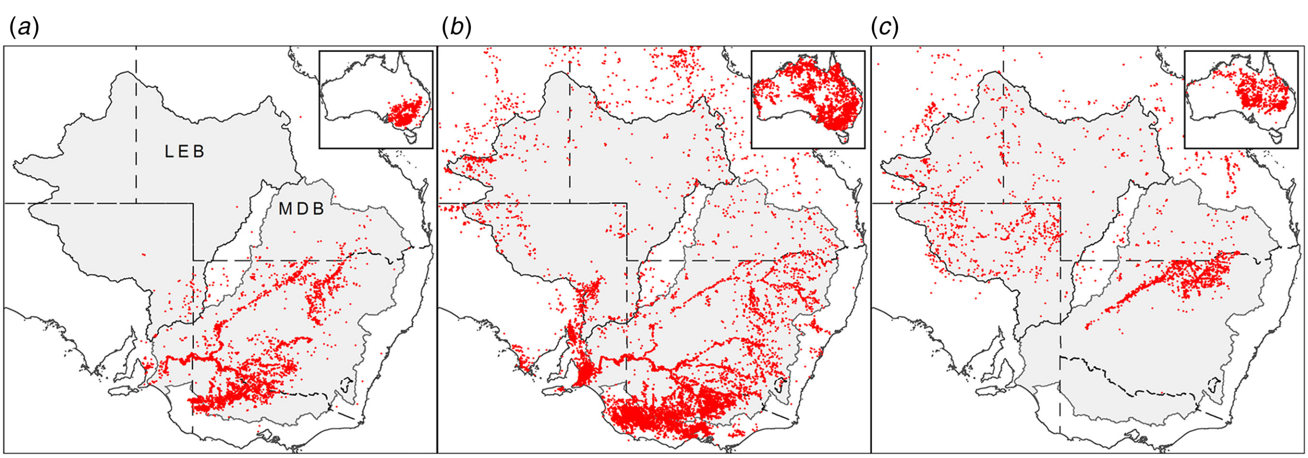

Fig. 2. Known occurrence of the three study species (Atlas of Living Australia, grid.506668.b, https://www.grid.ac/institutes/grid.506668.b). (*a*) *Eucalyptus largiflorens* (https://doi.org/10.26197/ala.3dba425c-3d04-4c7a-a88c-481d7b3a07e4), (*b*) *E. camaldulensis* (https://doi.org/10.26197/ala.12d0e0d8-4c01-467f-a961-8306f3d3f31e), (*c*) *E. coolabah* (https://doi.org/10.26197/ala.ca9ea3cb-a100-431a-9e77-4e0fcae9bdd0). The Murray–Darling Basin and Lake Eyre Basin are denoted as MDB and LEB.

effects. Although measurement of parameters such as new growth flush, leaf water potential and germination have been undertaken in discrete studies, these parameters variously depend on one or more factors such as time of collection and season.

Plant nutrition and soil chemistry are among the most important determinants of tree condition, but are generally overlooked in floodplain–riparian environments such as in the MDB. For example, many native tree-based studies have investigated water sources of the key native tree species in the basin (Mensforth *et al.* 1994*b*; Holland *et al.* 2005; Doody *et al.* 2009), tree water potential dynamics (Akeroyd *et al.* 1998; Zubrinich *et al.* 2000; Doody *et al.* 2009; Wallace *et al.* 2021), stomatal conductance (McEvoy 1992; Mensforth *et al.* 1994*a*), soil chloride concentrations and matric potential (Thorburn *et al.* 1993; Mensforth *et al.* 1994*a*; Wallace *et al.* 2020). An important study by McLennan *et al.* (2013) does however, provide some key insights into the potential use of plant biogeochemistry as an environmental monitoring tool, particularly in relation to molybdenum, sodium and potassium.

Soil characteristics, land topography and climate largely determine the natural distributions of tree species, and to some extent, their nutritional makeup, notwithstanding basic requirement by plants for certain essential macro- and micro-nutrients (Bedinger 1979; Medina and Cuevas 1994; Sakai and Ohsawa 1994; Marschner 2002). Therefore, any evaluation of nutritional data across a large geographically heterogenous area such as the MDB should take these external factors into consideration. Furthermore, genetic variation and local adaptations are similarly underpinned by such external factors. Scientific literature that presents empirical data on tree nutrition across river basin ecosystems remains scarce, possibly due in part to constraints of geographic scale, with evaluation of overall vegetation structure the most widely used approach to date (Bradley and Smith 1986; Sunil *et al.* 2010; Wallace *et al.* 2020). Although remote sensing techniques have previously been employed to assess MDB tree condition from far above canopy level (Cunningham *et al.* 2013), the relatedness of such data to *in situ* tree–soil interactions has not been sufficiently explored.

The management and accounting of water resources is an issue of mounting importance globally (Grafton *et al.* 2018), and to that extent, evaluation of tree nutrition on a broader scale, and with respect to hydrology, will ultimately assist future management practices. Fundamental parameters of tree condition besides canopy-related metrics from across the MDB have not been measured thus far, except in the far southwest corner (Slavich *et al.* 1999; Bramley *et al.* 2003; Miller *et al.* 2003; Smith and Smith 2014; Moxham *et al.* 2018). The low-resolution empirical study presented here assembled field data on the mineral-nutrient and aluminium (Al) concentrations in floodplain and riparian eucalypt foliage, and their host soils. Sampling from a vast area incorporating lowland sites across the MDB and an area outside was made possible by opportunistically collaborating with a network of researchers and seeking samples from their field sites. These sites were being studied for a variety of research objectives outside the scope of this present study. The sampling area also consisted of regions underlain by groundwater salinised through the complex interaction of several contributing factors (Herczeg *et al.* 2001). The objectives of this study were to (a) measure tree nutrition and soil chemistry by paired samplings of leaves and soils to identify new methods by which to inform water-management strategies, (b) compare foliage elemental concentrations for each tree species at different geographic locations, and (c) interpret field soil data obtained here against a surface-soil map of the regions studied.

Materials and methods

Paired plant and soil samples were accessed from locations 2–9 within the MDB, and two external locations 1 and 2 (Fig. 3 and Table 1) between May 2017 and July 2018. The latter sites in the Lake Eyre Drainage Basin were included to incorporate geographic outliers to the MDB, and additional *E. coolabah* trees, a species, whose distribution skirts the far northern MDB (Fig. 2*c*). As a great majority of these sites were already in use for a variety of research projects (Fig. 4), their inclusion in this present study enabled access to empirical sampling data from a wide geographic area otherwise unlikely to be investigated solely for the purposes of gathering tree nutritional and soil chemical data. The sites were grouped such that locations 1 and 2 were on the Diamantina River, locations 3–5 on the Murray River, locations 6–8 on the Murrumbidgee and Lachlan Rivers, and locations 9 and 10 in the Darling River. At each location, 10–20 mature leaves were collected from at least one of the tree species *E. largiflorens* (n = 57), *E. camaldulensis* (n = 40) and *E. coolabah* (n = 24). For each tree sampled, a paired soil sample was collected from the top 10-cm horizon within the dripline of that tree, by pooling 3–5 replicates. Leaves were collected in paper bags, and soil placed in plastic zip-lock bags. All samples were oven dried prior to being analysed as described by Fernando *et al.* (2018). For each leaf element, tissue-concentration data across species and sites were statistically examined for significant differences (P = 0.05) using one-way ANOVA and the *post hoc* Hochberg's GT2 test. Variance was assumed to be equal. Two-way ANOVA was used to test for significant species and site effects on leaf elemental concentrations (P = 0.05). Calculations were undertaken using SPSS (ver. 27, IBM Corporation, New York, NY, USA).

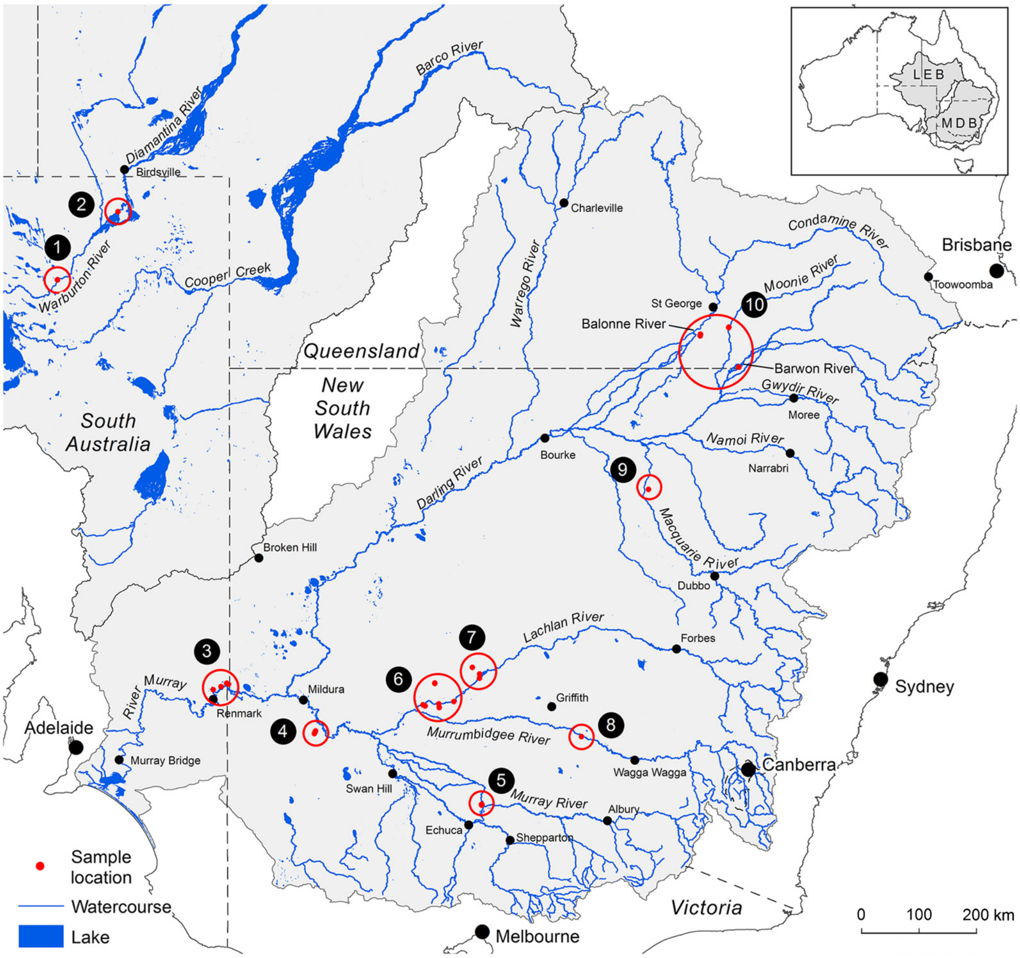

Fig. 3. Field sampling locations across the Murray–Darling Basin and Lake Eyre Drainage Basin. Sites 1 and 2 are grouped and referred to as the Diamantina Basin sites; sites 3–5 are referred to as the Murray Basin sites; sites 6–8 are referred to as the Murrumbidgee–Lachlan Basin sites; 9 and 10 are referred to as the Darling Basin sites.

Results

Soil composite maps of the study regions (Fig. 5) depict natural clay content shown here to vary between ~5 and 67% down to 1–2-m depths, and 11 soil classes. According to these data, soil clay content on the Murray (3–5) and Diamantina (1, 2) sites are the lowest of all sites, with soil types similar within each group, and differing between them. The most notable difference in soil clay content was between the Murray–Diamantina soils and the Murrumbidgee–Lachlan soils (6–8) that are similar within each of those groups. The Darling sites (9, 10) have medium to high clay content and similar soil types.

In general, average total soil Al concentrations (Tables 2–5) were higher in the Murrumbidgee–Lachlan (22 671 ± 1339) and Darling (20 691 ± 1137) basins than in the Murray (7093 ± 1339) and Diamantina (11 217 ± 1209) basins. Soil pH in each of the four river-basin datasets ranged from strong-moderately acidic, to moderately alkaline values of pH 4.70–7.50 in the Murray basin, pH 5.15–8.39 in the Murrumbidgee–Lachlan basin, pH 4.83–7.79 in the Darling basin, and, pH 5.97–7.97 in the Diamantina basin.

The leaf elemental concentration data (Fig. 6 and 7) showed some variation in the macronutrients P (P = 0.78), K ($P < 0.001$), S ($P < 0.05$) Mg ($P < 0.01$) and the beneficial element Si ($P = 0.92$) (Fig. 6) across all species and sites, with Ca concentrations in *E. coolabah* in the Diamantina basin sites and *E. largiflorens* in the Murray sites higher than those of all other trees studied ($P < 0.001$). Foliage micronutrient and Al concentration data (Fig. 7) suggest that for each species there was greater geographic and species-related variation compared with that of leaf macronutrients (Fig. 6). Foliar B concentrations were highest in *E. coolabah* ($P < 0.001$). Leaf Na concentrations among the three species were significantly different ($P < 0.05$) such that *E. largiflorens* > *E. camaldulensis* > *E. coolabah*. Foliar-Mn concentrations were generally elevated well above known plant nutritional requirements (Marschner 2002). Murray basin

Table 1. Sampling locations and species sampled across the Murray–Darling Basin region.

Sample	Location and date	Site	GPS coordinates	*Eucalyptus* species	Sample	Location	Site	GPS coordinates	*Eucalyptus* species
1	1-Geranium	Cowarie Station	−27.6088, 138.3087	*E. coolabah*	39	6-Lower	Lake Ita	−34.30068	*E. camaldulensis*
2	May–June 2017			*E. coolabah*	40	Lachlan		144.29028	*E. camaldulensis*
3				*E. coolabah*	41	Valley			*E. camaldulensis*
4				*E. coolabah*	42	May–June 2017	Lake Ita Inlet	−34.24554	*E. largiflorens*
5			−27.6071, 138.3082	*E. coolabah*	43			144.28330	*E. largiflorens*
6				*E. coolabah*	44				*E. largiflorens*
7				*E. coolabah*	45		Nooran Lake	−34.27569	*E. camaldulensis*
8				*E. coolabah*	46			144.07100	*E. camaldulensis*
117	2-Birdsville	Andrewilla	−26.5405, 139.255	*E. coolabah*	47				*E. camaldulensis*
118	May–June 2017	Waterhole (on Clifton Hills Station)		*E. coolabah*	57	7-Upper	Cobb Highway	−33.77473	*E. camaldulensis*
119				*E. coolabah*	58	Lachlan Valley		144.92259	*E. camaldulensis*
120				*E. coolabah*	59	Valley			*E. camaldulensis*
121				*E. coolabah*	60	July 2018			*E. largiflorens*
108	3-Chowilla		−34.02123, 140.75107	*E. largiflorens*	61				*E. largiflorens*
109	November 2017		−33.93427, 140.98930	*E. largiflorens*	62				*E. largiflorens*
110			−33.93435, 140.98927	*E. largiflorens*	63		Booligal Station	−33.83970	*E. camaldulensis*
111			−33.92054, 140.96038	*E. largiflorens*	64			144.91968	*E. camaldulensis*
112			−33.92081, 140.96051	*E. largiflorens*	65				*E. camaldulensis*
113			−33.92093, 140.96008	*E. largiflorens*	66				*E. largiflorens*
114			−33.97206, 140.87244	*E. largiflorens*	67				*E. largiflorens*
115			−33.97223, 140.87214	*E. largiflorens*	68				*E. largiflorens*
116			−33.97231, 140.87177	*E. largiflorens*	69				*E. largiflorens*
9	4-Hattah	Hattah Kulkyne National Park	−34.69370	*E. largiflorens*	103				*E. camaldulensis*
10	July 2018		142.34210	*E. largiflorens*	104	8-Narrandera	Murrumbidgee River	−34.75485	*E. camaldulensis*
11				*E. largiflorens*	105	July 2018		146.52156	*E. camaldulensis*
12				*E. largiflorens*	106				*E. camaldulensis*
13				*E. largiflorens*	107				*E. camaldulensis*

(*Continued on next page*)

Table 1. (*Continued*).

Sample	Location and date	Site	GPS coordinates	*Eucalyptus* species	Sample	Location	Site	GPS coordinates	*Eucalyptus* species
14			−34.66660	*E. largiflorens*	70	9-Macquarie Marshes	Gibson Way, Muggenbah Creek	−30.88954	*E. camaldulensis*
15			142.35170	*E. largiflorens*	71			147.57153	*E. camaldulensis*
16				*E. largiflorens*	72	July 2018			*E. camaldulensis*
17				*E. largiflorens*	73				*E. camaldulensis*
18				*E. largiflorens*	74				*E. camaldulensis*
19			−34.70710	*E. largiflorens*	75				*E. coolabah*
20			142.33390	*E. largiflorens*	76				*E. coolabah*
21				*E. largiflorens*	77				*E. coolabah*
22				*E. largiflorens*	78				*E. coolabah*
23				*E. largiflorens*	79				*E. coolabah*
48	5-Mathoura	Edwards River	−35.81298	*E. camaldulensis*	80				*E. largiflorens*
49	July 2018		144.95982	*E. camaldulensis*	81				*E. largiflorens*
50				*E. camaldulensis*	82				*E. largiflorens*
51				*E. camaldulensis*	83				*E. largiflorens*
52			−35.81882	*E. camaldulensis*	84				*E. largiflorens*
53			144.95114	*E. camaldulensis*	85	10-Narran Lakes	Gore Highway	−28.45984, 148.38503	*E. largiflorens*
54			−35.82875	*E. largiflorens*	86			−28.45978, 148.38471	*E. largiflorens*
55			144.95443	*E. largiflorens*	87	August 2017		−28.46027, 148.38471	*E. largiflorens*
56				*E. largiflorens*	88			−28.48479, 148.37914	*E. coolabah*
24	6-Lower		−33.67204	*E. largiflorens*	89			−28.48540, 148.38091	*E. coolabah*
25	Lachlan	Tom's Lake	144.81074	*E. largiflorens*	90			−28.48542, 148.38092	*E. coolabah*
26	Valley			*E. largiflorens*	91			−28.48549, 148.38037	*E. camaldulensis*
27	May–June 2017		−34.20677	*E. largiflorens*	92			−28.48532, 148.38062	*E. camaldulensis*
28		The Ville	144.51955	*E. largiflorens*	93			−28.48532, 148.38066	*E. camaldulensis*
29				*E. largiflorens*	94		Thallon	−28.34922, 148.82870	*E. largiflorens*
30		Lake Tarwong	−33.91526	*E. camaldulensis*	95			−28.34871, 148.82873	*E. largiflorens*
31			144.22058	*E. camaldulensis*	96			−28.35617, 148.82328	*E. largiflorens*
32				*E. camaldulensis*	97		Mungindi, Macintyre River	−28.97464, 148.98142	*E. coolabah*
33			−33.92303	*E. largiflorens*	98			−28.97454, 148.98149	*E. coolabah*
34			144.22143	*E. largiflorens*	99			−28.97428, 148.98171	*E. coolabah*

(*Continued on next page*)

Table 1. (*Continued*).

Sample	Location and date	Site	GPS coordinates	*Eucalyptus* species	Sample	Location	Site	GPS coordinates	*Eucalyptus* species
35				*E. largiflorens*	100			−28.97627, 148.98372	*E. camaldulensis*
36			−34.25685	*E. camaldulensis*	101			−28.97629, 148.98331	*E. camaldulensis*
37		Lake Marool	144.03414	*E. camaldulensis*	102			−28.97613, 148.98401	*E. camaldulensis*
38				*E. camaldulensis*					

E. camaldulensis foliage (Fig. 7) accumulated the highest levels of Mn ($P < 0.001$), Fe ($P < 0.01$), Co ($P < 0.05$) and Al ($P < 0.01$), with significant species effects for foliar Zn ($P < 0.01$) and non-significant species effect for foliar Cu ($P = 0.12$). There were significant site effects for foliar Mn ($P < 0.001$), Fe ($P < 0.001$), Co ($P < 0.001$), Al ($P < 0.001$), Cu ($P < 0.05$), Zn ($P < 0.01$). Significant site-species interactions were detected for foliar Co ($P < 0.001$) and Al ($P < 0.01$).

Of note were foliage Na concentrations across all three eucalypts examined here (Fig. 7), with highest foliar Na concentrations of ~4500 mg kg^{-1} were observed for *E. largiflorens* ($P < 0.001$ Murray and Murrumbidgee Lachlan sites, $P < 0.01$ Darling sites), with maximum observed *E. camaldulesis* leaf-Na concentrations of ~2500 mg kg^{-1}, and lowest foliar Na concentrations of ~500 mg kg^{-1} recorded for *E. coolabah*.

Discussion

Empirical data from this study provide a static view of the nutritional status of three eucalypts native to several south-eastern Australian river catchments. Macronutrients, micronutrients, beneficial elements, and Al concentrations in foliage and in soil, as well as other soil traits were mapped on a geographic scale previously not undertaken for the region. The trade-off between the low resolution of this study and its large sampling area was considered worthwhile because enabled eucalypt mineral nutrition to be placed in broad ecological context to offer new insights warranting future detailed field research. The integration of plant and soil data was not meaningful due to cross-seasonal samplings and varying site-specific conditions of waterflows that can ultimately influence plant soil nutrient availability (CSIRO 1983; White 1997; Marschner 2002; Fernando *et al.* 2021*a*), although several noteworthy observations highlight lesser considered aspects of these riverine eucalypt tree–soil systems. For example, certain leaf nutrient concentrations appeared to be associated with species and geography. Soil chemical and physical properties, many of which underpin nutrient acquisition by trees, were found to be highly heterogeneous within and among the 10 field sites of varying soil types and clay content. Soil pH and redox potential are among key factors affecting nutrient availability to plants, and systems reliant on periodic flooding undergo changes associated with such events (Fernando *et al.* 2021*a*).

Comparison of foliage macronutrients obtained here (Fig. 6) against standard 'normal' plant nutrient values drawn from crop studies (Marschner 2002; Taiz *et al.* 2015) shows lower P and K concentrations in these eucalypts, comparable S concentrations, much higher Ca concentrations, comparable Mg levels, and relatively lower foliage Si concentrations. Published leaf nutritional data for eucalypts from field samples and forestry plantings show greater nutritional enrichment in the latter due to the application of fertilisers and other soil amendments (Judd *et al.* 1996). Overall, the macronutrient data for *E. largiflorens*, *E. camaldulensis*, and *E. coolabah* (Fig. 6) indicated 'normal' levels of P, K, S, and Mg assimilation (Marschner 2002) despite substantial variation in their soil type and chemistry, suggesting that these eucalypts are able to adequately access macronutrients from highly variable soils.

Most striking of the leaf micronutrient data (Fig. 7) were Na concentrations ranging between ~4500 and ~500 mg kg^{-1}, well exceeding standard plant nutritional requirements (Marschner 2002; Taiz *et al.* 2015), most notably in *E. largiflorens*. Greatly elevated foliar Na concentrations in *E. largiflorens* on the Murray, Murrumbidgee–Lachlan and Darling sites consistently and significantly exceeded those in *E. camaldulensis*, which in turn significantly exceeded those of *E. coolabah*, pointing to species-wide salt tolerance by each of these species by varying or mixed strategies given these trees co-occurred at many sites. Strategies adopted by plants for tolerating soil-available toxins such as excess salt and metals commonly include: (a) uptake and sequestration in above-ground organs (Baker 1981), for example excessive foliage salt accumulation; (b) storage in roots with no or partial translocation to above-ground parts; and (c) uptake exclusion at the root–soil interface. In this study, strategy (a) was apparent for *E. largiflorens* (Fernando *et al.* 2021*b*), whereas strategy (b) and (c) may be occurring for *E. coolabah*, and a combinations of the above strategies may

Fig. 4. Examples of field locations and trees sampled for this study: *Eucalyptus largiflorens* at Hattah Kulkyne National Park (*a*), *E. largiflorens* on a Lower Lachlan Valley site at Lake Ita (*b*), *E. camaldulensis* on a Murray Basin site on the Edwards River at Mathoura (*c*), *E. coolabah* on a site near Birdsville (*d*), *E. coolabah* on a Darling Basin site at Macquarie Marshes (*e*), an Upper Lachlan Valley site (*f*), *E. largiflorens* on an Upper Lachlan Valley site.

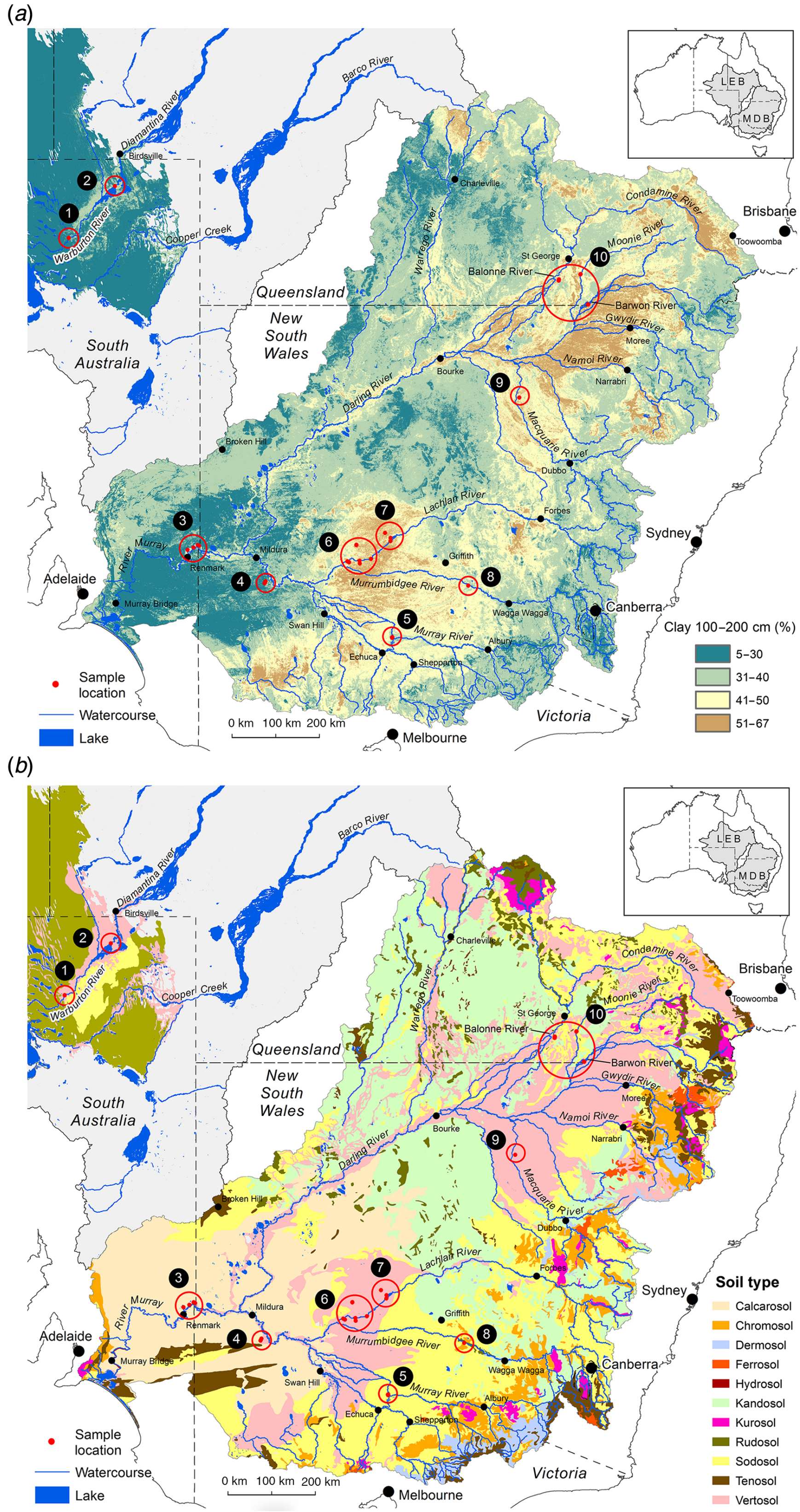

Fig. 5. Clay (above) and soil-type (below) distribution maps of field site locations 1–10. Generated from the Australian Soil Resource Information System (https://www.asris.csiro.au/index.html; Viscarra Rossel *et al.* 2014).

Table 2. Plant and soil analytical data for the Diamantina Basin sites.

Site	Sample number	Leaf data														Soil data												
		P (mg kg^{-1})	K (mg kg^{-1})	S (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Na (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	B (mg kg^{-1})	Co (mg kg^{-1})	Si (mg kg^{-1})	Al (mg kg^{-1})	pH	Conductivity (dS m^{-1})	Extr-Mn (mg kg^{-1})	C (%)	N (%)	C:N ratio	Zn (mg kg^{-1})	Mn (total; mg kg^{-1})	Al (total; mg kg^{-1})	Co (total; mg kg^{-1})	Ni (total; mg kg^{-1})	P (mg kg^{-1})
1	1	1802	6424	1360	21 033	4829	237	3.1	8.20	356	28	192	0.12	328	35	6.43	0.101	12	1.8	0.07	24	15	73	5620	2.6	3.8	139
	2	1265	7485	1240	13 760	2300	845	3.5	21	263	26	174	0.05	455	26	6.48	0.112	13	1.3	0.08	16	15	83	5898	2.8	3.8	139
	3	1636	8142	1350	18 116	2183	207	2.4	13	331	39	161	0.05	272	48	6.37	0.176	18	2.3	0.10	22	17	94	6831	3.3	4.4	169
	4	1917	9480	1250	19 282	2496	173	2.8	12	349	30	160	0.05	306	45	5.97	0.196	31	3.8	0.17	22	23	134	9748	4.5	6.2	256
	5	770	9468	1340	7319	2160	130	2.7	6.88	99	26	179	0.05	285	25	7.04	0.110	22	0.73	0.03	26	25	219	11 750	6.6	7.4	237
	6	1043	7503	1510	8428	2237	1066	1.9	6.91	161	37	131	0.05	323	40	7.17	0.068	9.0	0.47	0.00	NA	14	92	6132	3.0	4.0	138
	7	749	6625	1440	12 996	2987	142	2.1	8.20	202	41	144	0.05	350	43	6.78	0.087	17	1.6	0.07	22	23	143	10 027	4.7	5.9	205
	8	521	5883	1560	17 314	3715	302	2.6	8.35	152	23	118	0.05	320	33	6.81	0.085	19	1.6	0.10	16	32	216	14 697	6.8	8.6	282
2	117	757	4235	1080	10 995	3517	1098	3.6	18	102	37	102	<0.1	302	53	7.85	0.109	13	0.62	0.05	13	31	339	14 753	9.1	9.0	336
	118	840	7457	1260	10 960	2471	490	6.2	18	171	31	140	<0.1	280	41	7.97	0.123	20	0.84	0.05	16	31	340	14 406	9.0	9.5	339
	119	868	6549	1590	16 020	3335	194	4.4	13	186	48	222	<0.1	291	57	7.97	0.152	28	1.2	0.08	15	37	388	16 157	11	11	321
	120	518	6792	960	10 679	3279	<100	1.5	11	261	67	73	<0.1	283	38	7.80	0.173	20	1.7	0.09	18	24	247	10 836	7.2	7.5	307
	121	792	9585	1150	12 489	2890	<100	2.2	15	252	76	116	<0.1	338	34	6.30	0.254	50	6.3	0.27	24	39	247	18 971	8.2	12	355

Table 3. Plant and soil analytical data for the Murray Basin sites.

Site	Sample number	Leaf data														Soil data											
		P (mg kg^{-1})	K (mg kg^{-1})	S (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Na (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	B (mg kg^{-1})	Co (mg kg^{-1})	Si (mg kg^{-1})	Al (mg kg^{-1})	pH	Conductivity (dS m^{-1})	Extr-Mn (mg kg^{-1})	C (%)	N (%)	C:N ratio	Zn (mg kg^{-1})	Mn (total; mg kg^{-1})	Al (total; mg kg^{-1})	Co (total; mg kg^{-1})	Ni (total; mg kg^{-1})	P (mg kg^{-1})
3	108	872	5791	1570	14 171	3448	3691	4.9	17	336	129	61	0.14	537	227	6.10	0.258	51	8.7	0.46	19	35	282	13 627	6.1	12	433
	109	852	6494	1430	8282	3443	5118	3.8	12	330	69	70	0.11	502	73	6.02	0.239	40	10	0.49	21	40	249	16 415	5.8	13	328
	110	857	5094	1380	11 723	3241	3391	3.7	11	278	53	148	0.18	511	52	5.89	0.209	67	13	0.65	19	44	303	16 492	6.9	14	431
	111	1155	8468	1210	14 157	3251	5666	3.4	14	478	64	99	0.48	568	62	6.30	0.141	30	3.0	0.15	21	13	133	4730	2.0	4.2	181
	112	1639	6863	1510	20 388	4431	4753	4.2	14	575	69	108	0.30	487	65	6.98	1.493	33	2.9	0.17	17	14	144	4891	2.3	4.3	267
	113	1026	3781	1250	22 565	3645	4027	2.6	14	434	39	109	0.25	536	36	7.13	0.476	18	3.1	0.18	18	14	116	5375	2.5	4.9	213
	114	672	7097	1690	6039	2978	4581	7.7	17	332	74	39	0.70	509	101	7.40	0.098	14	2.5	0.16	16	22	226	7950	4.4	7.6	207
	115	739	5228	1640	10 131	3399	4395	9.0	19	659	67	47	0.75	557	101	7.50	0.212	14	4.3	0.27	16	30	281	10 324	4.8	7.4	323
	116	837	6440	1580	5056	2413	3532	7.5	16	386	60	45	0.73	528	94	7.18	0.135	20	3.7	0.23	16	26	256	8559	4.3	6.5	278
4	9	680	7483	1240	10 676	2476	4938	3.4	11	140	82	86	0.11	269	48	6.58	0.031	1.2	1.0	0.06	17	4.2	12	1890	0.4	1.3	2.3
	10	1010	8571	1420	10 147	2610	4364	4.1	15	145	67	51	0.12	267	38	6.31	0.034	1.2	0.95	0.06	16	4.0	11	2133	0.4	1.6	2.1
	11	801	6577	1410	8373	2609	3880	4.1	12	149	68	82	0.12	272	38	6.58	0.037	1.3	0.93	0.06	16	3.7	13	1833	0.3	1.3	2.9
	12	749	6212	1370	22 303	4186	3463	3.0	15	250	89	90	0.24	294	57	6.35	0.047	1.7	1.1	0.07	17	4.0	14	1919	0.4	1.4	3.0
	13	838	5175	1530	19 236	3803	5776	3.6	19	166	66	87	0.03	301	51	6.59	0.046	1.3	1.1	0.06	18	3.5	12	2117	0.4	1.6	2.2
	14	931	7027	1380	13 257	1787	5750	2.0	7.8	66	63	115	0.12	292	45	6.28	0.039	1.9	1.3	0.06	23	4.7	16	2233	0.6	1.7	2.8
	15	811	6253	1440	6326	1821	5317	2.0	28	54	62	106	0.11	276	42	6.33	0.032	1.7	1.0	0.06	18	4.5	12	2568	0.5	1.7	5.2
	16	724	7748	1500	7429	2207	4321	3.6	8.0	45	66	96	0.10	255	56	6.40	0.033	1.4	0.91	0.04	21	3.9	12	2291	0.4	1.5	3.9
	17	886	8919	1340	12 453	2914	4730	3.4	14	68	73	96	0.16	310	68	6.51	0.048	1.5	0.95	0.05	19	3.8	13	2057	0.4	1.3	3.3
	18	842	7988	1330	12 012	2233	5991	2.6	23	77	87	131	0.05	295	66	6.85	0.038	1.0	1.0	0.04	25	4.0	12	2127	0.5	1.5	3.8
	19	973	5355	1340	14 799	2187	3493	3.6	17	134	59	159	0.09	299	58	6.57	0.056	1.1	1.1	0.06	19	4.1	12	2237	0.4	1.5	3.4
	20	948	8015	1410	13 849	2021	4412	4.4	11	142	39	114	0.13	302	90	6.41	0.057	2.5	1.8	0.10	18	8.3	20	3711	0.8	3.0	3.9
	21	920	4191	1350	13 298	2328	3820	2.3	14	108	65	119	0.17	286	54	6.61	0.050	2.2	0.98	0.05	21	3.9	16	1517	0.4	1.4	2.5
	22	907	5974	1620	13 750	2758	4665	2.3	11	113	57	109	0.04	306	46	6.65	0.050	2.2	1.3	0.06	21	5.0	21	1778	0.4	1.6	4.3
	23	1944	7304	1440	12 386	1836	3275	3.8	16	68	58	138	0.06	276	49	6.47	0.044	2.0	1.3	0.08	17	7.8	18	3287	0.6	2.5	4.7
5	48	1125	5075	1480	6725	2313	1980	6.7	11	618	239	23	0.16	358	326	6.97	0.205	73	4.0	0.30	13	26	2112	17 169	5.1	8.6	272
	49	935	2975	1293	6550	2183	1135	8.2	15	708	162	42	0.24	296	217	6.92	0.111	37	2.4	0.19	12	22	1560	9918	4.4	7.3	182
	50	968	5100	1208	4500	1918	2040	4.8	14	440	136	13	0.24	318	187	6.09	0.107	65	4.0	0.26	15	22	750	7522	4.3	7.7	169
	51	1145	3325	1685	6300	1858	2023	4.4	17	410	182	44	1.61	283	285	6.72	0.118	47	2.1	0.15	14	18	559	6487	4.8	6.2	154
	52	858	3100	1420	4675	1198	1313	5.6	12	633	106	37	0.46	293	162	6.51	0.166	60	4.6	0.34	14	47	879	41 214	9.1	17	164
	53	1483	3175	1523	8625	1875	1365	2.8	25	890	119	61	2.52	337	225	6.86	0.134	29	3.7	0.23	16	22	381	8866	4.9	7.9	193
	54	910	7625	1055	6950	1823	468	1.2	20	423	268	82	0.13	286	325	6.14	0.122	14	3.1	0.25	13	25	215	9413	2.1	6.3	263
	55	1048	8700	978	4500	2018	375	3.2	18	618	172	36	0.10	440	262	4.71	0.136	13	2.1	0.18	12	17	117	7241	1.8	5.3	230
	56	1288	12 700	975	7475	2725	383	2.4	22	903	168	41	0.09	272	285	4.69	0.190	31	2.4	0.18	13	13	91	4177	1.2	3.7	199

Table 4. Plant and soil analytical data for the Murrumbidgee–Lachlan Basin sites.

Site	Sample number	Leaf data														Soil data											
		P (mg kg^{-1})	K (mg kg^{-1})	S (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Na (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	B (mg kg^{-1})	Co (mg kg^{-1})	Si (mg kg^{-1})	Al (mg kg^{-1})	pH	Conductivity (dS m^{-1})	Extr-Mn (mg kg^{-1})	C (%)	N (%)	C:N ratio	Zn (mg kg^{-1})	Mn (total; mg kg^{-1})	Al (total; mg kg^{-1})	Co (total; mg kg^{-1})	Ni (total; mg kg^{-1})	P (mg kg^{-1})
6	24	1426	7307	1280	10 746	2377	2519	3.4	16	152	16	48	0.12	251	29	6.88	0.194	16	2.4	0.17	14	53	245	26 249	9.1	17	311
	25	1226	9412	1200	7921	2168	3660	4.8	16	164	24	54	<0.1	233	31	6.88	0.140	12	1.4	0.12	12	42	222	22 730	8.5	16	242
	26	816	5226	1050	9932	1961	3621	3.8	9.7	173	25	51	0.22	260	25	6.33	0.386	44	6.8	0.47	14	44	198	20 598	7.2	16	472
	27	1568	6511	1040	8251	1910	2081	2.2	13	40	31	53	<0.1	245	30	7.07	0.254	28	5.0	0.35	14	51	299	29 510	9.5	24	488
	28	824	6523	1150	8737	2203	3408	2.6	10	55	39	44	<0.1	252	37	7.62	0.203	22	2.5	0.21	12	39	304	20 897	8.1	17	422
	29	953	6891	1160	9995	2430	3454	3.2	14	52	22	50	0.12	256	28	7.08	0.218	17	2.4	0.21	12	52	365	31 222	12	24	342
	30	952	7133	1150	7737	2543	1972	5.5	12	88	39	63	<0.1	303	39	7.52	0.424	60	5.3	0.43	12	42	262	20 821	5.9	14	1350
	31	845	5658	1200	7139	2094	1251	3.7	11	75	35	50	<0.1	255	37	7.59	0.383	48	5.2	0.43	12	47	262	23 173	6.2	15	1253
	32	1059	7368	1330	5705	1820	1965	3.2	17	108	29	35	<0.1	288	21	7.00	0.615	64	15	1.06	14	44	228	16 149	4.6	14	1134
	33	945	5318	1090	11 245	2269	3937	4.7	9.4	75	17	35	<0.1	262	23	7.03	0.437	26	5.4	0.43	12	50	259	30 240	8.8	21	466
	34	1014	6885	1270	8086	2189	3349	3.3	9.5	56	58	36	<0.1	251	16	7.24	0.386	18	4.2	0.31	14	43	218	26 298	7.7	20	327
	35	717	4892	1070	10 136	1742	3585	2.7	5.7	59	37	34	<0.1	256	26	6.73	0.503	25	5.9	0.44	13	55	243	34 900	8.7	23	484
	36	947	7221	1270	4288	2026	2064	3.9	13	108	42	56	<0.1	291	44	6.29	0.499	39	10	0.75	14	47	196	26 043	6.3	18	661
	37	1125	8083	1700	3752	2340	1886	4.8	17	82	41	99	<0.1	300	35	6.37	0.249	29	6.6	0.58	12	50	197	28 675	6.9	21	583
	38	1012	6096	1230	11 193	2799	2773	3.5	12	193	30	179	<0.1	344	55	8.39	0.395	25	2.5	0.22	11	39	342	23 387	7.2	21	367
	39	775	6422	1130	8143	2271	3560	1.8	6.6	84	14	52	<0.1	279	26	7.60	0.474	73	8.5	0.54	16	42	207	26 167	6.8	18	483
	40	732	5447	1100	6337	2129	2182	1.4	8.7	41	22	35	<0.1	286	26	7.99	0.467	16	2.8	0.25	11	44	183	26 799	7.4	20	382
	41	865	6594	1210	7286	1995	2239	4.2	9.1	53	29	23	<0.1	289	33	7.38	0.610	60	12	0.79	15	51	223	27 104	7.0	19	651
	42	712	6118	1060	8244	3646	4070	3.3	11	73	18	35	<0.1	287	25	8.00	0.535	22	2.2	0.20	11	45	324	28 695	8.9	20	267
	43	981	6541	1170	8456	3229	3123	4.6	11	57	18	34	<0.1	274	32	7.70	0.172	11	1.4	0.14	10	42	245	28 700	9.2	21	185
	44	794	5601	1210	8240	3014	4753	4.3	12	63	18	52	0.12	258	25	7.68	0.490	16	0.01	0.01	1.7	43	225	29 347	8.2	20	230
	45	894	6009	1380	11 701	3281	2945	3.0	10	79	44	166	<0.1	328	45	7.55	0.426	33	8.7	0.69	13	45	249	25 691	6.9	20	703
	46	874	5025	1480	11 111	3913	2624	2.0	6.6	55	39	229	<0.1	357	47	7.06	0.360	12	3.9	0.37	11	38	133	24 161	6.3	20	320
	47	1034	6788	1660	12 935	4815	1362	2.7	12	159	37	188	<0.1	349	43	7.48	0.273	14	3.5	0.32	11	42	153	24 040	6.6	20	321
7	57	673	4275	1453	6825	2500	1878	2.0	13	163	197	126	0.06	348	179	7.64	0.220	6.9	1.4	0.09	16	15	160	5367	2.6	5.2	207
	58	683	3250	1455	10 175	2078	1170	1.5	11	260	133	157	0.09	292	159	6.28	0.080	4.1	0.73	0.06	12	9.4	106	4144	1.1	3.5	96
	59	728	4575	1580	9300	1638	1465	1.7	6.2	233	206	217	0.09	367	224	6.38	0.177	6.2	0.92	0.10	9.2	10	124	5371	1.6	4.1	107
	60	768	3375	1165	8425	2110	1970	1.5	9.4	300	167	126	0.15	165	97	6.01	0.053	2.3	0.41	0.04	10	10	103	4965	1.2	4.2	115
	61	803	3750	955	10 900	2260	2750	2.4	10	325	119	104	0.12	224	117	5.15	0.036	1.4	0.32	0.03	11	7.5	108	3363	1.3	3.4	104
	62	520	4075	973	8050	2060	3025	0.9	9.2	181	68	103	0.15	247	91	5.86	0.103	3.8	0.44	0.05	8.8	15	118	7513	2.6	6.0	153
	63	693	3625	1588	5750	1233	2575	2.6	10	340	116	142	0.08	349	162	5.73	0.142	38	4.6	0.32	14	99	371	27 640	6.4	15	192
	64	718	3525	1608	7050	2043	1790	4.0	18	176	157	158	0.15	386	251	6.28	0.136	34	3.3	0.25	13	47	566	37 871	7.2	16	173
	65	590	2725	1483	4725	1370	2825	2.1	6.4	285	141	58	0.18	581	212	6.12	0.124	14	2.3	0.15	15	17	169	4981	4.7	7.1	83

(*Continued on next page*)

Table 4. (*Continued*).

Site	Sample number	Leaf data														Soil data											
		P (mg kg^{-1})	K (mg kg^{-1})	S (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Na (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	B (mg kg^{-1})	Co (mg kg^{-1})	Si (mg kg^{-1})	Al (mg kg^{-1})	pH	Conductivity (dS m^{-1})	Extr-Mn (mg kg^{-1})	C (%)	N (%)	C:N ratio	Zn (mg kg^{-1})	Mn (total; mg kg^{-1})	Al (total; mg kg^{-1})	Co (total; mg kg^{-1})	Ni (total; mg kg^{-1})	P (mg kg^{-1})
	66	675	3850	1528	6900	2525	2875	2.5	14	194	122	87	0.07	315	184	7.36	0.361	32	3.1	0.28	11	46	535	23 856	6.4	16	318
	67	653	3525	1510	9925	1350	4225	4.0	18	164	140	92	0.16	322	207	6.78	0.233	31	4.2	0.33	13	46	416	21 410	6.0	20	306
	68	613	3950	968	3825	1225	2625	1.6	9.9	119	89	30	0.08	253	139	7.76	0.319	9.0	3.9	0.29	13	40	534	26 653	6.1	15	309
	69	643	3050	1278	9725	2450	1730	2.3	25	338	87	74	0.11	238	118	7.18	0.211	17	3.8	0.36	10	41	587	22 166	6.9	13	374
8	103	873	4350	1300	4350	1465	1605	3.3	12	240	80	18	0.46	229	121	6.75	0.266	58	2.9	0.26	11	70	591	24 743	9.8	26	340
	104	995	4425	1450	6825	1908	1353	4.1	15	973	122	27	0.33	301	186	6.09	0.118	52	3.2	0.25	13	69	470	22 751	6.6	21	242
	105	1333	4925	1530	3825	1805	2475	6.2	18	210	135	17	0.29	238	141	6.56	0.146	86	2.3	0.19	12	66	1870	33 936	11	23	388
	106	905	3850	1288	4225	1755	2080	3.5	12	163	100	14	0.07	226	147	6.79	0.240	96	4.4	0.32	14	55	1326	24 535	9.8	22	335
	107	883	4475	1550	3650	1583	2415	4.6	16	151	94	18	0.14	398	136	5.84	0.118	82	3.8	0.30	13	67	648	29 317	8.7	26	321

Table 5. Plant and soil analytical data for the Darling Basin sites.

Site	Sample number	Leaf data														Soil data											
		P (mg kg^{-1})	K (mg kg^{-1})	S (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Na (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	B (mg kg^{-1})	Co (mg kg^{-1})	Si (mg kg^{-1})	Al (mg kg^{-1})	pH	Conductivity (dS m^{-1})	Extr-Mn (mg kg^{-1})	C (%)	N (%)	C:N ratio	Zn (mg kg^{-1})	Mn (totat; mg kg^{-1})	Al (total; mg kg^{-1})	Co (total; mg kg^{-1})	Ni (total; mg kg^{-1})	P (mg kg^{-1})
9	70	838	3400	1598	6200	2073	1725	2.9	11	625	102	54	0.10	185	84	5.66	0.176	57	4.2	0.31	13	51	389	28 553	6.6	19	230
	71	695	2550	1348	8350	2440	723	2.1	14	823	62	56	0.38	164	63	5.19	0.178	64	4.0	0.33	12	42	407	27 912	6.4	14	234
	72	538	3275	1445	4925	2248	1413	1.2	8.8	473	114	46	0.09	205	73	5.18	0.145	124	2.6	0.21	12	48	667	30 006	8.6	17	235
	73	530	2700	1403	8825	1733	1160	2.1	9.8	405	194	73	0.11	414	197	4.83	0.209	56	9.5	0.63	15	56	475	32 717	8.0	19	274
	74	585	3100	1185	7000	1363	1935	2.2	18	211	91	131	0.07	248	126	5.84	0.130	82	4.0	0.33	12	54	655	32 120	8.0	20	405
	75	848	6275	1590	8600	2625	458	3.0	16	189	118	101	0.05	288	177	6.04	0.161	46	2.3	0.20	12	33	420	16 473	5.1	16	290
	76	580	3950	1535	7450	1858	370	1.5	10	121	108	82	0.06	227	164	6.57	0.084	19	1.8	0.17	11	57	495	16 362	6.0	17	313
	77	825	7200	1460	5625	1618	295	2.0	12	127	74	68	0.03	164	75	5.88	0.138	55	2.2	0.19	12	40	672	22 305	7.5	16	314
	78	878	8200	1468	5600	2258	288	2.1	11	161	77	59	0.03	205	102	5.78	0.078	51	1.9	0.19	10	41	797	25 132	8.0	16	246
	79	578	4400	2085	13 075	3400	373	2.1	7.4	278	137	182	0.06	279	186	6.16	0.163	39	2.1	0.19	11	41	710	21 360	8.1	35	269
	80	638	2850	1713	11 350	1840	1670	1.8	9.4	263	129	171	0.06	253	158	7.14	0.564	42	1.8	0.19	9.4	32	494	14 338	5.9	16	303
	81	535	3725	1220	5625	1298	3025	4.0	8.6	235	89	90	0.24	266	129	7.79	0.209	3.6	1.3	0.13	10	37	503	22 044	6.4	54	224
	82	800	2575	1565	5950	1923	915	1.3	13	159	116	125	0.05	233	138	7.39	0.261	11	2.0	0.19	11	37	478	22 114	5.7	15	265
	83	695	8350	1478	7400	2273	763	2.9	16	156	102	52	0.09	242	149	7.46	0.212	8.2	3.2	0.29	11	41	607	27 446	6.4	17	291
	84	803	5575	1563	5950	2370	1795	5.1	13	187	69	56	0.06	169	97	6.80	0.121	18	2.4	0.21	11	31	394	14 322	5.1	13	318
10	85	598	3325	1470	4800	1940	1930	3.1	32	1810	144	74	0.39	474	207	7.23	0.159	50	3.4	0.29	12	27	1318	15 166	9.5	13	334
	86	615	5675	1533	2850	1378	6100	4.4	17	408	59	53	0.62	303	65	6.64	0.126	51	2.5	0.24	10	32	1253	16 133	8.8	14	330
	87	593	3000	1305	4225	2428	3050	3.9	29	783	48	46	0.47	392	75	6.47	0.040	37	2.1	0.22	10	32	1317	15 783	9.2	13	379
	88	758	2725	1438	9625	3250	3050	2.3	12	1108	106	148	0.17	348	153	6.57	0.237	32	4.5	0.31	14	37	760	19 129	6.0	11	314
	89	789	9400	1546	6988	2938	1041	2.2	9.4	553	61	136	0.06	361	64	5.81	0.074	50	2.7	0.24	11	36	591	15 272	6.2	11	289
	90	825	7025	1663	7475	2453	1218	1.6	6.8	313	55	141	0.06	298	43	7.22	0.428	31	4.9	0.36	14	40	796	21 570	6.6	13	438
	91	1288	5100	1525	2460	1138	1860	4.5	13	528	123	62	0.15	454	134	5.74	0.045	40	1.8	0.17	10	30	566	16 132	6.2	9.9	228
	92	1128	3325	1368	8725	2550	1023	3.5	30	3100	150	78	0.46	489	87	5.86	0.056	32	1.5	0.12	12	22	355	10 315	4.6	8.0	158
	93	1115	3175	1350	6800	1035	1323	2.9	23	1435	75	83	0.09	380	71	5.72	0.031	19	1.5	0.16	10	17	295	6875	3.5	5.4	123
	94	653	3900	1293	4225	1923	3600	2.8	16	378	155	79	0.66	374	285	6.60	0.162	32	0.8	0.07	11	33	1437	29 235	15	11	245
	95	638	5300	1365	9475	3150	3100	7.8	26	465	130	75	0.58	311	241	6.38	0.216	90	2.5	0.25	10	30	1143	20 491	12	9.0	338
	96	838	4150	1355	4475	2950	2625	3.9	21	713	103	132	0.57	367	215	6.57	0.084	24	1.7	0.15	11	31	1437	13 005	17	9.2	353
	97	1075	9275	1750	6675	2600	395	4.8	8.8	173	87	257	0.32	431	139	6.64	0.126	13	1.3	0.12	11	32	653	22 125	8	15	207
	98	760	6700	1818	5175	2625	298	3.9	7.6	253	77	180	0.52	389	127	6.09	0.076	24	1.0	0.12	8.5	33	802	22 467	10	15	187
	99	695	5350	1520	4750	2395	1363	6.1	11	138	135	51	0.22	353	229	6.59	0.132	10	1.2	0.14	8.6	35	1794	27 957	17	18	203
	100	1048	6825	1405	6400	2625	830	4.6	11	315	119	45	0.10	307	221	5.88	0.155	61	2.2	0.18	12	19	478	13 226	3.9	6.6	190
	101	958	3825	1388	3175	1788	2108	5.5	10	295	138	51	0.19	341	237	5.68	0.164	112	3.4	0.27	13	25	960	19 222	6.6	11	229
	102	1095	4525	1413	4225	2345	2175	7.7	18	463	156	33	0.10	197	326	6.52	0.112	30	1.8	0.15	12	25	1109	25 504	7.3	12	253

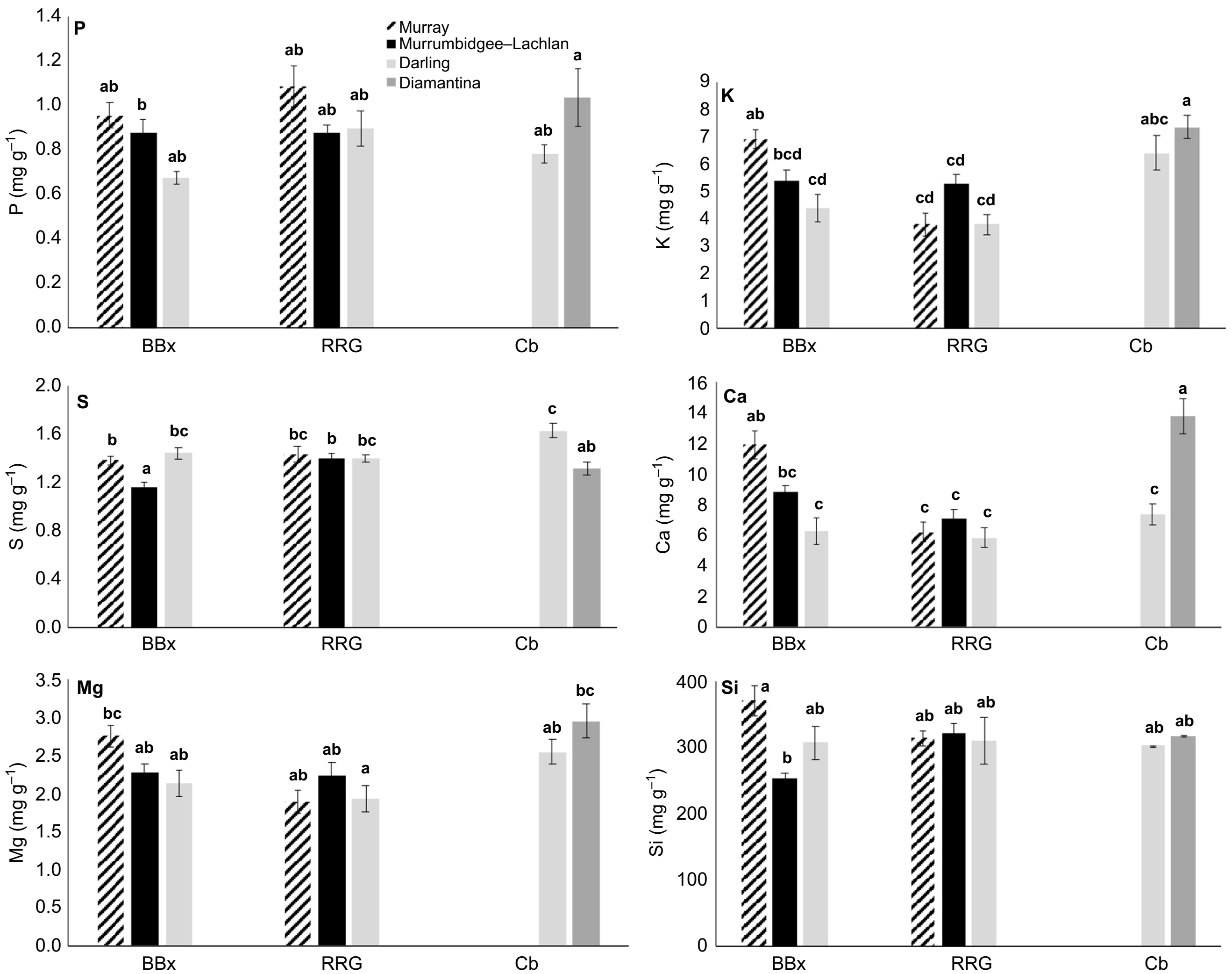

Fig. 6. Leaf (dry weight) concentrations of P, K, S, Ca, Mg (mg g^{-1}) and Si (mg kg^{-1}) grouped by tree species (BBx, Black Box (*Eucalyptus largiflorens*); RRG, River Red Gum (*E. camaldulensis*); Cb, Coolabah (*E. coolabah*)) sampled from the Murray, Murrumbidgee–Lachlan, Darling, Lachlan and Diamantina basins. Different letters above bars a, b, c denote significant differences ($P < 0.05$).

apply for *E. camaldulensis*. Recent studies of *E. largiflorens* on the Hattah Lakes system in the Murray basin (Fernando *et al.* 2018, 2021*a*) detected extremely high foliar Na concentrations, whereas its localised hybrid on the Chowilla Floodplain has already been noted for exceptional salt tolerance (Zubrinich *et al.* 2000; Koerber *et al.* 2013). *Eucalyptus camaldulensis* is known to harbour foliage Na concentrations as high as 1900 mg kg^{-1} (Hulme 2010). All three tree species in this present study are known to variously tolerate soil and groundwater salinity at specific locations (Roberts and Marston 2011), whereas isotope studies have demonstrated incidental salinity tolerance (Poss *et al.* 2000; Akeroyd *et al.* 2003; Costelloe *et al.* 2008). Species-wide salt tolerance by these eucalypts is consistent with adaptation to the presence of naturally saline groundwaters (Herczeg *et al.* 2001). There is evidence that in general, adventitious roots of eucalypts can occur close to the soil surface, enabling shallow access to water and nutrients (Robinson *et al.* 2006).

Past experiments and field studies of a wide range of western and eastern Australian eucalypts other than the focal species of this present study have examined salinity and waterlogging tolerance (van der Moezel *et al.* 1991; Marcar 1993; Adams *et al.* 2005; Woodward and Bennett 2005). They included exposing propagated plants to conditions of waterlogging and salt treatments to examine the interaction of stress effects, the association between foliar osmolytes and salt tolerance, and the effects of salt treatment on leaf content of abscisic acid, proline, and chlorophyll. An evaluation of how groundwater salinity interpreted by leaf-Na accumulation in *E. largiflorens* and *E. camaldulensis* (McLennan *et al.* 2013) found Na concentrations as high as 7300 mg kg^{-1}. The canopy condition of *E. camaldulensis* and *E. coolabah* has previously been

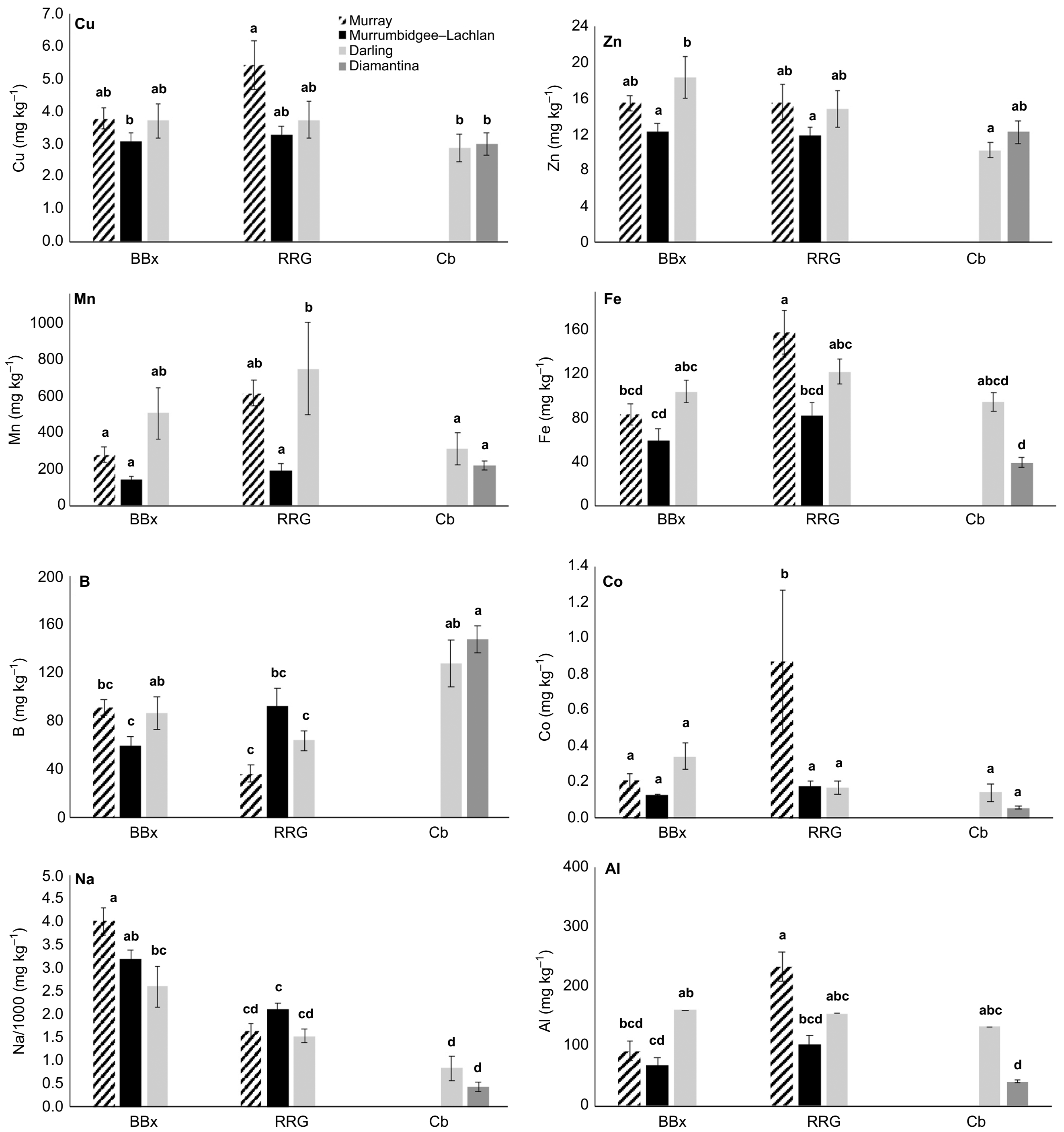

Fig. 7. Leaf (dry weight) concentrations of Cu, Zn, Mn, Fe, B, Co, Na and Al (mg kg^{-1}) grouped by tree species (BBx, Black Box (*Eucalyptus largiflorens*); RRG, River Red Gum (*E. camaldulensis*); Cb, Coolabah (*E. coolabah*)) sampled from the Murray, Murrumbidgee–Lachlan, Darling, –Lachlan and Diamantina basins. Different letters above bars a–d denote significant differences ($P < 0.05$).

observed to go into decline when exposed to substrate salinity greater than 30 000 µSv (Overton *et al.* 2006; Payne *et al.* 2006; Costelloe *et al.* 2008). However, *E. largiflorens* trees are known to tolerate soil salinity levels as high as 55 000 µSv (Slavich *et al.* 1999; Overton *et al.* 2006). A recent a study of *E. largiflorens* at Hattah Lakes showed gradual lowering of foliar-Na concentrations across the flooding period, with a steep increase in foliar-Na after water levels had subsided (Fernando *et al.* 2021*a*). These findings suggest that the species tolerates high salinity substrates by foliage Na overaccumulation while potentially being able to 'dilute' concentrated leaf-Na upon surface inundation. Further detailed temporal studies are required to investigate the utility of such measurements in informing environmental flow management. These recent findings on salt-accumulating Hattah Lakes *E. largiflorens* trees led to application of SEM-EDS and XRF analytical microprobe techniques, which established that Na and Cl were strongly accumulated in leaf cell vacuoles of *E. largiflorens*, thus pointing to a likely salt tolerance strategy (Fernando *et al.* 2021*b*).

There currently are no guidelines for trace nutrient concentrations in *Eucalyptus* foliage, and comparison of field data here (Fig. 7) with standard plant nutritional data (Marschner 2002; Taiz and Zeiger 2002) suggests much higher Mn values in the field samples, comparable Fe levels, and higher foliage B concentrations in these three eucalypts. In glasshouse experiments *E. camaldulensis* has been shown to have the capacity to strongly accumulate metals including micronutrients, often to levels well above their known nutritional requirements (Marschner 2002; Reichman *et al.* 2004, 2006). For example, dosing trials of juvenile *E. camaldulensis* trees by Reichman *et al.* (2004) showed foliar Mn accumulation as high as 7000 mg kg^{-1}, around sevenfold higher than concentrations observed in the present field dataset (Fig. 7). Foliar Cu accumulation in *E. camaldulensis* was similarly induced (Reichman *et al.* 2006) to around tenfold the maximum field data values observed here. Other growth experiments have found strong Pb accumulation by this species (Nawazi *et al.* 2016). Field studies of *E. camaldulensis* on ore deposits near Broken Hill at the north-western end of the MDB (Fig. 3) showed Zn, Pb, Ag, As and Au accumulation in foliage, suggesting that it may serve as an indicator species for undiscovered metal deposits (Hulme and Hill 2005). Although controlled experiments on plant uptake can induce responses not observed in the field, leaf micronutrient and Al data obtained in this study suggest *E. camaldulensis* trees sampled in the Murray and Darling basins in particular have a high capacity to accumulate foliar Cu, Zn, Mn, Fe, Co and Al (Fig. 7).

Plant acquisition of micronutrients from soil can be affected by several factors, which are often in dynamic states with the capability of interacting mutually (Leeper and Uren 1997; White 1997). Soil pH is one of these. It can be driven by wetness, microbial activity, plant root exudation, for example (Graham *et al.* 1988; Leeper and Uren 1997; White 1997; St Clair and Lynch 2004, 2010). The effect of soil pH on the plant bioavailability of micronutrients is generally more pronounced compared to that of macronutrients, particularly for plant acquisition of micronutrients whose accessibility increases with soil acidity (White 1997), although there are some recent examples to the contrary (Lambers and Oliveira 2019). The net effects of drivers of soil pH can expose a plant to a toxic or deficient supply of multiple micronutrients ions or non-nutrient metal ions, depending on the element, and the plant species or phenotypic response. Here, soil acidity within each of the four basin systems was highly variable given their soil pH values ranged from strongly acidic (down to pH ~4–5.5), through moderately acidic (pH ~5.5–6.5), neutral (pH ~6.5–7.5), to moderately alkaline (pH ~7.5–8.5) (Leeper and Uren 1997). Given these values represent a single sampling, and that it is possible that soil pH fluctuates with environmental conditions, the values obtained here may not strictly represent pH of corresponding soil solutions *in situ*. Nevertheless, they capture variation that warrants consideration when formulating management strategies tailored for local conditions. The net effects of the fluctuating accessibility to trees of various nutrients and other elements in soil requires continuous sampling and analysis.

The distribution patterns of soil clay content down to 1–2-m depth as mapped for this study (Fig. 5) should be interpreted as being highly generalised given that soil composition is commonly spatially heterogenous at a smaller scale than depicted here (CSIRO 1983; Leeper and Uren 1997; White 1997). The well documented association of Al with clays due to their aluminosilicate mineralogy was evident in this study (CSIRO 1983; Leeper and Uren 1997; White 1997). Highest total soil–Al concentrations (Tables 2–5) were detected in the Murrumbidgee–Lachlan and Darling sites that were broadly mapped here as having highest soil clay contents (Fig. 5). These soil clay maps (Fig. 5) do not capture capping clays of varying thickness overlaying sandy soils and lacustrine sediments on the Chowilla floodplain (site 9) in the Murray Basin (Fig. 3) (Overton and Jolly 2004; Overton *et al.* 2006; Overton and Doody 2010).

Notwithstanding the coarseness of this study and its one-off sampling approach that precluded measurement of tree–soil interactions, it highlights inherent heterogeneity in biotic and abiotic variables central to tree condition. An improved theoretical understanding of localised variation may ultimately benefit tree health in the longer term by better informing management strategies. Although further detailed work is clearly necessary for knowledge gathering on many fronts including tree phenotypic variation, soil chemistry and soil biota, extracting such empirical data is time-consuming, expensive and impractical to undertake on an extensive scale. Acknowledgement of the complexity of these systems is needed, with attention to localised drivers of tree condition, particularly in the management of valuable water resources. Modelling data useful for assessing large areas (Cunningham *et al.* 2009, 2013) are currently insufficiently combined with or compared with complementary basic on-ground field data. Such considerations would aid resolution of different localised tree–soil nutritional dynamics, particularly with respect to soil chemical changes due to wetting and drying. This study supports the need for continuous field data-gathering to inform management decisions, while also offering insight into broader patterns of *in situ* nutrient acquisition by mature *E. largiflorens*, *E. camaldulensis* and *E. coolabah* trees, which warrant further investigation.

References

Adams MA, Richter A, Hill AK, Colmer TD (2005) Salt tolerance in *Eucalyptus* spp.: identity and response of putative osmolytes. *Plant, Cell & Environment* **28**, 772–787. doi:10.1111/j.1365-3040.2005.01328.x

Akeroyd MD, Tyerman SD, Walker GR, Jolly ID (1998) Impact of flooding on the water use of semi-arid riparian eucalypts. *Journal of Hydrology* **206**, 104–117. doi:10.1016/S0022-1694(98)00092-4

Akeroyd AD, Walker GR, Kendall MB (2003) Response of *Eucalyptus largiflorens* to floodplain salinisation. *Water Science and Technology* **48**, 113–120. doi:10.2166/wst.2003.0431

Baker AJM (1981) Accumulators and excluders – strategies in the response of plants to heavy metals. *Journal of Plant Nutrition* **3**, 643–654. doi:10.1080/01904168109362867

Bedinger MS (1979) 'Forests and flooding with special reference to the White River and Ouachita River basins, Arkansas'. (United States Geological Survey: Reston, VA, USA)

Bradley CE, Smith DG (1986) Plains cottonwood recruitment and survival on a prairie meandering river floodplain, Milk River, southern Alberta and northern Montana. *Canadian Journal of Botany* **64**, 1433–1442. doi:10.1139/b86-195

Bramley H, Hutson J, Tyerman SD (2003) Floodwater infiltration through root channels on a sodic clay floodplain and the influence on a local tree species *Eucalyptus largiflorens*. *Plant and Soil* **253**, 275–286. doi:10.1023/A:1024531325281

Costelloe JF, Payne E, Woodrow IE, Irvine EC, Western AW, Leaney FW (2008) Water sources accessed by arid zone riparian trees in highly saline environments, Australia. *Oecologia* **156**, 43–52. doi:10.1007/s00442-008-0975-4

CSIRO (1983) 'Soils an Australian viewpoint.' (Academic Press: London, UK)

Cunningham S, MacNally R, Griffioen P, White M (2009) Mapping the condition of river red gum and black box stands in The Living Murray icon sites. Report Book Number 51/10. Murray–Darling Basin Authority, Canberra, ACT, Australia.

Cunningham SC, White M, MacNally R, Griffioen P (2013) 'Mapping floodplain vegetation types across the Murray–Darling Basin using remote sensing.' (Murray–Darling Basin Authority: Canberra, ACT, Australia)

Doody TM, Holland KL, Benyon RG, Jolly ID (2009) Effect of groundwater freshening on riparian vegetation water balance. *Hydrological Processes* **23**, 3485–3499. doi:10.1002/hyp.7460

Doody TM, Benger SN, Pritchard JL, Overton IC (2014) Ecological response of *Eucalyptus camaldulensis* (river red gum) to extended drought and flooding along the River Murray, South Australia (1997–2011) and implications for environmental flow management. *Marine and Freshwater Research* **65**, 1082–1093. doi:10.1071/MF13247

Doody TM, Colloff MJ, Davies M, Koul V, Benyon RG, Nagler PL (2015) Quantifying water requirements of riparian river red gum (*Eucalyptus camaldulensis*) in the Murray–Darling Basin, Australia – implications for the management of environmental flows. *Ecohydrology* **8**, 1471–1487. doi:10.1002/eco.1598

Fernando DR, Lynch JP (2015) Manganese phytotoxicity: new light on an old problem. *Annals of Botany* **116**, 313–319. doi:10.1093/aob/mcv111

Fernando DR, Lynch JP, Reichman SM, Clark GJ, Miller RE, Doody TM (2018) Inundation of a floodplain lake woodlands system: nutritional profiling and benefit to mature *Eucalyptus largiflorens* (Black Box) trees. *Wetlands Ecology and Management* **26**, 961–975. doi:10.1007/s11273-018-9623-x

Fernando DR, Fernando AE, Koerber GR, Doody TM (2021*a*) Tree–soil interactions through water release to a floodplain ecosystem: a case study of Black Box (*Eucalyptus largiflorens*) on loamy sands. *Wetlands* **41**, 17–35. doi:10.1007/s13157-021-01419-4

Fernando DR, Lynch JP, Hanlon MT, Marshall AT (2021*b*) Foliar elemental microprobe data and leaf anatomical traits consistent with drought tolerance in *Eucalyptus largiflorens* (Myrtaceae). *Australian Journal of Botany* **69**, 215–224. doi:10.1071/BT20170

Grafton RQ, Williams J, Perry CJ, Molle F, Ringler C, Steduto P, Udall B, Wheeler SA, Wang Y, Garrick D, Allen RG (2018) The paradox of irrigation efficiency: higher efficiency rarely reduces water consumption. *Science* **361**, 748–750. doi:10.1126/science.aat9314

Graham RD, Hannam RJ, Uren NC (Eds) (1988) 'Manganese in Soils and Plants. Proceedings of the International Symposium', 22–26 August 1988, Glen Osmond, SA, Australia. (Springer)

Herczeg AL, Dogramaci SS, Leaney FWJ (2001) Origin of dissolved salts in a large, semi-arid groundwater system: Murray Basin, Australia. *Marine and Freshwater Research* **52**, 41–52. doi:10.1071/MF00040

Holland KL, Tyerman SD, Mensforth LJ, Walker GR (2005) Tree water sources over shallow, saline groundwater in the lower River Murray, south-eastern Australia: implications for groundwater recharge mechanisms. *Australian Journal of Botany* **54**, 193–205. doi:10.1071/BT05019

Hulme KA (2010) '*Eucalyptus camaldulensis* (river red gum) biogeochemistry: an innovative tool for mineral exploration in the Curnamona Province and adjacent regions.' (University of Adelaide: Adelaide, SA, Australia)

Hulme K, Hill S (2005) Mineralisation discovery through transported cover using River Redgums (*Eucalyptus camaldulensis*). In 'Minerals explorations seminar.' (Ed. RAD Gee) pp. 31–33. (CRC LEME: Perth, WA, Australia)

Jensen AE, Walker KF, Paton DC (2008) The role of seedbanks in restoration of floodplain woodlands. *River Research and Applications* **24**, 632–649. doi:10.1002/rra.1161

Judd TS, Attiwill PM, Adams MA (1996) Nutrient concentrations in *Eucalyptus*: a synthesis in relation to differences between taxa, sites and components. In 'Nutrition of eucalypts.' (Eds PM Attiwill, MA Adams) pp. 123–153. (CSIRO Publishing: Melbourne, Vic., Australia)

Koerber GR, Anderson PA, Seekamp JV (2013) Morphology, physiology and AFLP markers validate that green box is a hybrid of *Eucalyptus largiflorens* and *E. gracilis* (Myrtaceae). *Australian Systematic Botany* **26**, 156–166. doi:10.1071/SB12034

Lambers H, Oliveira RS (2019) 'Plant physiological ecology.' (Springer Nature: Cham, Switzerland). doi:10.1007/978-3-030-29639-1

Leeper GW, Uren NC (1997) 'Soil science: an introduction.' (Melbourne University Press: Melbourne, Vic., Australia)

Marcar NE (1993) Waterlogging modifies growth, water use and ion concentrations in seedlings of salt-treated *Eucalyptus camaldulensis*, *E. tereticornis, E. robusta* and *E. globulus*. *Australian Journal of Plant Physiology* **20**, 1–13. doi:10.1071/PP9930001

Marschner H (2002) 'Mineral nutrition of higher plants.' (Academic Press: London, UK)

McEvoy PK (1992) 'Ecophysiological comparisons between *Eucalyptus camaldulensis* Denh., *E. largiflorens* F. Muell. and *E. microcarpa* (Maiden) Maiden on the River Murray floodplain.' (University of Melbourne: Melbourne, Vic., Australia)

McLennan SM, Hill SM, Hatch M, Barovich K, Berens V (2013) Riparian eucalypt biogeochemical expression of groundwater salinity, Murray River, South Australia. *Geochemistry* **13**, 159–168. doi:10.1144/geochem2011-116

Medina E, Cuevas E (1994) Mineral nutrition: humid tropical forests. *Progress in Botany* **55**, 115–129. doi:10.1007/978-3-642-78568-9_6

Mensforth LJ, Thorburn PJ, Tyerman SD, Walker GR (1994*a*) Sources of water used in riaprian *Eucalyptus camaldulensis* overlying highly saline groundwater. *Oecologia* **100**, 21–28. doi:10.1007/BF00317126

Mensforth LT, Thorburn PT, Tyerman SD, Walker GR (1994*b*) Sources of water used by riparian *Eucalyptus camaldulensis* overlying highly saline groundwater. *Oecologia* **100**, 21–28. doi:10.1007/BF00317126

Miller AC, Watling JR, Overton IC, Sinclair R (2003) Does water status of *Eucalyptus largiflorens* (Myrtaceae) affect infection by the mistletoe *Amyema miquelii* (Loranthaceae)? *Functional Plant Biology* **30**, 1239–1247. doi:10.1071/FP03117

Moxham C, Duncan M, Moloney P (2018) Tree health and regeneration response of Black Box (*Eucalyptus largiflorens*) to recent flooding. *Ecological Management and Restoration* **19**, 58–65. doi:10.1111/emr.12288

Nawazi MF, Gul S, Tanvir MA, Akhtar J, Chaudary S, Ahmad I (2016) Influence of NaCl-salinity on Pb-uptake behavior and growth of River Red gum tree (*Eucalyptus camaldulensis* Dehnh.). *Turkish Journal of Agriculture and Forestry* **40**, 425–432. doi:10.3906/tar-1407-73

Overton I, Doody T (2010) Ecosystem response modelling in the Chowilla floodplain, Lindsay and Wallpolla islands icon site. In 'Ecosystem response modelling in the Murray–Darling Basin'. (Eds N Saintilan, I Overton) pp. 357–372. (CSIRO Publishing: Melbourne, Vic., Australia)
Overton IC, Jolly ID (2004) Integrated studies of floodplain vegetation health, saline groundwater and flooding on the Chowilla floodplain South Australia. CSIRO Land and Water Technical Report 20/04. (CSIRO: Canberra, ACT, Australia)
Overton IC, Jolly ID, Slavich PG, Lewis MM, Walker GR (2006) Modelling vegetation health from the interaction of saline groundwater and flooding on the Chowilla floodplain, South Australia. *Australian Journal of Botany* **54**, 207–220. doi:10.1071/BT05020
Overton IC, Colloff MJ, Doody TM, Henderson B, Cuddy SM (2009) 'Ecological outcomes of flow regimes in the Murray–Darling Basin.' (CSIRO: Canberra, ACT, Australia)
Payne EGI, Costelloe JF, Woodrow IE, Irvine EC, Western AW, Herczeg AL (2006) Riparian tree water use by *Eucalyptus coolabah* in the Lake Eyre Basin. In '30th Hydrology & Water Resources Symposium: Past, Present & Future', 4–7 December 2006, Launceston, Tas., Australia. (Engineers Australia) Available at https://search.informit.org/doi/book/10.3316/informit.0858257904
Pittock J, Finlayson CM (2011) Australia's Murray–Darling Basin: freshwater ecosystem conservation options in an era of climate change. *Marine and Freshwater Research* **62**, 232–243. doi:10.1071/MF09319
Poss JA, Grattan SR, Suarez DL, Grieve CM (2000) Stable carbon isotope discrimination: an indicator of cumulative salinity and boron stress in *Eucalyptus camaldulensis*. *Tree Physiology* **20**, 1121–1127. doi:10.1093/treephys/20.16.1121
Rahimi-Nasrabadi M, Nazarian S, Farahani H, Reza G, Koohbijari F, Ahmadi F, Batooli H (2013) Chemical composition, antioxidant, and antibacterial activities of the essential oil and methanol extracts of *Eucalyptus largiflorens* F. Muell. *International Journal of Food Properties* **16**, 369–381. doi:10.1080/10942912.2010.551310
Reichman SM, Menzies NW, Asher CJ, Mulligan DR (2004) Seedling responses of four Australian tree species to toxic concentrations of manganese in solution culture. *Plant and Soil* **258**, 341–350. doi:10.1023/B:PLSO.0000016564.14512.eb.
Reichman SM, Menzies NW, Asher CJ, Mulligan DR (2006) Responses of four Australian tree species to toxic concentrations of copper in solution culture. *Journal of Plant Nutrition* **29**, 1127–1141. doi:10.1080/01904160600689274
Roberts J, Marston F (2011) 'Water regime for wetland and floodplain plants: a source book for the Murray–Darling Basin.' (National Water Commission, Commonwealth of Australia: Canberra, ACT, Australia)
Robinson N, Harper RJ, Smettem KRJ (2006) Soil water depletion by *Eucalyptus* spp. integrated into dryland agricultural systems. *Plant and Soil* **286**, 141–151. doi:10.1007/s11104-006-9032-4
Sakai A, Ohsawa M (1994) Topographical pattern of the forest vegetation on a river basin in a warm-temperate hilly region, central Japan. *Ecological Research* **9**, 269–280. doi:10.1007/BF02348413
Slavich PG, Walker GR, Jolly ID, Hatton TJ, Dawes WR (1999) Dynamics of *Eucalyptus largiflorens* growth and water use in response to modified watertable and flooding regimes on a saline floodplain. *Agricultural Water Management* **39**, 245–264. doi:10.1016/S0378-3774(98)00081-X
Smith P, Smith J (2014) Floodplain vegetation of the River Murray in 1987–1988: an important pre-drought benchmark for subsequent studies. *Cunninghamia* **14**, 97–151. doi:10.7751/cunninghamia.2014.14.007
St Clair SB, Lynch JP (2004) Base cation stimulation of mycorrhization and photosynthesis of sugar maple on acid soils are coupled by foliar nutrient dynamics. *New Phytologist* **165**, 581–590. doi:10.1111/j.1469-8137.2004.01249.x
St Clair SB, Lynch JP (2010) The opening of Pandora's Box: climate change impacts on soil fertility and crop nutrition in developing countries. *Plant and Soil* **335**, 101–115. doi:10.1007/s11104-010-0328-z
Stone C, Bacon PE (1995) Influence of herbivory on the decline of Black Box (*Eucalyptus largiflorens*). *Australian Journal of Botany* **43**, 555–564. doi:10.1071/BT9950555
Sunil C, Somashekar RK, Nagaraja BC (2010) Riparian vegetation assessment of Cauvery River Basin of South India. *Environmental Monitoring and Assessment* **170**, 545–553. doi:10.1007/s10661-009-1256-3
Swirepik JL, Burns IC, Dyer FJ, Neave IA, O'Brien MG, Pryde GM, Thompson RM (2016) Establishing environmental water requirements for the Murray–Darling Basin, Australia's largest developed river system. *River Research and Applications* **32**, 1153–1165. doi:10.1002/rra.2975
Taiz L, Zeiger E (2002) 'Plant physiology', 2nd edn. (Sinauer Associates, Inc: Sunderland, MA, USA)
Taiz L, Zeiger E, Moller IM, Murphy AS (2015) 'Plant physiology and development.' (Sinauer Associates: Sunderland, MA, USA)
Thorburn PJ, Hatton TJ, Walker GR (1993) Combining measurements of transpiration and stable isotopes of water to determine groundwater discharge from forests. *Journal of Hydrology* **150**, 563–587. doi:10.1016/0022-1694(93)90126-T
Treloar GK (1959) Some factors affecting seedling survival of *Eucalyptus largiflorens* F. Muell. *Australian Forestry* **23**, 46–48. doi:10.1080/00049158.1959.10675863
van der Moezel PG, Pearce-Pinto GVN, Bell DT (1991) Screening for salt and waterlogging tolerance in *Eucalyptus* and *Melaleuca* species. *Forest Ecology and Management* **40**, 27–37. doi:10.1016/0378-1127(91)90089-E
Viscarra Rossel R, Chen C, Grundy M, Searle R, Clifford D, Odgers N, Holmes K, Griffin T, Liddicoat C, Kidd D (2014) Soil and landscape grid national soil attribute maps – clay (3″ resolution) – release 1. v5. Data collection. (CSIRO: Canberra, ACT, Australia) Available at https://data.csiro.au/collections/collection/CI10168v005
Wallace TA, Gehrig S, Doody TM (2020) A standardised approach to calculating floodplain tree condition to support environmental watering decisions. *Wetlands Ecology and Management* **28**, 315–340. doi:10.1007/s11273-020-09716-1
Wallace TA, Gehrig SL, Doody TM, Davies MJ, Walsh R, Fulton C, Cullen R, Nolan M (2021) A multiple lines of evidence approach for prioritising environmental watering of wetland and floodplain trees. *Ecohydrology* **14**, e2272. doi:10.1002/eco.2272
White RE (1997) 'Principles and practices of soil science – the soil as a natural resource.' (Blackwell Science: Melbourne, Vic., Australia)
Woodward AJ, Bennett IJ (2005) The effect of salt stress and abscisic acid on proline production, chlorophyll content and growth of in vitro propagated shoots of *Eucalyptus camaldulensis*. *Plant Cell, Tissue and Organ Culture* **82**, 189–200. doi:10.1007/s11240-005-0515-4
Zubrinich TM, Loveys B, Gallasch S, Seekamp JV, Tyerman SD (2000) Tolerance of salinised floodplain conditions in a naturally occurring *Eucalyptus* hybrid related to lowered plant water potential. *Tree Physiology* **20**, 953–963. doi:10.1093/treephys/20.14.953

Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

Conflicts of interest. The authors declare that they have no conflicts of interest.

Declaration of funding. D. R. Fernando acknowledges funding from the Australian Research Council (ARC grant number DE120100510) and Eucalypt Australia; and in-kind contribution from the University of New South Wales.

Acknowledgements. The support and expertise of Parks Victoria and New South Wales National Parks and Wildlife Service staff Shane Southon, Rhett Cameron, Nicola Brookhouse, Mick Lalor and Amanda Lavender were invaluable. The authors thank Myra Tolhurst for welcoming us to her property during fieldwork at Macquarie Marshes. We thank Jane Roberts and Heather McGinness for their guidance and expert advice on this project. The authors thank Angus Fernando-Plant for fieldwork assistance.

Author affiliations

[A]Department of Ecology, Environment and Evolution, La Trobe University, Bundoora, Vic. 3085, Australia.

[B]Centre for Applied Water Science, University of Canberra, Canberra, ACT 2617, Australia.

[C]Flora, Flow & Floodplains, Mildura, Vic., Australia.

[D]Australian Rivers Institute, Griffith University, South Brisbane, Qld 4101, Australia.

[E]Ecolinc Science and Technology Innovations Centre, Maddingley, Vic. 3340, Australia.

[F]Centre for Applied Water Science, University of Canberra, Canberra, ACT 2617, Australia.

[G]CSIRO Land and Water, Glen Osmond, SA 5064, Australia.

[H]School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW 2052, Australia.