

## Original Article

# Leaf water storage increases with salinity and aridity in the mangrove *Avicennia marina*: integration of leaf structure, osmotic adjustment and access to multiple water sources

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## ABSTRACT

Leaf structure and water relations were studied in a temperate population of *Avicennia marina* subsp. *australasica* along a natural salinity gradient [28 to 49 parts per thousand (ppt)] and compared with two subspecies grown naturally in similar soil salinities to those of subsp. *australasica* but under different climates: subsp. *eucalyptifolia* (salinity 30 ppt, wet tropics) and subsp. *marina* (salinity 46 ppt, arid tropics). Leaf thickness, leaf dry mass per area and water content increased with salinity and aridity. Turgor loss point declined with increase in soil salinity, driven mainly by differences in osmotic potential at full turgor. Nevertheless, a high modulus of elasticity ( $\epsilon$ ) contributed to maintenance of high cell hydration at turgor loss point. Despite similarity among leaves in leaf water storage capacitance, total leaf water storage increased with increasing salinity and aridity. The time that stored water alone could sustain an evaporation rate of  $1 \text{ mmol m}^{-2} \text{ s}^{-1}$  ranged from 77 to 126 min from subspecies *eucalyptifolia* to ssp. *marina*, respectively. Achieving full leaf hydration or turgor would require water from sources other than the roots, emphasizing the importance of multiple water sources to growth and survival of *Avicennia marina* across gradients in salinity and aridity.

**Key-words:** leaf hydration; LMA; modulus of elasticity; PV curve; SLA; turgor loss point; water relations.

## INTRODUCTION

There is an urgent need to understand relationships between leaf traits and drought tolerance (Bartlett *et al.* 2012). The urgency arises because an understanding of leaf design may help to anticipate responses of trees to edaphic and

atmospheric drought and mitigate tree dieback. Tree death in response to severe drought has been reported to occur globally (Allen *et al.* 2010; McDowell & Allen 2015) in forest systems as different as tropical rainforests (Phillips *et al.* 2009; Rowland *et al.* 2015) and mangroves (Lovelock *et al.* 2009; Duke *et al.* 2017). Mangroves are halophytic woody trees and shrubs that occur in tidal, saline wetlands (Feller *et al.* 2010). These systems contribute important ecosystem services to fisheries, forestry and the social well-being of coastal communities in the tropics and subtropics. Mangroves are also a fundamental model study system for genetic capacity for salt tolerance. The structure and function of mangrove forests varies along complex environmental gradients in salinity and climatic aridity (Duke *et al.* 1998), factors that, respectively, affect the availability of water at the roots and the demand for water at the leaves. These factors will change in response to altered climate and sea level due to global warming. It is important to understand how mangroves cope with salinity and aridity to better manage these resources in a changing environment.

Mangroves, like other plants, must take up and store water to maintain leaf hydration. However, coping with a saline environment entails special challenges for the maintenance of favourable water and ion balances. Despite the abundance of water in mangrove habitats, salinity can limit the capacity of roots to absorb water while excluding most ions from entry into the transpiration stream. Standard seawater, for example, contains 35 parts per thousand (ppt) solute which includes 483 mM  $\text{Na}^+$  and 558 mM  $\text{Cl}^-$  (Harvey 1966) and has an osmotic potential of  $-2.4 \text{ MPa}$ . For plants to absorb water, water potentials in roots must be lower than in surrounding soil. In halophytes like mangroves, turgor is maintained in tissues despite very negative water potentials through adjustment of intracellular solute concentrations, including high levels of  $\text{Na}^+$  and  $\text{Cl}^-$ . These ions are sequestered from sensitive metabolic sites as metabolism in halophytes is as sensitive to high ion concentrations as in glycophytes (Flowers 1972; Ball & Anderson 1986), and the ions contribute to osmotic adjustment in their primary storage site, the vacuole

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(Flowers *et al.* 1977). Osmotic adjustment in the cytoplasmic compartment occurs mainly through the accumulation of compatible solutes (Jefferies 1981; Flowers & Colmer 2008). While these principles of halophytic cellular physiology are well established, questions remain about the contributions to salinity tolerance of higher levels of organization, i.e. organs such as leaves.

As carbon cannot be gained without the expenditure of water, acquisition of adequate water to sustain carbon gain is essential for both survival and growth. Under extreme conditions, leaves may close stomata and persist on stored water until conditions become favourable for water uptake. However, mangroves that cope with persistently highly saline soil must continue to spend water for carbon gain. Water uptake (Ball 1988; Bazihizina *et al.* 2009; Reef *et al.* 2015), transport (Sperry *et al.* 1988; Melcher *et al.* 2001; Ewers *et al.* 2004; Lopez-Portillo *et al.* 2005; Lovelock *et al.* 2006) and use (Ball & Farquhar 1984a, b; Clough & Sim 1989; Nguyen *et al.* 2015) are typically lower in high than low salinities. These characteristics would lead to a higher requirement for leaf water storage for transient water use at high salinity. Indeed, Lechthaler *et al.* (2016) showed that leaf evaporation rates in the mangroves *Bruguiera gymnorhiza* and *Rhizophora mucronata* depended on stored water because water transport to leaves was not sufficient to balance rates of water loss, especially when salinity was high.

Stored water can play an important role in drought tolerance. Leaf water storage depends on mass investment in structure, and thus, leaf dry mass and water content per area should tend to scale proportionally. Further, leaf mass per area, i.e. LMA, is a key trait that often, but not always, correlates with tolerance of drought (Niinemets 2001; Bartlett *et al.* 2012) and salinity (Ball *et al.* 1988). In a meta-analysis, Poorter *et al.* (2009) reported a simple linear increase in LMA with increasing substrate salinity. However, LMA alone is not a general adaptation to drought tolerance. Bartlett *et al.* (2012) found no direct linkage between LMA and the maintenance of turgor and hydration during dehydration to the turgor loss point. They suggested that reported correlations between LMA and drought tolerance in specific plant groups probably reflected 'the coincidence of drought stress and other environmental conditions for which high LMA confers a benefit' (Bartlett *et al.* 2012).

In addition to having thick leaves for water storage, species must have sufficient solute concentrations to allow maintenance of turgor even as the water is withdrawn. Sufficient osmotica depends on the habitat occupied. Indeed, leaf water potentials reported for field-grown mangroves vary with the natural soil salinities in which they grow, which range from slightly brackish to hypersaline (Scholander *et al.* 1964; Scholander 1968; Naidoo 1989; Rada *et al.* 1989; Sternberg *et al.* 1991; Constable 2014; Walker 2014). Maintenance of a minimal level of hydration is essential for survival, and maintenance of turgor is required for growth. Both are achieved through osmotic adjustment. Lower (i.e. more negative) osmotic potential and turgor loss point with increasing growth salinity are common features in mangroves (Rada *et al.* 1989; Suarez & Sobrado 2000; Melcher *et al.*

2001; Paliyavuth *et al.* 2004; Sobrado 2007). Indeed, osmotic potential at full turgor is a reliable predictor of the turgor loss point, which in turn correlates with drought tolerance (Bartlett *et al.* 2012), and is likely also to correlate with salinity tolerance.

Rigid cell walls, which are often associated with high LMA, also have consequences for leaf water relations. The bulk modulus of elasticity is defined as the change in turgor pressure per fractional change in cell volume (Cheung *et al.* 1975). In other words, the bulk modulus of elasticity increases with the rigidity of the cell walls. Variation in bulk modulus of elasticity affects cellular water relations because the more rigid the cell wall, the greater the change in turgor pressure, and hence also water potential, for a given water loss above the turgor loss point. In this way, mechanical constraints on water loss by rigid walls conserve water content at the turgor loss point (Cheung *et al.* 1975). It follows from this interpretation that cell wall rigidity would increase with increasing salinity. However, both increases and decreases have been reported: bulk modulus of elasticity decreased with increasing salinity in *Rhizophora mangle*, *Conocarpus erectus*, *Coccoloba uvifera* (Rada *et al.* 1989) and *Avicennia germinans* (Suarez *et al.* 1998) but increased with increasing salinity in *A. germinans* (Suarez & Sobrado 2000), *Avicennia alba*, *Bruguiera gymnorhiza*, *Heritiera littoralis* and *Xylocarpus granatum* (Paliyavuth *et al.* 2004). Thus, the role and variability in the modulus of elasticity require clarification.

Pressure–volume relationships (PV curves) provide a way to examine most aspects of leaf water relations, enabling determination of the modulus of elasticity, water storage capacitance, osmotic potential at full turgor and at the turgor loss point. Analysing PV curves with respect to leaf anatomy, Nguyen *et al.* (2016) revealed a cascade of water storage compartments that were operational over different ranges of leaf water potentials in one population of field-grown *Avicennia marina*. They showed that liquid water can be absorbed from the lamina surface and stored in cells and specialized extracellular spaces (trichome lumina and cisternae) at water potentials higher than those experienced at the roots. This stored water, thus, must come from sources that are distinct from the soil. Quantification of the amount of extracellular water was problematic, but it could account for as much as 10% of total leaf water based on the average size and density of trichomes. Thus, Nguyen *et al.* (2016) estimated that extracellular water together with that stored inside the cells, especially in the hypodermis, could support a sustained evaporation rate of  $1 \text{ mmol m}^{-2} \text{ s}^{-1}$  for approximately 2 h without input from the roots as leaves dehydrated from full hydration to the turgor loss point. These results invite the following question: how do changes in leaf anatomy relate to water relations of *A. marina* with variation in environmental conditions?

*Avicennia marina* is one of the most salt tolerant and widely distributed of mangrove species along complex gradients in salinity and aridity. There are three subspecies of *A. marina* whose Australian distribution varies with climatic conditions: subsp. *eucalyptifolia* in wet tropics; subsp. *marina* in arid tropics; and subsp. *australasica* in temperate areas with intermediate rainfall (Duke *et al.* 1998; Li *et al.* 2016). These

subspecies were used as sources of variation in the present study. The leaf water relations, anatomy and physical properties of naturally field grown leaves were measured to test the hypotheses that with increasing salinity and aridity, (1) LMA increases with increases in the bulk modulus of elasticity and leaf succulence, (2) osmotic potentials at full turgor and at the turgor loss point decrease, (3) leaf water storage capacitance and total water storage increase and (4) leaf water relations reflect increasing importance of access to multiple water sources additional to the soil.

## MATERIALS AND METHODS

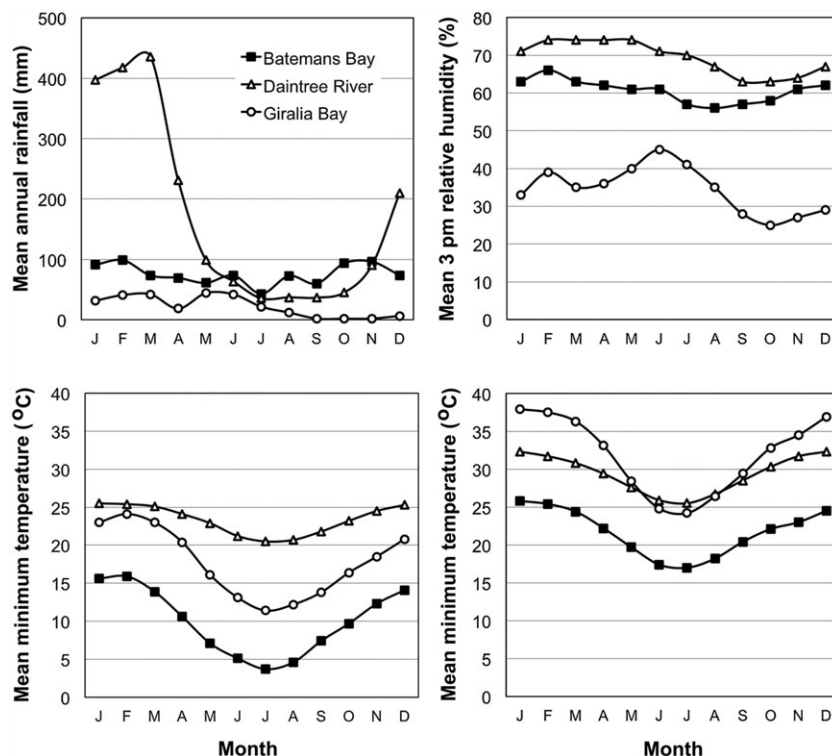
### Plant materials

All leaf samples were collected from plants growing naturally along gradients in salinity and aridity. Variation in leaf traits with salinity was studied in *A. marina* subsp. *australasica* growing at three sites along the Clyde River (Batemans Bay, New South Wales, Australia) where salinity of soil water extracted from 30 cm depth at low tide (McKee 1993) averaged  $28 \pm 0.4$  ( $35^{\circ}38'50.3''\text{S}$   $150^{\circ}08'39.5''\text{E}$ ),  $40 \pm 0.4$  ( $35^{\circ}42'15.1''\text{S}$   $150^{\circ}10'25.2''\text{E}$ ) and  $49 \pm 0.6$  ppt ( $35^{\circ}42'16.2''\text{S}$   $150^{\circ}10'18.8''\text{E}$ ). Seawater (35 ppt) has a water potential of  $-2.4$  MPa, and so, soil water salinities at the three sites were approximately equivalent to water potentials of  $-1.9$ ,  $-2.7$  and  $-3.4$  MPa. Differences among subspecies were based on comparison of *A. marina* subsp. *australasica* with subsp. *eucalyptifolia* from

the wet tropics (Daintree, Queensland,  $16^{\circ}17'29.8''\text{S}$   $145^{\circ}25'10.2''\text{E}$ ) and subsp. *marina* from the arid tropics (Giralia Bay, Western Australia,  $22^{\circ}27'34.0''\text{S}$   $114^{\circ}14'31.9''\text{E}$ ). Soil salinity where subsp. *eucalyptifolia* grew was  $30 \pm 0$  ppt ( $-2.1$  MPa) and where subsp. *marina* grew was  $46 \pm 0.7$  ppt ( $-3.2$  MPa). Hereafter, the five groups of plants are referred to by the first two letters of the subspecies names followed by a subscript with the soil salinity in which the plants grew, i.e. Au<sub>28</sub>, Au<sub>40</sub>, Au<sub>49</sub>, Eu<sub>30</sub> and Ma<sub>46</sub>. Note that some data for Au<sub>49</sub> were reproduced from Nguyen *et al.* (2016) and are identified in table captions where appropriate. Differences between climatic conditions at the study sites are summarized in Fig. 1.

### Leaf features

One fully exposed branch bearing only sun leaves was chosen from each of five co-occurring trees in each of the five study sites for all measurements of leaf properties as previously described (Nguyen *et al.* 2016). Care was taken to select leaves that appeared average in size for a given population under a given set of conditions, i.e. similar age, aspect and exposure to full sunlight. Briefly, branches were rehydrated and two well-matched leaf pairs were selected for study and randomly allocated to one of two sets of measurements. One pair of leaves was used for measurement of physical properties and construction of a PV curve relationship with both sets of measurements made on the same leaf, and the second leaf used



**Figure 1.** Long-term average monthly rainfall, relative humidity at 3 pm, minimum and maximum air temperature at weather stations nearest the three study sites along the tidal margins of Batemans Bay, New South Wales (temperate oceanic, solid square), Daintree River, Queensland (wet tropics, open triangle), and Giralia Bay, Western Australia (arid tropics, open circle). All data were collected by the Australian Bureau of Meteorology at Low Isles lighthouse (No. 031037) for Daintree River, Learmonth airport (No. 005007) for Giralia Bay and Catalina Country Club (No. 069134) for Batemans Bay.

as a spare if measurements needed to be repeated. The second leaf pair was used for anatomical measurements.

### Leaf physical properties

Leaf area ( $S$ ,  $\text{m}^2$  unless otherwise specified), dry mass ( $DM$ ,  $\text{g}$ ), maximum water content ( $WC_{\max}$ ,  $\text{g}$ ), leaf dry mass per area ( $LMA$ ,  $\text{g m}^{-2}$ ), maximum leaf water content per area ( $WCA_{\max}$ ,  $\text{g m}^{-2}$ ) and per dry mass ( $WCD_{\max}$ ,  $\text{g g}^{-1}$ ) were measured on the same set of leaves used for PV analyses, as described in Nguyen *et al.* (2016).

### Leaf anatomy

Transverse and paradermal leaf sections were prepared, stained and observed as previously described (Nguyen *et al.* 2015, 2016). Lamina thickness and the fractional contribution of each tissue layer to total lamina thickness were calculated from transverse sections. The number of cells per unit cross-sectional area ( $\text{mm}^{-2}$ ) in the hypodermis, palisade mesophyll and spongy mesophyll was calculated from transverse sections through these tissues; the number of trichomes and upper epidermal cells per unit leaf area were calculated from paradermal sections.

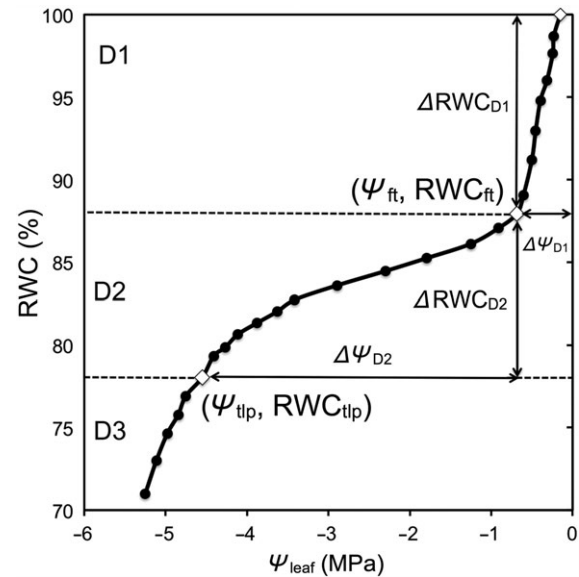
### Leaf water relations

Pressure–volume curves with three domains (Fig. 2) were constructed and analysed as in Nguyen *et al.* (2016) where relative water content (RWC) was plotted as a function of leaf water potential ( $\psi_{\text{leaf}}$ ) with one exception. Bulk modulus of elasticity ( $\epsilon$ ,  $\text{MPa}$ ) was calculated only for domain 2 of the PV curve as follows:  $\epsilon_{D2} = \frac{\Delta P}{\Delta V/V}$  where  $\Delta P$  is the difference in turgor pressure and  $\Delta V/V$  is the corresponding fractional difference in cellular volume between the points at full turgor ( $\psi_{\text{ft}}$ ,  $RWC_{\text{ft}}$ ) and at turgor loss ( $\psi_{\text{tlp}}$ ,  $RWC_{\text{tlp}}$ ) as shown in Fig. 2. Those two points were determined by conventional methods (Scholander *et al.* 1964; Tyree & Hammel 1972; Cheung *et al.* 1975; Turner 1988) using linear regressions of  $1/\psi_{\text{leaf}}$  as a function of relative water deficit, i.e.  $1 - RWC$ , for the appropriate regions of the PV curves (Nguyen *et al.* 2016). These calculated values of  $\psi_{\text{ft}}$  and  $\psi_{\text{tlp}}$  mark the transitions between domains 1 and 2, and domains 2 and 3, respectively (Nguyen *et al.* 2016).

The difference in turgor pressure between  $\psi_{\text{ft}}$  and  $\psi_{\text{tlp}}$  was calculated as  $\Delta P = \psi_{\text{ft}} - \psi_{\pi}^{\text{ft}}$  where  $\psi_{\text{ft}}$  is leaf water potential at full turgor and  $\psi_{\pi}^{\text{ft}}$  is the osmotic potential at full turgor. The corresponding fractional difference in cellular volume between  $\psi_{\text{ft}}$  and  $\psi_{\text{tlp}}$  was calculated as follows:

$$\Delta V/V = \frac{WC_{\text{ft}} - WC_{\text{tlp}}}{WC_{\text{ft}}} = \frac{(FM_{\max} - DM)(RWC_{\text{ft}} - RWC_{\text{tlp}})}{(FM_{\max} - DM)RWC_{\text{ft}}} = \frac{RWC_{\text{ft}} - RWC_{\text{tlp}}}{RWC_{\text{ft}}}$$

where  $WC$  is leaf water content,  $FM_{\max}$  is leaf maximum fresh mass,  $DM$  is leaf dry mass,  $RWC$  is relative water content; ft and tlp denote the points of full turgor and turgor loss,



**Figure 2.** An exemplary pressure–volume curve of *A. vicennia marina* subsp. *marina* constructed with leaf relative water content (RWC) as a function of leaf water potential ( $\psi_{\text{leaf}}$ ). The curve shows three domains: D1 dominated by extracellular water; D2 dominated by decline in turgor; and D3 dominated by osmotic effects after turgor loss (Nguyen *et al.* 2016). Open diamond symbols indicate the points of leaf saturation (100% RWC), full turgor ( $\psi_{\text{ft}}$ ,  $RWC_{\text{ft}}$ ) and turgor loss ( $\psi_{\text{tlp}}$ ,  $RWC_{\text{tlp}}$ ). The ranges in leaf water potential ( $\Delta\psi_{\text{leaf}}$ ) and RWC ( $\Delta RWC$ ) that span domains 1 and 2 are indicated by subscripts D1 and D2, respectively.

respectively, on the PV curve as shown in Fig. 2. Substituting terms, the bulk modulus of elasticity was calculated for domain 2 of the PV curve as follows:

$$\epsilon_{D2} = \frac{(\psi_{\text{ft}} - \psi_{\pi}^{\text{ft}})RWC_{\text{ft}}}{RWC_{\text{ft}} - RWC_{\text{tlp}}}$$

Water storage capacitance ( $Q$ ,  $\text{mol m}^{-2} \text{MPa}^{-1}$ ), i.e. the amount of water released per unit leaf area per unit change in leaf water potential, was calculated for domains 1 and 2, following Brodribb & Holbrook (2003) as follows:

$$Q = \frac{DM}{S} \frac{WC_{\max}}{DM} \frac{1}{M} \frac{\Delta RWC}{\Delta\psi_{\text{leaf}}}$$

where  $M$  is molar mass of water ( $\text{g mol}^{-1}$ ),  $\Delta RWC$  is the difference between RWC spanning a domain as shown for  $\Delta RWC_{D1}$  and  $\Delta RWC_{D2}$  in Fig. 2 and  $\Delta\psi_{\text{leaf}}$  is the difference between leaf water potentials spanning a domain as shown for  $\Delta\psi_{D1}$  and  $\Delta\psi_{D2}$  in Fig. 2.

Leaf water storage per unit area was calculated, respectively, for domains 1 ( $W_{D1}$ ,  $\text{mol m}^{-2}$ ) and 2 ( $W_{D2}$ ,  $\text{mol m}^{-2}$ ) of the three-domain PV curves (Nguyen *et al.* 2016) as follows:  $W = Q(\Delta\psi_{\text{leaf}})$ . The sum of  $W_{D1}$  and  $W_{D2}$  is the total water storage ( $W_{\text{tot}}$ ,  $\text{mol m}^{-2}$ ).

### Data analysis

Data were analysed with Genstat version 16 (Payne *et al.* 2014) through one-way ANOVA and simple linear regression. Data



were normally distributed and did not require transformation before analyses. Fisher's least significant difference and Tukey tests were applied *post hoc* to determine differences between treatment means whenever relationships with  $P \leq 0.050$  were found.

Note that abbreviations used in the text are summarized in Table 1.

## RESULTS

Testing the four key hypotheses revealed strong differences in leaf water storage across the aridity and salinity gradients. Firstly, an increase in LMA with salinity and aridity was linked to increase in leaf water storage, which was achieved through increase in number of cell layers while maintaining fractional tissue contributions to lamina thickness. Secondly, turgor loss points declined with increase in soil salinity, driven primarily by differences in osmotic potential at full turgor as there were no consistent effects of salinity on the bulk modulus of elasticity. Thirdly, there was little variation in leaf water storage capacitance ( $\text{mol m}^{-2} \text{MPa}^{-1}$ ), but total leaf water storage

( $\text{mol m}^{-2}$ ) increased with increase in salinity and aridity. Finally, PV curves revealed that water from sources other than roots would be required for maximum leaf hydration and turgor. These results are presented in detail in the following texts.

## Physical properties of the leaves

Leaf physical properties varied both within and among subspecies (Table 2). Within *A. marina* subsp. *australasica*, leaf area, dry mass and maximum water content were smaller at higher salinity (Fig. 3a–c). Leaf area declined more than dry mass with increasing salinity, and consequently, LMA significantly increased with salinity ( $P = 0.01$ , Fig. 3d). However, the maximum water content per unit dry mass ( $\text{WCD}_{\text{max}}$ ,  $\text{g g}^{-1}$ ) decreased slightly with increasing salinity ( $P = 0.02$ , Fig. 3e). As maximum water content per unit leaf area ( $\text{WCA}_{\text{max}}$ ,  $\text{g m}^{-2}$ ) is the product of LMA and  $\text{WCD}_{\text{max}}$ , opposing variation in these two factors prevented significant ( $P = 0.15$ ) variation in  $\text{WCA}_{\text{max}}$  with salinity within subsp. *australasica* (Fig. 3f). The tendency for  $\text{WCA}_{\text{max}}$  to increase with increasing salinity within subsp. *australasica* was mainly driven by LMA ( $r^2 = 0.55$ ,  $P = 0.001$ ). A similar pattern was evident with comparison of all subspecies in which LMA, and hence also  $\text{WCA}_{\text{max}}$ , increased with increasing salinity and aridity (Table 2, Fig. 3d–f).

## Leaf anatomy

All three subspecies shared similar structures with five major tissue layers comprising the lamina (Fig. 4). These layers were the adaxial epidermis, hypodermis, palisade mesophyll, spongy mesophyll and the abaxial epidermis, which was covered with trichomes and contained stomata. There were no significant differences in either lamina thickness ( $P = 0.99$ ) or the fraction each tissue contributed to lamina thickness within subsp. *australasica* grown in a range of salinities (Table 3, Fig. 5a).

In contrast, lamina thickness differed among the three subspecies ( $P < 0.001$ ) being smallest in  $\text{Eu}_{30}$  ( $418 \pm 16 \mu\text{m}$ ) and largest in  $\text{Ma}_{46}$  ( $761 \pm 26 \mu\text{m}$ ) despite these subspecies growing in salinities similar to those of  $\text{Au}_{28}$  and  $\text{Au}_{49}$ , respectively. There were no significant differences in the fraction that the photosynthetic tissues contributed to lamina thickness (Table 3), whereas significant differences occurred in the water storage tissues, i.e. the hypodermal and trichome layers. While the fraction of lamina thickness contributed by the hypodermis was lower in  $\text{Eu}_{30}$  than in  $\text{Ma}_{46}$  ( $P = 0.01$ ), that of the trichomes followed the opposite pattern. Nevertheless, the actual thickness of each tissue layer was the greatest in  $\text{Ma}_{46}$  and the smallest in  $\text{Eu}_{30}$  (Table 3, Fig. 5a). Thus, averaging across all subspecies, lamina thickness increased with increasing salinity and aridity, consistent with the parallel increase in  $\text{WCA}_{\text{max}}$  (Fig. 5b) and LMA (Fig. 5c).

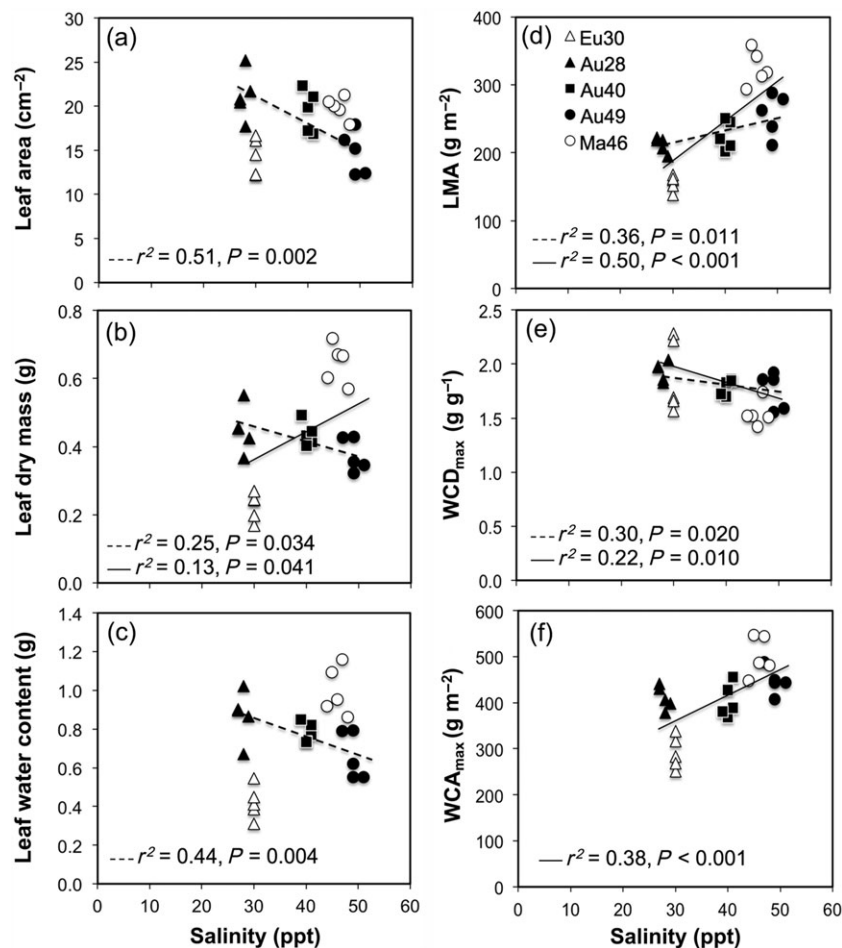
There were differences in the ways in which variation in the thicknesses of tissue layers was achieved. There was no significant difference in either the proportion or number of cells per unit leaf area in the adaxial epidermis among subspecies, but the cuticle layer in  $\text{Ma}_{46}$ , averaging  $10 \mu\text{m}$ ,

**Table 1.** Abbreviations

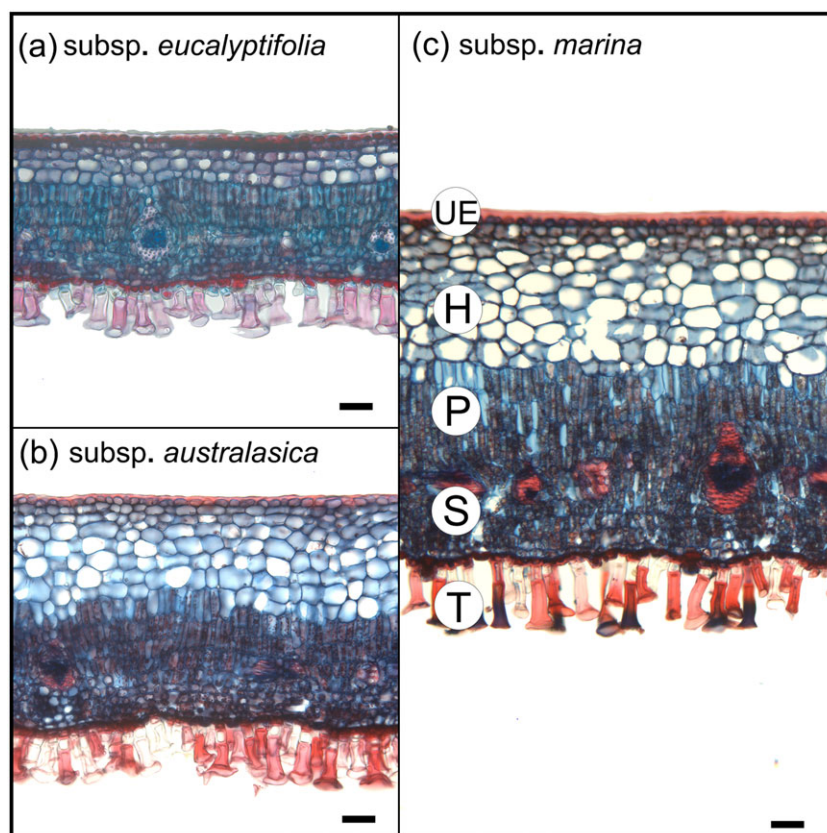
Abbreviations	Symbol	Unit
Plant materials		
<i>Avicennia marina</i> subsp. <i>australasica</i> grown at 28, 40 and 49 ppt seawater	$\text{Au}_{28}$ , $\text{Au}_{40}$ and $\text{Au}_{49}$	
<i>A. marina</i> subsp. <i>eucalyptifolia</i> grown at 30 ppt seawater	$\text{Eu}_{30}$	
<i>A. marina</i> subsp. <i>marina</i> grown at 46 ppt seawater	$\text{Ma}_{46}$	
Parameters		
Bulk modulus of elasticity	$\epsilon$	MPa
Difference	$\Delta$	
Fractional difference in cellular volume	$\Delta V/V$	
Leaf area	S	$\text{m}^2$
Leaf dry mass	DM	g
Leaf dry mass per area	LMA	$\text{g m}^{-2}$
Leaf fresh mass	FM	g
Leaf water content	WC	g
Leaf water content per area	WCA	$\text{g m}^{-2}$
Leaf water content per dry mass	WCD	$\text{g g}^{-1}$
Leaf water potential	$\psi_{\text{leaf}}$	MPa
Osmotic potential	$\psi_{\pi}$	MPa
Relative water content	RWC	%
Turgor pressure	P	MPa
Water storage capacitance	Q	$\text{mol m}^{-2} \text{MPa}^{-1}$
Water storage (per unit leaf area)	W	$\text{mol m}^{-2}$
Subscripts and superscripts		
Maximum value	max	
(Calculated for) Domain 1	D1	
(Calculated for) Domain 2	D2	
(Measured at the point of)	ft	
Full turgor		
(Measured at) Turgor loss point	tlp	
Total	tot	

**Table 2.** Physical properties of leaves of the three subspecies of *A. vicennia marina*: subsp. *australasica* (Au), subsp. *eucalyptifolia* (Eu) and subsp. *marina* (Ma) grown under temperate, wet tropical and arid tropical climates, respectively, in salinities ranging from 28 to 49 ppt. These salinities are given as a subscript following the two-letter subspecies designations. Values are means  $\pm$  SE ( $n = 5$ ). Superscript letters denote significant differences among means as determined by one-way ANOVA with *post hoc* Tukey test when  $P \leq 0.05$ . The grey block shows responses of leaf physical properties to salinity within subsp. *australasica*. Note that effects of subspecies were confounded with environment. Data for Au<sub>49</sub> was reproduced from Nguyen *et al.* (2016).

Parameter	Symbol	Unit	Eu <sub>30</sub>		Au <sub>28</sub>		Au <sub>40</sub>		Au <sub>49</sub>		Ma <sub>46</sub>	
			Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Salinity		ppt	30	0	28	0.4	40	0.4	49	0.6	46	0.7
Leaf area	S	cm <sup>2</sup>	14.4 <sup>a</sup>	0.9	21.2 <sup>c</sup>	1.2	19.5 <sup>b</sup>	1.1	14.8 <sup>a</sup>	1.1	19.9 <sup>bc</sup>	0.6
Leaf dry mass per area	LMA	g m <sup>-2</sup>	156 <sup>a</sup>	5	212 <sup>b</sup>	5	226 <sup>bc</sup>	10	256 <sup>c</sup>	14	325 <sup>d</sup>	11
Maximum water content per area	WCA <sub>max</sub>	g m <sup>-2</sup>	292 <sup>a</sup>	16	411 <sup>b</sup>	11	404 <sup>b</sup>	16	447 <sup>bc</sup>	13	501 <sup>c</sup>	19
Maximum water content per dry mass	WCD <sub>max</sub>	g g <sup>-1</sup>	1.89 <sup>ab</sup>	0.15	1.94 <sup>b</sup>	0.04	1.79 <sup>ab</sup>	0.03	1.76 <sup>ab</sup>	0.08	1.54 <sup>a</sup>	0.05



**Figure 3.** Physical properties of field-grown sun leaves of three subspecies of *Avicennia marina* as a function of soil pore water salinity. Panels show (a) leaf area, (b) leaf dry mass, (c) leaf water content, (d) leaf mass per area (LMA), (e) leaf maximum water content per dry mass (WCD<sub>max</sub>), and (f) leaf maximum water content per area (WCA<sub>max</sub>). Symbols: subsp. *eucalyptifolia* (Eu<sub>30</sub> – open triangle), subsp. *australasica* grown at salinities of 28 ppt (Au<sub>28</sub> – solid triangle), 40 ppt (Au<sub>40</sub> – solid square), and 49 ppt (Au<sub>49</sub> – solid circle) and subsp. *marina* (Ma<sub>46</sub> – open circle). Each point represents one leaf from one of the five trees that were chosen for the experiment. Lines drawn by linear regression show relationships for subsp. *australasica* (dashed line, solid black symbols) and for all three subspecies (solid line, all symbols).



**Figure 4.** Transverse sections through the leaf lamina of the three subspecies of *A. vicennia marina*: (a) subsp. *eucalyptifolia*, (b) subsp. *australasica* and (c) subsp. *marina* grown under temperate, wet tropical and arid tropical climates, respectively, in salinities ranging from 28 to 49 ppt. Bars are 50  $\mu\text{m}$ . Abbreviations: UE: upper (adaxial) epidermis, H: hypodermis, P: palisade mesophyll, S: spongy mesophyll, T: trichome layer. Notice the differences in lamina thickness between subspecies, especially in the number of cell layers of the hypodermis.

was twice as thick as that of other groups ( $P < 0.001$ ). The smaller proportion of hypodermis in Eu<sub>30</sub> was due to two factors: fewer hypodermal cell layers ( $P < 0.001$ , Table 3, Fig. 4b) composed of a greater number of smaller cells per unit cross-sectional area ( $P = 0.01$ , Table 3, Fig. 4b). Variation in the thickness of photosynthetic tissues occurred mainly through the number of palisade cell layers (Table 3). There was no significant difference in the number of trichomes per unit leaf area between subspecies grown in similar salinities; however, the leaves of Eu<sub>30</sub> and Au<sub>28</sub> had significantly higher number of trichomes per unit area than those of Ma<sub>46</sub> and Au<sub>49</sub> ( $P < 0.001$ ). Nevertheless, the average volume of individual trichomes was not significantly different among subspecies ( $P = 0.69$ , Table 3).

### Leaf water relations

Key leaf water relations parameters were calculated from PV curves constructed for leaves from all five sites as summarized in Table 4. All PV curves had a similar shape with three domains as described in Nguyen *et al.* (2016). Domains 1, 2 and 3 were dominated respectively by loss in extracellularly stored water, decline in turgor and decline in osmotic potential during leaf dehydration. On average, for each 0.1 MPa

decrease in  $\Psi_{\text{leaf}}$ , RWC decreased by 1.5–2% in domain 1, 0.3–0.4% in domain 2 and 1% in domain 3.

There were no detectable effects of salinity on domain 1 in subsp. *australasica*. Domain 1 represented the decrease in RWC from 100% to approximately 87% with a corresponding decrease in leaf water potential ( $\Psi_{\text{leaf}}$ ) from  $-0.1$  MPa to the transition between domains 1 and 2 ( $\Psi_{\text{ft}}$ ) at  $-0.9$  MPa. This domain accounted for an average of 13% of RWC of the leaf. There were no significant differences between these characteristics measured in subsp. *australasica* and those of the other two subspecies, except that average  $\Psi_{\text{ft}}$  was significantly less negative in Eu<sub>30</sub> ( $-0.7$  MPa) than Au<sub>28</sub> ( $-0.9$  MPa,  $P = 0.04$ ).

Once the extracellular water was exhausted, further decline in  $\Psi_{\text{leaf}}$  with decreasing RWC was driven mainly by decline in turgor over domain 2. The turgor loss point defined the transition from domain 2 to domain 3. Leaf water potential at the turgor loss point ( $\Psi_{\text{tlp}}$ ) became more negative with increasing soil water salinity both within subsp. *australasica* ( $r^2 = 0.77$ ,  $P < 0.001$ ) and among subspecies ( $r^2 = 0.71$ ,  $P < 0.001$ ). Within subspecies grown in similar salinities,  $\Psi_{\text{tlp}}$  was significantly less negative in Eu<sub>30</sub> ( $-4.1$  MPa) than in Au<sub>28</sub> ( $-4.5$  MPa), and in Ma<sub>46</sub> ( $-4.9$  MPa) than in Au<sub>49</sub> ( $-5.1$  MPa,  $P < 0.001$ ).

**Table 3.** Anatomical features of leaves of the three subspecies of *A. vicennia marina*: subsp. *australasica* (Au), subsp. *eucalyptifolia* (Eu) and subsp. *marina* (Ma) grown under temperate, wet tropical and arid tropical climates, respectively, in salinities ranging from 28 to 49 ppt. These salinities are given as a subscript following the two-letter subspecies designations. Values are means  $\pm$  SE ( $n = 5$ ). Superscript letters denote significant differences among means as determined by one-way ANOVA with *post hoc* Tukey test when  $P \leq 0.05$ . The grey block shows responses of leaf anatomical features to salinity within subsp. *australasica*. Note that effects of subspecies were confounded with the environment. Part of data for Au<sub>49</sub> was reproduced from Nguyen *et al.* (2016).

Parameter	Symbol	Unit	Eu <sub>30</sub>		Au <sub>28</sub>		Au <sub>40</sub>		Au <sub>49</sub>		Ma <sub>46</sub>	
			Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Lamina thickness	Lth	$\mu\text{m}$	418 <sup>a</sup>	16	566 <sup>b</sup>	24	565 <sup>b</sup>	14	569 <sup>b</sup>	13	761 <sup>c</sup>	26
Contribution to lamina thickness												
Adaxial epidermis	UEP	%	3	0	3	0	3	0	3	0	3	0
Hypodermis	HP	%	31 <sup>a</sup>	2	38 <sup>b</sup>	1	38 <sup>b</sup>	2	36 <sup>ab</sup>	1	38 <sup>b</sup>	0
Palisade mesophyll	PP	%	30	1	29	1	26	1	30	1	29	1
Spongy mesophyll	SP	%	16	1	13	1	14	1	12	0	15	1
Trichome	TP	%	19 <sup>b</sup>	1	17 <sup>ab</sup>	0	19 <sup>b</sup>	1	19 <sup>b</sup>	1	15 <sup>a</sup>	0
Number of cell layers												
Hypodermis	HN		5.8 <sup>a</sup>	0.4	8.0 <sup>b</sup>	0.5	8.0 <sup>b</sup>	0.3	8.0 <sup>b</sup>	0.0	9.2 <sup>b</sup>	0.2
Palisade mesophyll	PN		3.6 <sup>ab</sup>	0.2	3.6 <sup>ab</sup>	0.2	3.2 <sup>a</sup>	0.2	3.0 <sup>a</sup>	0.0	4.0 <sup>b</sup>	0.0
Spongy mesophyll	SN		4.2	0.4	4.6	0.2	5.0	0.3	5.0	0.3	4.8	0.2
Number of cells per unit leaf or lamina cross-sectional area												
Adaxial epidermis (leaf area)	UED	$\text{mm}^{-2}$	3091 <sup>a</sup>	251	3613 <sup>ab</sup>	154	3861 <sup>b</sup>	147	2997 <sup>a</sup>	22	3459 <sup>ab</sup>	225
Hypodermis	HD	$\text{mm}^{-2}$	1442 <sup>b</sup>	135	1302 <sup>ab</sup>	54	1569 <sup>b</sup>	57	1420 <sup>b</sup>	125	962 <sup>a</sup>	56
Palisade mesophyll	PD	$\text{mm}^{-2}$	2598 <sup>b</sup>	206	2110 <sup>ab</sup>	190	2340 <sup>ab</sup>	75	2352 <sup>ab</sup>	205	1663 <sup>a</sup>	120
Spongy mesophyll	SD	$\text{mm}^{-2}$	4357	505	3389	158	4000	472	4265	494	3160	124
Trichome												
Number per unit leaf area	TD	$\text{mm}^{-2}$	2827 <sup>b</sup>	115	2690 <sup>b</sup>	48	2729 <sup>b</sup>	82	2188 <sup>a</sup>	88	1863 <sup>a</sup>	79
Internal lumen diameter	$\mu\text{m}$	$\mu\text{m}$	24	1	20	2	22	1	20	2	19	1
Length	$\mu\text{m}$	$\mu\text{m}$	81 <sup>a</sup>	3	96 <sup>ab</sup>	3	107 <sup>b</sup>	2	109 <sup>b</sup>	5	114 <sup>b</sup>	4
Volume*	TV	$\mu\text{m}^3$	24 181	3226	16 054	2602	22 374	2578	20 460	3288	15 903	2794

Leaf osmotic potential at full turgor ( $\Psi_{\pi}^{\text{ft}}$ ) was about 0.8 MPa higher than  $\Psi_{\text{tlp}}$  for all leaves and was correlated with  $\Psi_{\text{tlp}}$  both within ( $r^2 = 0.48$ ,  $P = 0.002$ ) and among subspecies ( $r^2 = 0.72$ ,  $P < 0.001$ , Fig. 6a). Although  $\Psi_{\text{tlp}}$  varied within and among subspecies, RWC at turgor loss points (RWC<sub>tlp</sub>) differed only between Eu<sub>30</sub> and Au<sub>28</sub> in which the turgor loss point occurred at significantly lower RWC<sub>tlp</sub> in Eu<sub>30</sub> (71%) than in Au<sub>28</sub> (78%,  $P = 0.04$ ).

### Bulk modulus of elasticity

Bulk modulus of elasticity calculated for domain 2 ( $\epsilon_{\text{D2}}$ ) was highly variable, and average values were not significantly different either within subsp. *australasica* grown at a range of salinities ( $P = 0.95$ ) or among subspecies ( $P = 0.51$ ). Thus, the variation in  $\epsilon_{\text{D2}}$  did not correlate with the progressive decrease in  $\Psi_{\text{tlp}}$  with increasing salinity (Fig. 6b). There was also no correlation between  $\epsilon_{\text{D2}}$  and increase in LMA within subsp. *australasica* ( $P = 0.52$ ) or among subspecies ( $P = 0.88$ ).

### Water storage

Water content per unit leaf area was plotted as a function of  $\psi_{\text{leaf}}$  to show variation across leaves from the five sites during dehydration (Fig. 7a). There was a correlation between WCA<sub>max</sub> and that at the turgor loss point (WCA<sub>tlp</sub>) within

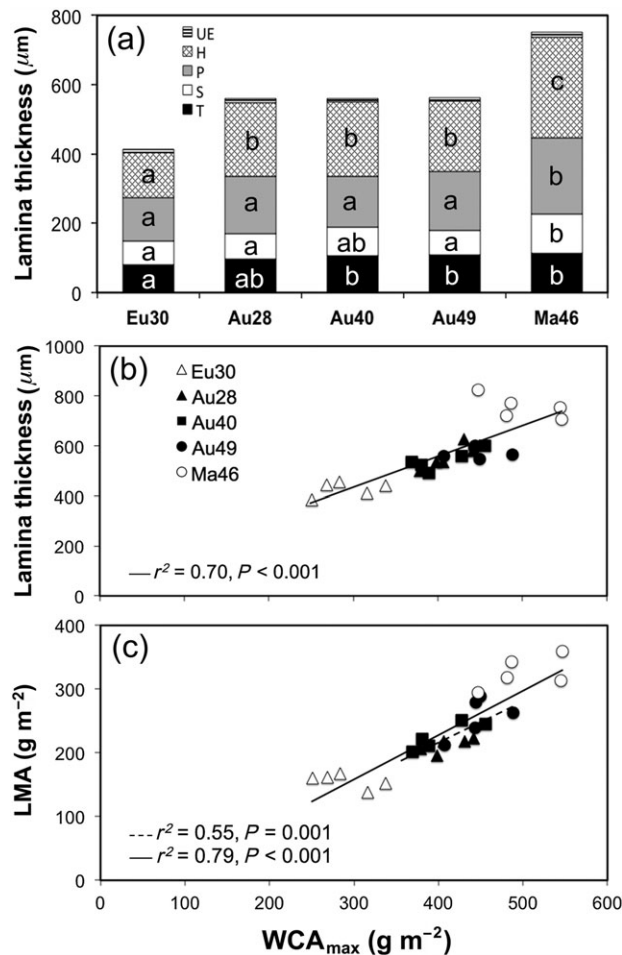
subsp. *australasica* ( $r^2 = 0.68$ ,  $P < 0.001$ ). This correlation became stronger with the addition of data for the other two subspecies ( $r^2 = 0.92$ ,  $P < 0.001$ , Fig. 7b).

Despite the differences in water content between leaves, there were no significant differences in water storage capacitances calculated from either domain 1 ( $Q_{\text{D1}}$ ,  $P = 0.26$ ) or domain 2 ( $Q_{\text{D2}}$ ,  $P = 0.75$ ), between subsp. *australasica* grown in the three salinities. Similarly, neither  $Q_{\text{D1}}$  nor  $Q_{\text{D2}}$  were significantly ( $P = 0.30$ ,  $P = 0.18$ , respectively) different among subspecies (Table 4).

The total of amount of water released per unit leaf area during dehydration from full hydration to the turgor loss point was related to salinity and evaporative demand. The average total water storage ( $W_{\text{tot}}$ ) was lowest ( $4.63 \pm 0.37$  mol H<sub>2</sub>O m<sup>-2</sup>) in leaves grown in the low salinity, wet tropics site (Eu<sub>30</sub>), and highest ( $7.56 \pm 0.44$  mol H<sub>2</sub>O m<sup>-2</sup>) in leaves grown in the high salinity, arid tropics site (Ma<sub>46</sub>) (Table 4). Linear regression showed a significant increase in  $W_{\text{tot}}$  with salinity both within subsp. *australasica* ( $r^2 = 0.32$ ,  $P = 0.02$ ) and among all three subspecies ( $r^2 = 0.44$ ,  $P < 0.001$ ). Domains 1 and 2 contributed roughly equally to total water storage, i.e.  $W_{\text{D1}} \approx W_{\text{D2}}$  (Table 4). However, the percentage contribution from domain 2 increased at the expense of domain 1 from 47.8% (Eu<sub>30</sub>) to 52.2% (Ma<sub>46</sub>) with increasing salinity and aridity.

These data were placed in a field context by dividing  $W_{\text{D2}}$  into two sub-components:  $W_{\text{D2-s}}$  where the stored water could





**Figure 5.** Lamina thickness and its components in field grown sun leaves of three subspecies of *Avicennia marina*. (a) The fractional distribution of five major tissues comprising the leaf lamina. Subspecies designations as in Fig. 3. Fillings indicate upper epidermis (UE, dash), hypodermis (H, hatch), palisade mesophyll (P, grey), spongy mesophyll (S, white) and trichome layer (T, black). Values are means ( $n = 5$ ). Letters denote significant differences between tissue types among means as determined by one-way ANOVA with *post hoc* Tukey test when  $P \leq 0.05$ . (b) Lamina thickness as a function of maximum water content per unit leaf area ( $\text{WCA}_{\text{max}}$ ). (c) LMA as a function of maximum  $\text{WCA}_{\text{max}}$ . Symbols as given in panel (b). Each point represents one leaf from one tree with five trees per group. Lines drawn by linear regression show significant relationships for subsp. *australasica* (dashed line, solid black symbols) and for all three subspecies (solid line, all symbols).

be sourced from the soil, i.e.  $\Psi_{\text{leaf}} < \Psi_{\text{soil}}$ , and  $\text{W}_{\text{D2-ns}}$  where the stored water would have to be obtained from sources other than soil, i.e.  $\Psi_{\text{soil}} < \Psi_{\text{leaf}} < \Psi_{\text{ft}}$ . Note that soil water salinities were measured at a depth of 30 cm and so do not include lower salinities that can occur at the soil surface during tidal flooding. In this calculation, soil water contributed exclusively to water storage in domain 2. Figure 8 showed that the contribution of soil water ( $\text{W}_{\text{D2-s}}$ ) to total leaf water storage ( $\text{W}_{\text{tot}}$ ) ranged from 28% (Eu30) to 35% (Ma46). These data indicated that alternative water sources with salinities lower than those in the soil were required to achieve maximum water storage in all subspecies and sites.

## DISCUSSION

Variation in LMA, osmotic adjustment, water storage and access to multiple sources of water was reflected in the structure of *A. marina* leaves grown in environments of increasing salinity and evaporative demand. Increase in LMA was a consequence of greater water storage with increasing salinity and aridity. The core feature of leaf water relations was the capacity to maintain low (i.e. more negative) osmotic potential at full turgor, which, when combined with high bulk modulus of elasticity, enabled maintenance of high cellular water contents with dehydration to the turgor loss point. That in itself would enhance survival, but maintenance of cell hydration during high transpiration rates would also require water storage when water loss exceeds rates of water supply. Indeed, water storage was increased by increasing lamina thickness, particularly through increasing layers of cells (Table 3, Fig. 4). Finally, linking leaf anatomy with leaf function as described by PV relationships showed that achieving either full hydration or full turgor required access to sources of water in addition to that supplied by the roots.

### Increase in leaf mass per area was associated with increase in leaf water content per area

Leaf dry mass per unit area increased with increasing soil salinity and aridity of the environments in which the plants were grown (Fig. 3d), consistent with a recent meta-analysis of halophytic and glycophytic species (Poorter *et al.* 2009). Previous studies have shown that species with higher LMA had higher cell wall concentrations of cellulose and hemicellulose per leaf dry mass, implying greater structural reinforcement than in leaves with lower LMA (Mediavilla *et al.* 2008). Structural compounds would have contributed to the high LMA of the sclerophyllous leaves of *A. marina* (Choong *et al.* 1992). However, in the present study, LMA was not correlated with the bulk modulus of elasticity, a measure of cell wall rigidity, consistent with the global meta-analysis of Bartlett *et al.* (2012). Differences in LMA among subspecies were related to differences in lamina thickness associated with differences in numbers and sizes of cells comprising lamina tissues (Figs 4 & 5). Finally, increase in intracellular solute concentrations to maintain favourable water relations would also contribute to the increase in LMA with increasing salinity. For example, Ball (1981) estimated the accumulation of NaCl for osmotic adjustment would account for approximately 10% of leaf dry mass in lab grown *A. marina*. Thus, no single attribute accounted for the increase in LMA with increase in growth salinity. Instead, increase in LMA involved different combinations of more supportive structure, higher numbers of cells per unit leaf area and higher solute concentrations that depended on the subspecies.

These results invite the following question: what drives the salinity-dependent increase in LMA across subspecies? Decreasing osmotic potentials with increasing growth salinity required increasing cellular solute concentrations, which would contribute to the increase in LMA. However, such

**Table 4.** Water relations parameters derived from three-domain PV curves constructed from leaves of the three subspecies of *A. vicennia marina*: subsp. *australasica* (Au), subsp. *eucalyptifolia* (Eu) and subsp. *marina* (Ma) grown under temperate, wet tropical and arid tropical climates, respectively, in salinities ranging from 28 to 49 ppt. These salinities are given as a subscript following the two-letter subspecies designations. Values are means  $\pm$  SE ( $n = 5$ ). Superscript letters denote significant difference among means as determined by one-way ANOVA with *post hoc* Tukey test when  $P \leq 0.05$ . The grey block shows responses of leaf water relations to salinity within subsp. *australasica*. Note that effects of subspecies were confounded with environment. Part of data for Au<sub>49</sub> was reproduced from Nguyen *et al.* (2016).

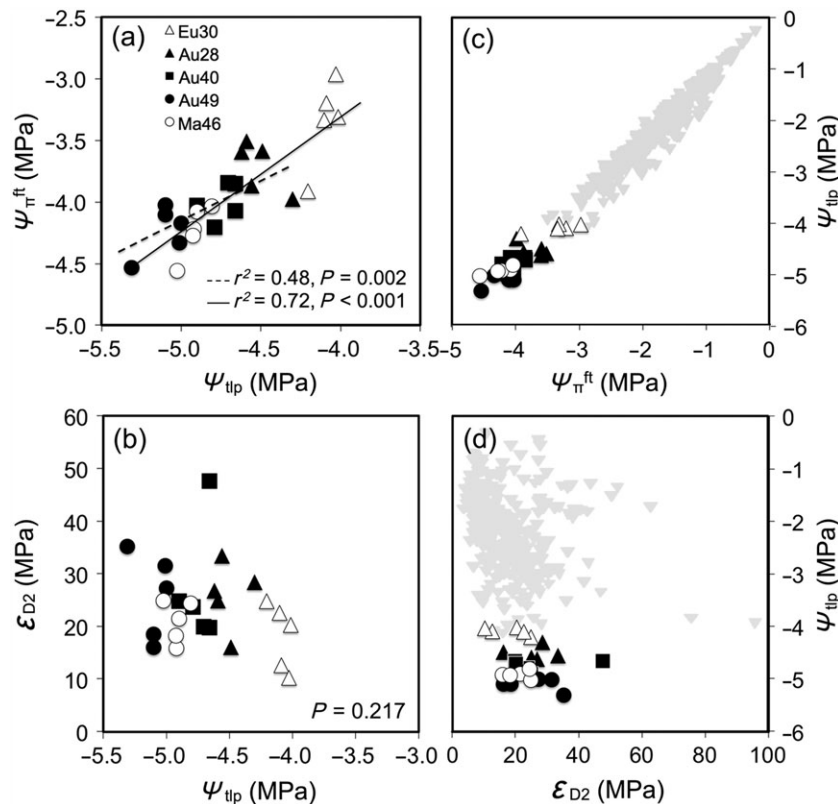
Parameter	Symbol	Unit	Eu <sub>30</sub>		Au <sub>28</sub>		Au <sub>40</sub>		Au <sub>49</sub>		Ma <sub>46</sub>	
			Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Leaf water potential at full turgor	$\Psi_{ft}$	MPa	-0.69 <sup>a</sup>	0.04	-0.87 <sup>b</sup>	0.03	-0.82 <sup>ab</sup>	0.04	-0.85 <sup>ab</sup>	0.03	-0.86 <sup>ab</sup>	0.04
Osmotic potential at full turgor	$\Psi_{\pi}^{ft}$	MPa	-3.3 <sup>a</sup>	0.2	-3.7 <sup>ab</sup>	0.1	-4.0 <sup>BC</sup>	0.1	-4.2 <sup>c</sup>	0.1	-4.2 <sup>c</sup>	0.1
Water potential at turgor loss point	$\Psi_{tlp}$	MPa	-4.1 <sup>a</sup>	0.0	-4.5 <sup>b</sup>	0.1	-4.7 <sup>c</sup>	0.0	-5.1 <sup>d</sup>	0.1	-4.9 <sup>cd</sup>	0.0
RWC at full turgor	RWC <sub>ft</sub>	%	85	1	88	1	87	1	87	1	87	1
RWC at turgor loss point	RWC <sub>tlp</sub>	%	71 <sup>a</sup>	1	78 <sup>b</sup>	1	76 <sup>ab</sup>	1	75 <sup>ab</sup>	3	73 <sup>ab</sup>	1
Modulus of elasticity for domain 2	$\epsilon_{D2}$	MPa	18	3	26	3	27	5	26	4	21	2
Water storage capacitance for domain 1	Q <sub>D1</sub>	mol m <sup>-2</sup> MPa <sup>-1</sup>	3.57	0.27	3.13	0.38	3.61	0.44	3.83	0.35	4.23	0.56
Water storage capacitance for domain 2	Q <sub>D2</sub>	mol m <sup>-2</sup> MPa <sup>-1</sup>	0.66	0.13	0.64	0.08	0.64	0.07	0.72	0.09	1.00	0.11
Total water storage	W <sub>tot</sub>	mol m <sup>-2</sup>	4.63 <sup>a</sup>	0.37	4.85 <sup>a</sup>	0.18	5.60 <sup>a</sup>	0.25	6.28 <sup>ab</sup>	0.63	7.56 <sup>b</sup>	0.44
Water storage for domain 1	W <sub>D1</sub>	mol m <sup>-2</sup>	2.43 <sup>a</sup>	0.05	2.56 <sup>a</sup>	0.12	2.95 <sup>ab</sup>	0.25	3.26 <sup>ab</sup>	0.34	3.62 <sup>b</sup>	0.28
Water storage for domain 2	W <sub>D2</sub>	mol m <sup>-2</sup>	2.20 <sup>a</sup>	0.37	2.23 <sup>a</sup>	0.28	2.65 <sup>ab</sup>	0.15	3.02 <sup>ab</sup>	0.36	4.00 <sup>b</sup>	0.42

increase in the solute concentration comes at the expense of the amount of water per unit dry mass, WCD<sub>max</sub> (Fig. 3e). Thus, increase in numbers or sizes of cells per unit area, thereby increasing leaf thickness and hence also LMA, would be required to maintain or increase maximum WCA<sub>max</sub> in increasingly saline soils. Indeed, WCA<sub>max</sub> increased with increasing LMA in response to increasing salinity and evaporative demand (Fig. 5c), requiring coordination between leaf structure and leaf water relations. These effects were more pronounced among subspecies than within subspecies grown along a salinity gradient (Fig. 3f). Thus, the salinity-dependent increase in LMA appears driven by increasing requirements for water storage. In other environments, species from seasonally dry or xeric habitats typically have high values of LMA (Poorter *et al.* 2009). Based on the present study, such high LMA in combination with increasing leaf thickness, as for example in Neotropical savannas (Rossatto *et al.* 2015), may also be related to demands for water storage.

#### Leaf osmotic potentials at full turgor ( $\Psi_{\pi}^{ft}$ ) and at the turgor loss point ( $\Psi_{tlp}$ ) declined with increase in the growth salinity and evaporative demand of the climate in which the plants were grown

Regardless of the sources of variation including subspecies and climate, soil water salinity was the major determinant

of  $\Psi_{\pi}^{ft}$  and  $\Psi_{tlp}$ , consistent with the requirements to maintain a favourable water balance and the turgor essential for growth under increasingly saline edaphic conditions. Indeed, the capacity to vary osmotic potentials and thereby adjust water potentials at the turgor loss point must play critical roles in growth and survival of *A. marina* over a wide range of salinities. Specifically, *A. marina* had a low osmotic potential at full turgor,  $\Psi_{\pi}^{ft}$ , and it became more negative with increase in the soil water salinity in which the plants were grown. This is consistent with a study showing acclimation in osmotic potentials associated with accumulation of progressively increasing ion levels in leaves of *A. marina* (Downton 1982). The osmotic potential at full turgor,  $\Psi_{\pi}^{ft}$ , was correlated with the osmotic potential at the turgor loss point,  $\Psi_{tlp}$  (Fig. 6a), as predicted by theoretical equations (Bartlett *et al.* 2012). These results obtained from *A. marina* were consistent with those from a meta-analysis (Fig. 6c) of responses to drought where species was the source of variation (Bartlett *et al.* 2012) and from a study of multispecies responses to imposed and natural seasonal drought in a tropical rainforest (Binks *et al.* 2016). Thus, growth of *A. marina* in wet soil with high salinity elicited similar responses to those of plants subjected to drying soil. Bartlett *et al.* (2012) concluded from meta-analysis that leaf osmotic potentials at full turgor ( $\Psi_{\pi}^{ft}$ ) and at the turgor loss point ( $\Psi_{tlp}$ ) were important determinants of drought tolerance. The results of the present study extend that conclusion to include salt tolerance.



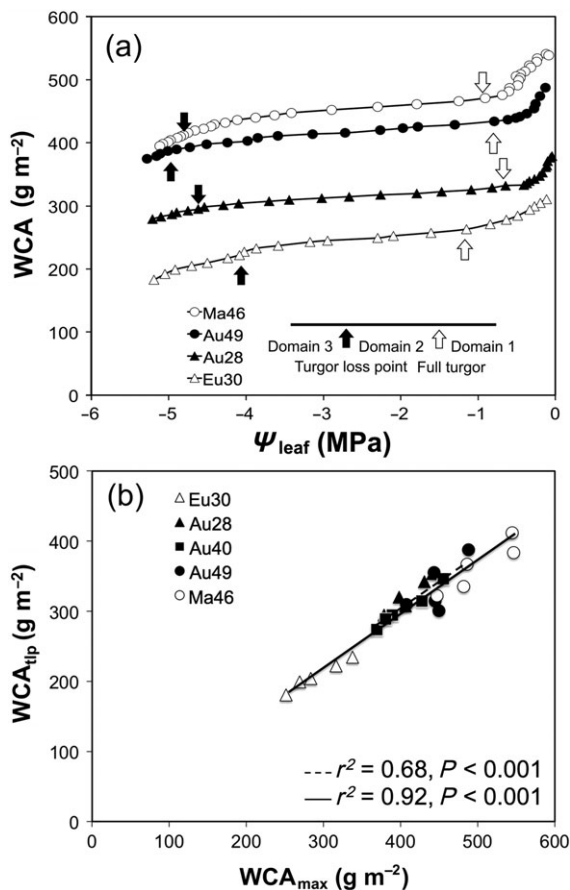
**Figure 6.** (a) Osmotic potential at full turgor ( $\Psi_{\pi}^{\text{ft}}$ ) and (b) bulk modulus of elasticity ( $\epsilon$ ) as functions of osmotic potential at the turgor loss point ( $\Psi_{\text{tlp}}$ ) when salinity was the source of variation in subsp. *australasica* (dashed line, black symbols) and when subspecies combined with environmental factors were the sources of variation (solid line, all symbols). Symbols as given in panel (a). Lines drawn by linear regression only for relationships with  $P \leq 0.05$ . Data from panels (a) and (b) were replotted, respectively, in panels (c) and (d) relative to a global meta-analysis (Bartlett *et al.* 2012).

### Leaves had a high bulk modulus of elasticity that provided mechanical strength and contributed to maintenance of high levels of cellular hydration during dehydration to the turgor loss point

A consequence of decreasing  $\Psi_{\pi}^{\text{ft}}$  and  $\Psi_{\text{tlp}}$  with increasing growth salinity is the potential for turgor stress when either soil salinity is low or leaves are fully hydrated and, conversely, the potential for osmotic stress when soil salinity is high or leaves are dehydrated. The average bulk modulus of elasticity,  $\epsilon_{\text{D2}}$  (18 to 27 MPa), in *A. marina* was highly variable with no significant difference among subspecies grown in salinities ranging from 28 to 49 ppt (Fig. 6b). Our results contrasted with the expectation that  $\epsilon_{\text{D2}}$  would increase, i.e. that cell walls would become more rigid, with increasing growth salinity as observed in *A. germinans* grown in salinities ranging from 0 to 32 ppt under laboratory conditions (Suarez & Sobrado 2000). In the present study, high  $\epsilon_{\text{D2}}$  may reflect a need for mechanical strength in field-grown leaves subject to a wide range of leaf water potentials over both daily and seasonal time scales. For example, under natural field conditions,  $\Psi_{\text{leaf}}$  of *A. marina* growing in soil with pore water salinity of 40 to 49 ppt (−2.7 to −3.4 MPa) varied from −0.1 MPa at dawn following a leaf wetting event to −6 MPa in mid-afternoon without perceptible damage (Constable 2014; Walker 2014). In this example, if  $\Psi_{\pi}^{\text{ft}}$  equals

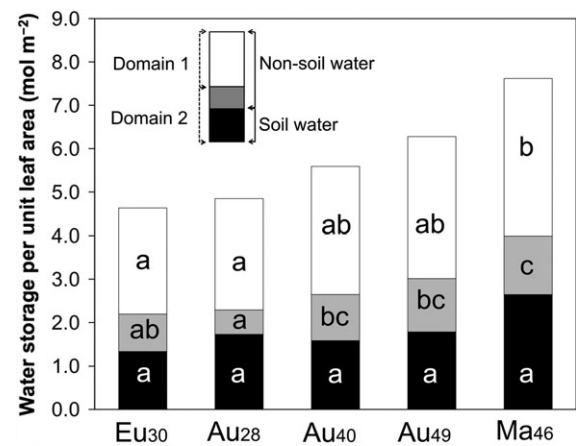
−4.2 MPa, then the turgor pressure would be as high as 4.1 MPa. Conversely, cells would be subjected to extreme osmotic stress when midday or afternoon  $\Psi_{\text{leaf}}$  approaches or is more negative than a turgor loss point of, say, −5 MPa. Maintenance of a high  $\epsilon_{\text{D2}}$  would offer protection against cell wall failure over the wide range of leaf water potentials encountered daily by leaves of *A. marina* under natural field conditions.

In the present study, there was no correlation between bulk modulus of elasticity and turgor loss points (Fig. 6b), consistent with the global meta-analysis (Fig. 6d) of Bartlett *et al.* (2012). Nevertheless, in the present study, cells remained well hydrated at the turgor loss point. Indeed, in leaves of subsp. *australasica* grown in soil water salinity ranging from 28 to 49 ppt,  $\text{RWC}_{\text{tlp}}$  decreased from 78 to 75%, respectively, while  $\epsilon_{\text{D2}}$  averaged 26 MPa (Table 4). Similarly, average  $\text{RWC}_{\text{tlp}}$  ranged from 71 to 78% across all three subspecies. However, these  $\text{RWC}_{\text{tlp}}$  values were calculated from leaf saturated water content, which included the extracellular water that dominated domain 1 (Nguyen *et al.* 2016). If domain 1 was excluded from calculations, effectively shifting the leaf saturated water content to that at  $\Psi_{\text{ft}}$ , then  $\text{RWC}_{\text{tlp}}$  based solely on domain 2 (dominated by cellular water) ranged from 82 to 90%. These values are greater than the estimated minimum requirement of 75% RWC to sustain cell function (Lawlor & Cornic 2002). These



**Figure 7.** Variation in water content per unit leaf area with dehydration in the three subspecies of *A. vicennia marina*. (a) Exemplary curves of water content per unit leaf area (WCA) as a function of leaf water potential ( $\Psi_{\text{leaf}}$ ) during air-drying. Data are shown for two pairs of leaves, with each pair contrasting subspecies grown under similar soil pore water salinities but different climatic conditions. Symbols: subsp. *eucalyptifolia* (Eu30 – open triangle), subsp. *australasica* grown at salinities of 28 ppt (Au28 – solid triangle) and 49 ppt (Au49 – solid circle) subsp. *marina* (Ma46 – open circle). Arrows show WCA at full turgor (open arrows) and at the turgor loss points (solid arrows). (b) Water content per unit leaf area at the turgor loss point ( $\text{WCA}_{\text{tlp}}$ ) as a function of maximum water content per unit leaf area ( $\text{WCA}_{\text{max}}$ ) when salinity was the source of variation in subsp. *australasica* (dashed line, black symbols) and when subspecies combined with environmental factors were the sources of variation (solid line, all symbols). Lines drawn by linear regression only for relationships with  $P \leq 0.05$ .

data agreed with the suggestion by Cheung *et al.* (1975) and meta-analysis by Bartlett *et al.* (2012) that high bulk modulus of elasticity played an important role in conserving cell hydration during leaf dehydration. Based on the PV curves, a 1% decrease in RWC was associated with a decrease in  $\Psi_{\text{leaf}}$  of 0.1 MPa with reduction in hydration below the turgor loss point (domain 3). These data suggest *A. marina* would be able to maintain cell function for a further 0.7–1.5 MPa decrease in  $\Psi_{\text{leaf}}$  below the turgor loss point. This is consistent with the occurrence of plasmolysis in most living cells at 1 MPa lower than  $\Psi_{\text{tlp}}$  in leaves of *A. marina* (Nguyen *et al.* 2016).



**Figure 8.** Average water storage per unit leaf area among the three subspecies of *A. vicennia marina*. The water storage column is divided into components indicating the water storage in domains 1 (white) and 2 (shaded). Three storage components were defined by regions along a pressure–volume (PV) curve where  $\Psi_{\text{leaf}}$  is less negative than  $\Psi_{\text{tlp}}$  (white,  $\text{W}_{\text{D1}}$ ),  $\Psi_{\text{leaf}}$  is less negative than  $\Psi_{\text{soil}}$  and more negative than  $\Psi_{\text{tlp}}$  (grey,  $\text{W}_{\text{D2-ns}}$ ) and  $\Psi_{\text{leaf}}$  is less negative than  $\Psi_{\text{tlp}}$  and more negative than  $\Psi_{\text{soil}}$  (black,  $\text{W}_{\text{D2-s}}$ ). Column height gives the total water storage. Parameter values are means,  $n = 5$  independent PV curves (one per tree). Letters denote significant differences among means as determined by one-way ANOVA with *post hoc* Tukey test when  $P \leq 0.05$ .

### Leaf water storage increased with increase in the growth salinity and evaporative demand of the climate in which the plants were grown

Leaf water storage may play critical roles in drought survival and in buffering fluctuation in leaf water potentials when rates of evaporation exceed rates of water re-supply from the roots (Lechthaler *et al.* 2016). In *A. marina*,  $\text{WCA}_{\text{max}}$  differed among subspecies and was correlated strongly with  $\text{WCA}_{\text{tlp}}$  (Fig. 7b).  $\text{WCA}_{\text{max}}$  is a component of leaf water storage capacitance ( $Q$ , mol m<sup>-2</sup> MPa<sup>-1</sup>), the amount of water released per unit leaf area per unit change in water potential (Fig. 2). There was a tendency, albeit not significant, for  $Q$  to increase with increasing salinity and aridity (Table 4), partly due to increase in  $\text{WCA}_{\text{max}}$  and, hence, also LMA, consistent with previous studies in other drought-affected systems (Blackman & Brodribb 2011). The combined effects of increasing  $Q$ , driven by increasing  $\text{WCA}_{\text{max}}$ , and decrease in the turgor loss point ( $\Psi_{\text{tlp}}$ ) resulted in an increase in total water storage,  $\text{W}_{\text{tot}}$ , with increasing salinity and aridity.

Although salinity strongly affected leaf water storage, the ways in which water was stored differed among subspecies and appeared to be related to the evaporative demands of the environments in which the subspecies grew. For example, leaves of Eu30 from the wet tropics were almost half the thickness of those of Ma46 from the arid tropics and had correspondingly less  $\text{WCA}_{\text{max}}$ . These subspecies differed in the relative contributions of different tissues to lamina thickness. Specifically, the hypodermal layer occupied 31% of lamina thickness in Eu30 and 38% in Ma46 while the layer accounted for 19% of lamina thickness in Eu30 and 15% in



Ma<sub>46</sub> (Table 4). In addition, the greater number of trichomes per unit area with similar average volumes (Table 4) would enable greater extracellular water storage in the leaf lamina of Eu<sub>30</sub> than Ma<sub>46</sub>. This mechanism might be favoured by two factors in a wet tropical environment. Firstly, trichomes of *A. marina* leaves rapidly absorb liquid water from wet epidermal surfaces (Nguyen *et al.* 2016), enabling rapid replenishment of leaf water from frequent leaf-wetting events, such as showers. Secondly, the highly humid atmosphere would limit evaporation, enhancing the duration of extracellular water storage in the trichome layer during the day. In contrast, water absorption by the trichome layer in Ma<sub>46</sub> would occur predominantly during nocturnal leaf-wetting events in its arid tropical environment. However, that water would need to be stored intracellularly to prevent its rapid loss from the trichomes upon increase in evaporative demand after sunrise. This may account for a greater allocation of lamina thickness to the hypodermal layer in the much thicker and more heavily cutinized leaves of Ma<sub>46</sub> than Eu<sub>30</sub> (Figs 4 & 5). Such differences among subspecies reflect coordination between leaf structure and leaf water relations under different environmental conditions. Further work is required to distinguish the relative contributions of genotypes and environments.

### The pressure–volume curves showed that leaves of *Avicennia marina* must access water from sources with salinities lower than those measured in the soil to achieve either full hydration or full turgor

Mangroves such as *A. marina* growing in saline wetlands are subject to spatial and temporal variation in salinity, which would affect the sources of water available for uptake. Soil pore water salinity would typically be higher than that of flooding tidal water because exclusion of salt during water uptake by the roots leads to the accumulation of salt in the rhizosphere (Passioura *et al.* 1992). The salinity of soil pore water would fluctuate less than that of surface water. Depending on conditions, the salinity of surface flood water

can vary from nearly freshwater to seawater while at the same time that of underlying soil water can be hypersaline. Thus, roots of a single plant may be exposed to a wide range of salinities over a vertical gradient from flood water through the soil. Indeed, split-root experiments have shown preferential water uptake when salinity was low in soil with spatial (Bazihizina *et al.* 2009; Reef *et al.* 2015) or temporal variation in salinity (Lechthaler *et al.* 2016). Meanwhile, leaves can also be rehydrated by different sources of water, such as fog, dew and rainfall (Eller *et al.* 2013) even in hypersaline mangrove environments (Constable 2014; Walker 2014).

Water potentials measured during leaf dehydration ranged from  $-0.1$  MPa at full hydration to values more negative than those at the turgor loss points. This range of potentials can be experienced in a single day (Constable 2014; Walker 2014). Thus, the PV relationship informs interpretation of the daily variation in leaf water potentials. Total water storage was estimated for domains 1 and 2 of the PV curves. These domains contributed almost equally to total leaf water storage, which increased with increases in the salinity and aridity in which the plants were grown. Summing the water storage from domains 1 and 2 (i.e. from full hydration to the turgor loss point), the total water storage in leaves of the present study could alone supply the water loss needed to support photosynthesis at an evaporation rate of  $1 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$  for up to 77 min in the wet tropics (Eu<sub>30</sub>) and 126 min in the arid tropics (Ma<sub>46</sub>) (Table 5, Fig. 8). These calculations underscore the increasing importance of stored water to leaf function with increase in salinity and aridity of the environment.

The ranges of water potentials involved in domains 1 and 2 suggest contributions of water from different sources. Extraction of water from soil and its subsequent transport to leaves requires leaf water potentials to be lower than those of soil water. If  $\psi_{\text{leaf}}$  was less negative than  $\psi_{\text{soil}}$ , then water supply to leaves must be from sources other than soil water. For domain 1, water storage ( $W_{D1}$ ) was exhausted with dehydration from  $-0.1$  MPa to an average of  $-0.8$  MPa, which is equivalent to the water potential of 34‰ seawater (12 ppt), much lower than the salinities measured in soil pore water at

**Table 5.** Estimation of the time that stored water obtained from soil or alternative sources could contribute to gas exchange in leaves of the three subspecies of *Avicennia marina*: subsp. *australasica* (Au), subsp. *eucalyptifolia* (Eu) and subsp. *marina* (Ma) grown under temperate, wet tropical and arid tropical climates, respectively, in salinities ranging from 28 to 49 ppt. Calculations were based on the distribution of water stored over different ranges of leaf water potentials as shown in Fig. 8 and assumed a leaf evaporation rate of  $1 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$ . Values are means  $\pm$  SE ( $n = 5$ ). Superscript letter denoted significant difference among means as determined by one-way ANOVA with *post hoc* Tukey test when  $P \leq 0.05$ . The grey block shows responses of leaf water storage to salinity within subsp. *australasica*. Note that effects of subspecies were confounded with environment. Data for Au<sub>49</sub> were reproduced from Nguyen *et al.* (2016).

Source of stored water	Environmental source of water	Time	$\psi_{\text{leaf}}$	Eu <sub>30</sub>		Au <sub>28</sub>		Au <sub>40</sub>		Au <sub>49</sub>		Ma <sub>46</sub>	
				Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Domain 1 (mostly extracellular)	Alternative	min	$\psi_{\text{ft}} < \psi_{\text{leaf}}$	41 <sup>a</sup>	1	43 <sup>a</sup>	3	49 <sup>ab</sup>	4	54 <sup>ab</sup>	6	60 <sup>b</sup>	5
Domain 2 (cellular)	Alternative	min	$\psi_{\text{soil}} < \psi_{\text{leaf}} < \psi_{\text{ft}}$	14 <sup>ab</sup>	2	9 <sup>a</sup>	2	18 <sup>bc</sup>	3	21 <sup>bc</sup>	2	22 <sup>c</sup>	1
	Soil	min	$\psi_{\text{tlp}} < \psi_{\text{leaf}} < \psi_{\text{soil}}$	22	5	29	3	26	4	30	5	44	7
	Total	min		77 <sup>a</sup>	6	81 <sup>a</sup>	3	93 <sup>a</sup>	4	105 <sup>ab</sup>	11	126 <sup>b</sup>	7

any sites in the present study. Water stored in domain 1 could be contributed by roots if salinity was lower than 12 ppt or by leaves receiving dew or intercepting rainfall. Indeed, Lechthaler *et al.* (2016) reported rapid recharge of water storage in leaves of seedlings in the Rhizophoraceae when salinities around roots were lowered from 30 to 5 ppt. Leaves of *A. marina* can absorb liquid water through salt secretion glands (Tan *et al.* 2013) and through the trichome layer (Nguyen *et al.* 2016) and have the capacity for extracellular storage of such water as reflected in domain 1 (Nguyen *et al.* 2016). Thus, leaf-wetting events could reverse the water potential gradient from the atmosphere to the plant to the soil (Goldsmith 2013), enabling rehydration of leaves to water potentials as high as  $-0.1$  MPa even when roots are exposed to very high soil salinities, as has been observed under natural field conditions (Constable 2014; Walker 2014).

Water stored in domain 2 was released from cells with dehydration from an average leaf water potential of  $-0.8$  MPa to the turgor loss point. The cellular water storage of domain 2,  $W_{D2}$ , was divided into two components: water storage when  $\psi_{\text{leaf}}$  was less negative ( $W_{D2-\text{ns}}$ ) or more negative ( $W_{D2-\text{s}}$ ) than the soil water potentials measured at the time the PV curves were constructed. On this basis, water sourced from soil would most likely contribute to storage in domain 2. Furthermore, as leaf full hydration and full turgor occurred at leaf water potentials much higher than those of  $\psi_{\text{soil}}$ , leaves would be neither fully hydrated nor fully turgid if soil pore water was the only source of water unless salinity was lowered by rainfall events or roots near the soil surface accessed flood water of lower salinity. This analysis shows the importance of spatial and temporal variation in soil salinity, together with access to alternative water sources, to the water balance of these leaves.

## CONCLUSIONS

Comparative analyses of PV curves revealed intricate integration of leaf structure and water relations that may contribute to growth and survival of *A. marina* along complex gradients in salinity and aridity. As expected, osmotic adjustment together with a high cellular modulus of elasticity enables maintenance of turgor and hydration over progressively lower leaf water potentials with increase in soil water salinity, consistent with the analyses of leaf properties in relation to drought tolerance (Bartlett *et al.* 2012). The high LMA values of the scleromorphic leaves of *A. marina* played no direct role in leaf water relations, again consistent with the meta-analysis of drought tolerant species (Bartlett *et al.* 2012). Nevertheless, variation in LMA in *A. marina* was largely a consequence of the increasing thickness of the lamina required for both extracellular and intracellular water storage in response to increasing salinity and aridity. These two storage compartments contributed approximately equally to total leaf water storage, but were operational over different ranges of leaf hydration. Indeed, when placed in context with the soil water salinities of the growth conditions, the PV curves revealed that access to alternative water sources was required to achieve full hydration or turgor. This requirement could be

met by foliar water uptake under moist atmospheric conditions as leaves of *Avicennia* can absorb liquid water via trichomes (Nguyen *et al.* 2016) and salt secretion glands (Tan *et al.* 2013). These results merit further study as they may help to define safety margins analogous to those of cloud forests (Oliveira *et al.* 2014) for the maintenance of favourable hydration and leaf function with natural variation in soil salinity and atmospheric moisture through the progression of wet and dry seasons or exposure to extreme drought conditions. In the latter case, increasing soil salinity in association with drought would reduce the hydration state that could be achieved through supply of soil water from the roots, while a dry atmosphere could limit the supply of water obtained via foliar water uptake. Indeed, such combined effects may have contributed to drought-induced dieback of mangroves growing in hypersaline soils (Lovelock *et al.* 2009) and may underlie the recent large-scale dieback of a 700 km stretch of mangrove forest in Northern Australia following unusually hot and dry atmospheric conditions (Duke *et al.* 2017). Thus, the results of the present study underscore the importance of understanding leaf features that may provide a means of assessing responses of key vegetation types to climate change and climate extremes.

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