



## Contrasting photosynthetic characteristics of forest vs. savanna species (Far North Queensland, Australia)

K. J. Bloomfield<sup>1,\*</sup>, T. F. Domingues<sup>2,\*\*</sup>, G. Saiz<sup>3,\*\*\*</sup>, M. I. Bird<sup>4</sup>, D. M. Crayn<sup>5</sup>, A. Ford<sup>6</sup>, D. J. Metcalfe<sup>6</sup>, G. D. Farquhar<sup>1</sup>, and J. Lloyd<sup>7,8,\*</sup>

<sup>1</sup>Division of Plant Sciences, Research School of Biology, The Australian National University, Canberra, ACT 2601, Australia

<sup>2</sup>Universidade de São Paulo, Faculdade de Filosofia Ciências e Letras de Ribeirão Preto, São Paulo, Brazil

<sup>3</sup>Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research, Garmisch-Partenkirchen, Germany

<sup>4</sup>School of Earth and Environmental Sciences and Centre for Tropical Environmental and Sustainability Science, James Cook University, Cairns, Queensland, Australia

<sup>5</sup>Australian Tropical Herbarium and Centre for Tropical Biodiversity and Climate Change, James Cook University, Cairns, Queensland, Australia

<sup>6</sup>CSIRO Ecosystem Sciences Tropical Forest Research Centre, Atherton, Queensland, Australia

<sup>7</sup>Department of Life Sciences, Imperial College London, Silwood Park Campus, Ascot, SL5 7PY, UK

<sup>8</sup>School of Marine and Tropical Biology and Centre for Tropical Environmental and Sustainability Science, James Cook University, Cairns, Queensland, Australia

\*previously at: School of Geography, University of Leeds, Leeds, LS2 9JT, UK

\*\*previously at: School of Geosciences, University of Edinburgh, Edinburgh, EH8 9XP, UK

\*\*\*previously at: School of Geography & Geosciences, University of Saint Andrews, Saint Andrews, KY16 9AL, UK

Correspondence to: K. J. Bloomfield (keith.bloomfield@anu.edu.au)

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**Abstract.** Forest and savanna are the two dominant vegetation types of the tropical regions with very few tree species common to both. At a broad scale, it has long been recognised that the distributions of these two biomes are principally governed by precipitation and its seasonality, but with soil physical and chemical properties also potentially important. For tree species drawn from a range of forest and savanna sites in tropical Far North Queensland, Australia, we compared leaf traits of photosynthetic capacity, structure and nutrient concentrations. Area-based photosynthetic capacity was higher for the savanna species with a steeper slope to the photosynthesis ↔ nitrogen (N) relationship compared with the forest group. Higher leaf mass per unit leaf area for the savanna trees derived from denser rather than thicker leaves and did not appear to restrict rates of light-saturated photosynthesis when expressed on either an area or mass basis. Median ratios of foliar N to phosphorus (P) were relatively high (> 20) at all sites, but we found no evidence for a dominant P limitation of photosynthesis

for either forest or savanna trees. A parsimonious mixed-effects model of area-based photosynthetic capacity retained vegetation type and both N and P as explanatory terms. Resulting model-fitted predictions suggested a good fit to the observed data ( $R^2 = 0.82$ ). The model's random component found variation in area-based photosynthetic response to be much greater among species (71 % of response variance) than across sites (9 %). These results suggest that, on a leaf-area basis, savanna trees of Far North Queensland, Australia, are capable of photosynthetically outperforming forest species at their common boundaries.

### 1 Introduction

Forests and savannas dominate the tropical vegetated regions covering 15–20 % of Earth's surface (Torello-Raventos et al., 2013). At a broad scale, it has been long recognised that the distribution of these two biomes, each with its own

**Table 1.** Key symbols and abbreviations.

|                 |   |
|-----------------|---|
| FNQ             | Far North Queensland  |
| N               | Nitrogen  |
| P               | Phosphorus  |
| V               | Vegetation type   |
| F               | Forest  |
| S               | Savanna   |
| $\Phi$          | Plant functional type   |
| $A_{\max}$      | Rate of CO <sub>2</sub> assimilation, light and CO <sub>2</sub> saturated |
| $A_N$           | Photosynthetic nitrogen use efficiency                                    |
| $A_P$           | Photosynthetic phosphorus use efficiency                                  |
| $g_s$           | Stomatal conductance to CO <sub>2</sub> diffusion                         |
| $J_{\max}$      | Light saturated potential rate of electron transport                      |
| $V_{\max}$      | Maximum carboxylation velocity  |
| $d$             | Leaf (lamina) thickness   |
| $\rho$          | Leaf density  |
| $M_a$           | Leaf mass per unit area   |
| $\xi$           | Leaf dry matter content   |
| Subscripted “a” | Per unit leaf area  |
| Subscripted “m” | Per unit leaf dried mass  |

structural characteristics and species composition, is principally governed by precipitation and its seasonality (Schimper, 1903), but with soil chemical characteristics also important (Lloyd et al., 2008; Lloyd et al., 2009; Lehmann et al., 2011). Edaphic conditions are especially influential in regions where the two biomes intersect – often referred to as “ecotones” or “zones of (ecological) tension” (ZOT) – both forest and savanna existing as discrete “patches” under similar climatic conditions (Cochrane, 1989; Ratter, 1992; Thompson et al., 1992; Hoffmann et al., 2009; Lehmann et al., 2011; Saiz et al., 2012; Veenendaal et al., 2014). The patchiness of the ZOT mosaic at small spatial scales has led some to argue that disturbances, principally fire, must interact with climatic/edaphic boundaries in determining the transition between the two alternative vegetation types (e.g. Lehmann et al., 2011; Hoffmann et al., 2012). Whatever the drivers, feedbacks associated with changes to distributions of these biomes in response to anthropogenic climate change have the potential to substantially modify the rate of future global warming (e.g. Malhi et al., 2009).

The underlying causes of variation in photosynthetic carbon acquisition across and within these two biomes remain, however, poorly understood. There is, nevertheless, accumulating evidence that for tropical forest species phosphorus (P) availability may limit photosynthetic rates and productivity (Vitousek, 1984; Domingues et al., 2010; Mercado et al., 2011; Quesada et al., 2012). Whereas in savanna ecosystems nitrogen (N) may be more important as a limiting nutrient (Lloyd et al., 2009). Soils in Australia are generally highly weathered with the consequence that plant performance, even in the subtropical and temperate regions, is often considered more limited by the supply of P than of N (Beadle, 1962, 1966; Webb, 1968). Nevertheless, in Far North Queensland (FNQ), where almost all the Australian tropical forest occurs, recent volcanic activity (0.01–4.5 Ma BP –

before present) has produced some very young soils. These young basaltic soils cover about 60 % of FNQ’s land area (Whitehead et al., 2007) and display higher levels of organic matter and total P when compared with other parent material groupings such as granitic or metamorphic (Spain, 1990). Direct links from soil P status to measures of forest productivity are not straightforward, however, and interspecific variations in P use efficiency are likely to have contributed to the varied composition of local plant communities (Gleason et al., 2009). Likely selection pressures, on infertile soils, for enhanced P use efficiency coupled with FNQ’s recent volcanic history mean that primacy for P as the major limiting nutrient to photosynthetic capacity is still hypothetical.

The forest and savanna vegetation types (Vs) have very few plant species in common (Torello-Raventos et al., 2013) and the edaphic determinants of the ZOT are of particular interest in Australia (Beadle, 1962, 1966; Russell-Smith et al., 2004). The savannas of FNQ are distinctive globally being dominated by eucalypts (Myrtaceae). Here, species of the closely related genera *Eucalyptus* and *Corymbia* are characterised by sclerophyllous (hard) leaves with relatively low leaf [N], but a high oil content and correspondingly high heat of combustion (Beadle, 1966) – traits that contribute to a highly flammable leaf litter. In contrast to the tree species of the moist forests, such evergreen savanna species are expected to be able to withstand periods of water shortage and high water vapour pressure deficit. Sclerophylly imparts both structural and physiological leaf traits but, to date, most research has focused on the structural aspects: leaf thickness and density combining in the ratio of leaf mass per unit area ( $M_a$ , g m<sup>-2</sup>). Sclerophyllous leaves are often amphistomatous (i.e. with stomata abundant on both the adaxial and abaxial surfaces) displaying an isobilateral mesophyll distribution (Burrows, 2001) – characteristics thought to be associated with both high photosynthetic potentials (Mott et al., 1982) and high-insolation environments (Pyykko, 1966; Parkhurst, 1978). Such ecophysiological associations are expected on theoretical grounds, especially under conditions of low water availability (Buckley et al., 2002) and it may be that sclerophyllous eucalypt leaves display an “investment strategy” that at once combines resilience with high photosynthetic return (Cernusak et al., 2011).

Broad overlap in leaf traits has been reported for savanna and forest tree species, but, due to different soils and the drier conditions typical of savannas, we might expect differences between the two vegetation types in leaf N and P content, rates of photosynthesis, morphology and longevity (Wright et al., 2001; Buckley et al., 2002; Meir et al., 2007; Domingues et al., 2010). It remains unclear, however, whether such differences persist within the relatively narrow boundaries of a ZOT. In addition, within individual tropical forest stands, leaves can vary markedly in their physiological and structural properties depending on canopy position and the availability of gaps (Popma et al., 1992; Lloyd et al., 2010). Indeed tropical forest tree species are

**Table 2.** Plot coordinates after Torello-Raventos et al. (2013), vegetation classification  $\nabla$ , elevation a.s.l.  $E_V$ , mean annual temperature  $T_A$ , mean annual precipitation  $P_A$ , 0.95 quantile upper stratum canopy height  $H^*$ , upper stratum canopy area index  $C_U$ , soil pH, soil exchangeable cations, soil extractable phosphorus and World Reference Base (WRB) soil classification for the study site's soil values represent the top 0.3 m of soil.

| Plot   | Lat       | Long       | $\nabla$              | $E_V$<br>(m) | $T_A$<br>(°C) | $P_A$<br>(m) | $H^*$<br>(m) | $C_U$<br>(m <sup>2</sup> m <sup>-2</sup> ) | pH   | [Al] <sub>ex</sub> | [Ca] <sub>ex</sub> | [K] <sub>ex</sub> | [Mg] <sub>ex</sub> | [Na] <sub>ex</sub> | [P] <sub>ex</sub><br>(μg g <sup>-1</sup> ) | WRB soil classification                           |
|--------|-----------|------------|-----------------------|--------------|---------------|--------------|--------------|--|------|--------------------|--------------------|-------------------|--------------------|--------------------|--|---|
|        |           |            |                       |              |               |              |              |  |      |                    |                    |                   |                    |                    |  |   |
| CTC-01 | 16.103° S | 145.447° E | Tall forest           | 90           | 25.2          | 3.20         | 38.9         | 2.36                                       | 5.56 | 0.48               | 17.94              | 0.71              | 7.65               | 0.65               | 208  | Haplic Cambisol (Hyperdystric, Alu-mic, Skeletic) |
| KBL-01 | 17.764° S | 145.544° E | Tall forest           | 761          | 20.5          | 1.75         | 38.0         | 1.45                                       | 4.79 | 0.27               | 4.71               | 0.35              | 2.58               | 0.36               | 952  | Haplic Regosol (Siltic, Hyperdystric)             |
| KBL-03 | 17.685° S | 145.535° E | Tall forest           | 1055         | 19.1          | 1.34         | 35.8         | 2.30                                       | 4.38 | 4.84               | 0.90               | 0.47              | 1.82               | 0.62               | 227  | Haplic Nitisol (Hyperdystric, Rhodic)             |
| KCR-01 | 17.107° S | 145.604° E | Tall forest           | 813          | 20.5          | 1.96         | 44.0         | 2.21                                       | 5.40 | 0.60               | 16.11              | 0.78              | 5.71               | 0.39               | 165  | Haplic Cambisol (Dystric, Alu-mic)                |
| DCR-01 | 17.026° S | 145.597° E | Tall savanna woodland | 683          | 21.2          | 1.45         | 26.2         | 1.63                                       | 5.65 | 0.90               | 8.78               | 0.71              | 6.93               | 0.71               | 79   | Haplic Cambisol (Orthodystric, Alu-mic)           |
| DCR-02 | 17.021° S | 145.584° E | Tall savanna woodland | 653          | 21.3          | 1.46         | 22.1         | 0.70                                       | 5.52 | 1.27               | 8.82               | 0.55              | 5.74               | 0.33               | 56   | Arenic Cambisol (Epieutric)                       |
| KBL-02 | 17.849° S | 145.532° E | Tall savanna woodland | 860          | 20.1          | 1.43         | 28.1         | 0.77                                       | 5.28 | 0.26               | 4.78               | 0.17              | 7.66               | 0.77               | 216  | Geric Acrisol (Hyperdystric, Rhodic)              |

often grouped according to their degree of shade tolerance and/or light requirement (e.g. Swaine and Whitmore, 1988; but see Poorter, 1999). Shade-tolerant species in the understorey may receive less than 2 % of full light at the canopy crown (Chazdon, 1992) whilst pioneer species typically require high light exposure for germination and survival and depend on the creation of canopy gaps (Turner, 2001). As a result, species characteristic of differing light niches have commonly been considered to display distinctive photosynthetic traits linked to nutrient investment, allocation and leaf architecture (Niinemets, 1997; Carswell et al., 2000; Wright et al., 2001). In the context of P availability, a study in the forest of Guyana, on relatively infertile Ferralsols, found that pioneer tree species exhibited higher photosynthetic nitrogen and phosphorus use efficiencies than neighbouring climax species (defined here as those species whose seeds can germinate and establish in the shade) (Raaimakers et al., 1995). Fyllas et al. (2012), in describing forest tree species of the Amazon Basin, derived four discrete PFTs (plant functional types) aligned with the species' stature, canopy position and pioneering ability. It remains to be seen whether such an attractively simple system can be applied to tropical forest species of FNQ.

In this study we contrast leaf photosynthetic traits for tree species from forest and savanna communities of northern Australia addressing the following questions.

1. Are there differences in photosynthetic capacity and nutrient use efficiency between adjacent forest and savanna vegetation types?
2. And, if so, are these distinctions associated with systematic differences in leaf structural traits?
3. Is there evidence of a greater role for P rather than N (or vice versa) in determining photosynthetic capacity across both sites and species?

4. Can a simple classification system based on light requirement and adult stature help to describe observed variation in photosynthetic traits of tropical forest trees?

## 2 Materials and method

### 2.1 Sites and species

A series of sites was selected in FNQ, Australia, in an arc from the Atherton Tablelands, inland from Cairns, to Cape Tribulation, north of the Daintree River. The series, which forms part of the Tropical Biomes in Transition (TROBIT) network, was designed to provide a contrast of vegetation types, specifically forest (F) and savanna (S), and are located on diverse soils (Table 2). Further descriptions of all sites and the rationale (both structural and floristic) for our distinction between F and S are available in Torello-Raventos et al. (2013). Seven sites were visited in 6 weeks of fieldwork during April and May 2009 and measurements were performed on 125 trees representing 30 species. A full list of species by site is presented in Table S1 (Supplement).

### 2.2 Gas exchange measurements

Leaf gas-exchange measurements were performed using a portable photosynthesis system (Li-Cor 6400, Li-Cor, Lincoln, NE, USA) on young, fully developed leaves. During the measurements, chamber conditions were set with block temperature (mean 27 °C) held slightly above ambient air temperature to avoid problems of condensation; relative humidity remained close to ambient (mean = 67 %). The rate of air flow to the sample cell was held constant at 500 μmol s<sup>-1</sup> but, exceptionally, when faced with very low stomatal conductance this was reduced (minimum 250 μmol s<sup>-1</sup>). Light ( $A \leftrightarrow Q$ ) curves were generated for each tree species to determine the saturating light level for adoption in subsequent CO<sub>2</sub> response curves ( $A_a \leftrightarrow C_i$  curves). Those saturating light levels ranged from 500 to 2000 μmol m<sup>-2</sup> s<sup>-1</sup>.

Measurements of light-saturated net CO<sub>2</sub> assimilation per unit leaf area ( $A_a$ ) were then obtained for a range of intercellular CO<sub>2</sub> concentrations ( $C_i$ ) by varying chamber CO<sub>2</sub> concentration ( $C_a$ ). The  $A_a \leftrightarrow C_i$  curves provided area-based values of light-saturated photosynthesis under ambient and elevated atmospheric [CO<sub>2</sub>] ( $A_{\text{sat}, a}$  and  $A_{\text{max}, a}$ , respectively). For the purposes of modelling photosynthetic capacity we focus on variations in  $A_{\text{max}}$  – preferred over  $A_{\text{sat}}$  in this context as it is less susceptible to limitations of stomatal conductance ( $g_s$ ).

In the absence of cranes or suspended walkways, branches had to be cut from trees. Sun-exposed branches for short trees were reached using handheld secateurs or forestry shears on telescopic poles; for taller tree branches were pulled down using a weighted line shot from a catapult. Trees of subcanopy species were rarely found growing in full sunlight; therefore, their leaves, although sampled from upper branches free of self-shading, developed in a relatively low-light environment. Once detached, the stem was recut under water in order to re-establish the xylem water column (Domingues et al., 2010). Performing gas exchange measurements on excised branches can affect subsequent calculations where stomatal conductance is heavily depressed (Santiago and Mulkey, 2003). The  $A_a \leftrightarrow C_i$  curves were reviewed for such instances and where necessary the data excluded from all further analysis ( $n = 11$ ). A further check on data integrity proposed by Kattge et al. (2009) rejects those measurements where  $A_{\text{sat}} / [\text{N}]_{\text{m}}$  is  $< 2 \mu\text{mol CO}_2 \text{ g}^{-1} \text{N s}^{-1}$ ; any such curves were likewise excluded ( $n = 2$ ).

### 2.3 Leaf morphology and nutrient analysis

At the completion of gas-exchange measurements, the leaf (gas leaf) was cut from the branch and leaf thickness ( $d$ ,  $\mu\text{m}$ ) taken by averaging repeated measurements (Mitutoyo dial thickness gauge,  $n = 6$ ) alternating back and forward across the mid-vein and proceeding down the lamina from tip to base. A series of discs (6.6 mm, diameter) was then punched from the leaf avoiding veins and necrosis or other damage. The discs with the remainder of the leaf (petiole and mid-vein discarded) were oven dried at 70 °C for a minimum of 48 h before their dried mass was recorded. The combination for the discs of known area and dried mass allowed calculating leaf mass per unit area ( $M_a$ ,  $\text{g m}^{-2}$ ). Leaf density ( $\rho$ ,  $\text{g cm}^{-3}$ ) was estimated using the equation

$$\rho = M_a/d. \quad (1)$$

In addition to the gas leaf, the opposing leaf was also cut from the branch, petiole and mid-vein discarded, and placed in a ziplock plastic bag with moist cotton wool until fresh mass could be measured that evening (or exceptionally the next day). The leaf was then placed in an envelope, oven-dried as above and dried mass recorded. The ratio of the leaf's dried to fresh mass is termed leaf dry matter content ( $\xi$ ). All subsequent references to  $\xi$  relate to opposing and not gas leaves.

Logistical constraints imposed by repeated changes of base camp and lack of electricity supply meant that delays were experienced between harvesting the leaves and oven drying (maximum delay of 30 days).

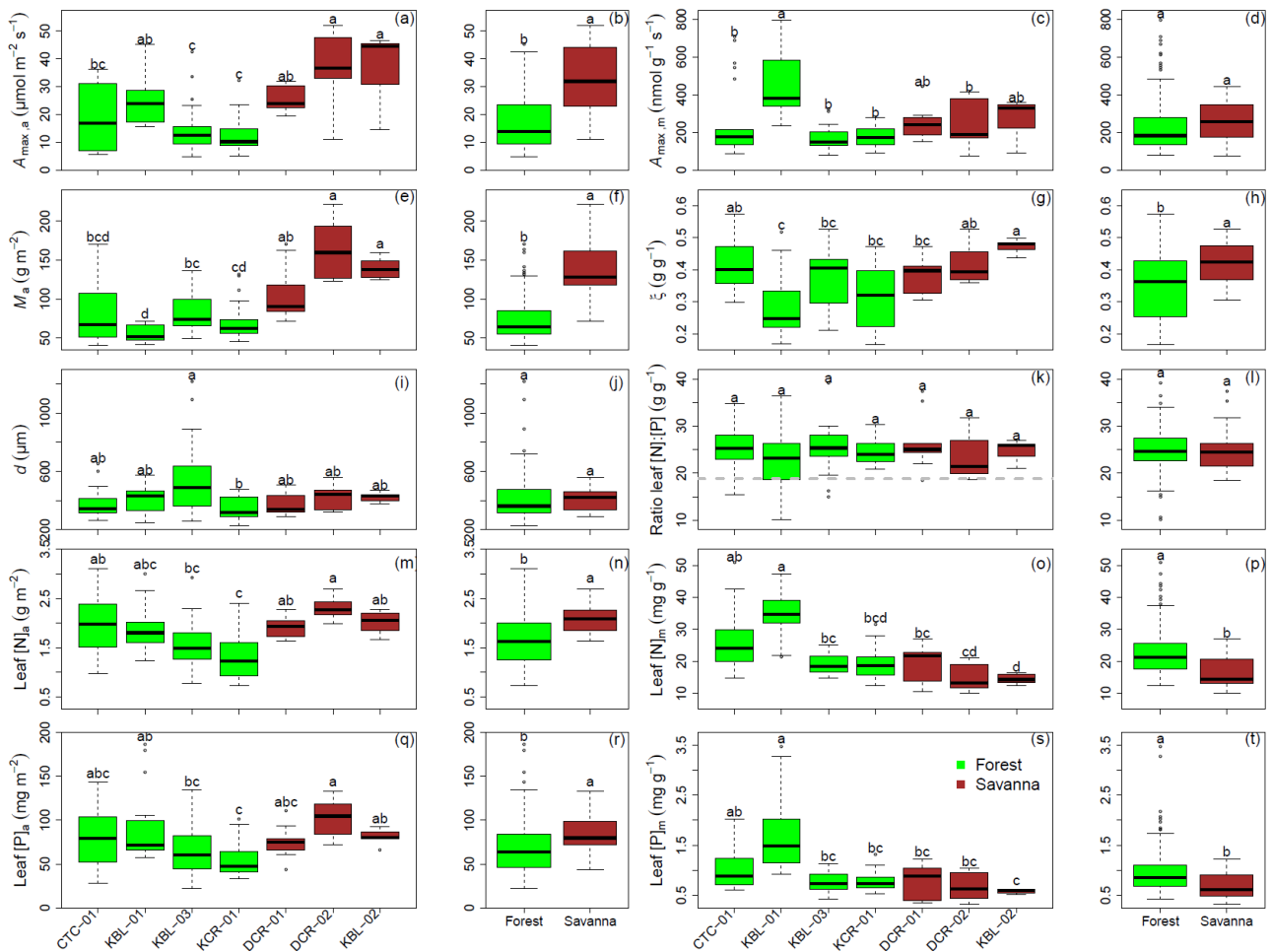
Oven-dried material was used for determination of total leaf [N] and [P]: dried ground leaf material was acid-peroxide digested before colorimetric analysis using a segmented flow analyser (Skalar San<sup>+</sup> System, Breda, the Netherlands). The photosynthetic efficiency of nutrient use was estimated as the maximal rate of carbon gain per unit of leaf N and P ( $A_N$  and  $A_P$ , respectively).

### 2.4 Statistical analyses

All statistical analysis and modelling was conducted using the open-source statistical environment R (R Development Core Team, 2011). As initial data exploration revealed wide variation in many trait values across the different sites, non-parametric Kruskal–Wallis tests were used to test for differences among the categorical factors of site and  $\nabla$  using the coin package (Hothorn et al., 2008). Where significant, differences among factor levels were assigned using Tukey's HSD (honest significant difference) post hoc tests ( $p < 0.05$ ) applied to data rankings. After exclusion of poor  $A_a \leftrightarrow C_i$  curves ( $n = 13$ , described above) and replicates with other missing values ( $n = 3$ ), the revised data-set of 109 leaf measurements contained many more observations for  $\mathbb{F}$  ( $n = 85$ ) than  $\mathbb{S}$  ( $n = 24$ ); therefore, there is an element of imbalance in the test specification where  $\nabla$  is adopted as the fixed factor. Bivariate relationships were described using standardised major axis (SMA) line fits using smatr-3 (Warton et al., 2006). Relationships between replicated foliar traits (photosynthesis, nutrient content) and site-dependent variables (soil, climate) were quantified using Kendall's non-parametric rank-order correlation ( $\tau$ ,  $\tau$ ); especially appropriate in cases with many replicated response values for each value of the predictor variable (Legendre and Legendre, 2012).

### Mixed-effects linear model of photosynthetic capacity

The study involved replicated measurements of tree species within and across forest and savanna plots. Such a design introduced the strong likelihood that measurements within the same site would be influenced by spatial proximity. In specifying a model that attempted to explain differences in photosynthetic capacity between  $\nabla$ , it was necessary to recognise this hierarchical structure in order to avoid systematic variation in the residuals leading to potentially biased interpretation (Zuur et al., 2009). The sites and species selected, rather than considered of primary interest per se, were viewed as representative of a wider population and focus was placed on their variance. The model's random component therefore included the categorical variables of species nested within sites. Unfortunately, because not all tree species at all



**Figure 1.** Paired boxplots of key leaf traits (untransformed data) by site and  $\nabla$ . The two  $\nabla$  classes are distinguished by colour: green for forest and brown for savanna. Site abbreviations are laid out in Table 2. Leaf traits are photosynthetic capacity (**a**, **b**) per unit leaf area and (**c**, **d**) per unit leaf dried mass; (**e**, **f**) leaf mass per unit area; (**g**, **h**) leaf dried matter content; (**i**, **j**) leaf thickness; (**k**, **l**) ratio of total leaf nitrogen to phosphorus; total leaf nitrogen (**m**, **n**) per unit leaf area and (**o**, **p**) per unit leaf dried mass; total leaf phosphorus (**q**, **r**) per unit leaf area and (**s**, **t**) per unit leaf dried mass. The box and whiskers show the median result as a thick horizontal band, the ends of the box denote the interquartile range; the whiskers extend 1.5 times the interquartile range or to the most extreme value, whichever is smaller; any points outside these values are shown as outliers. The grey dashed line in plot *k* represents a mean N:P ratio of 18.8 reported for tropical forests by Reich et al. (2009).

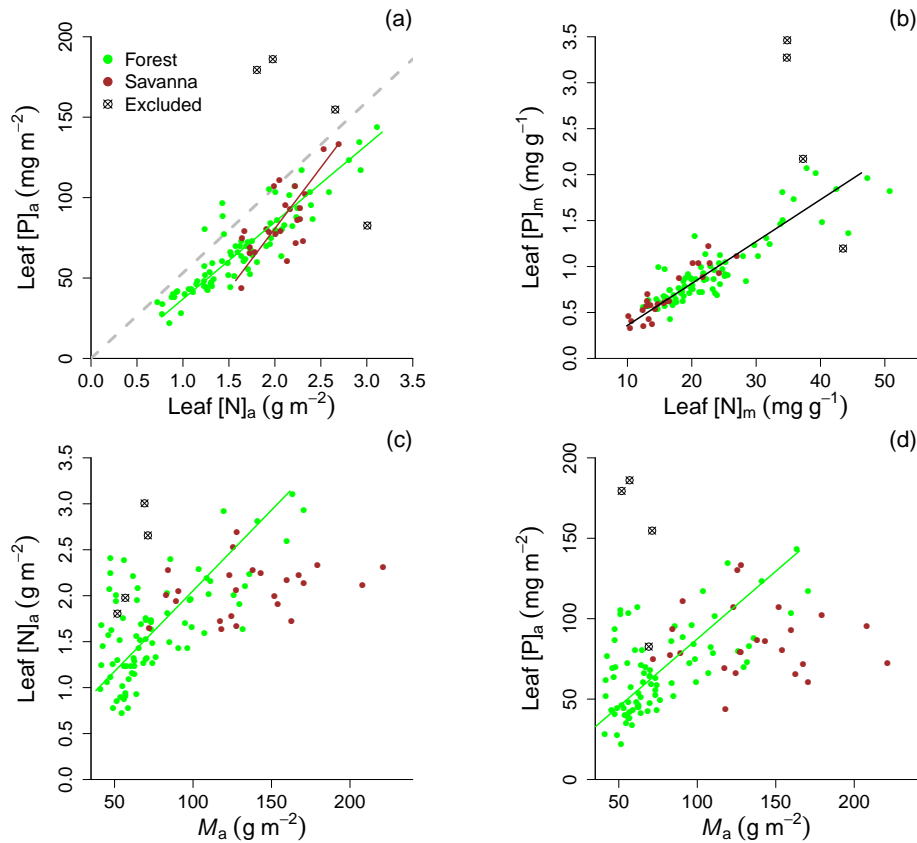
sites were measured with replication (see instances of  $n = 1$  in Table S1), convergence problems meant that the random component of the model could not accommodate differing slopes as well as intercepts for species within a site.

The final model (fitted using the nlme package in R) may be expressed as

$$A_{\max, a[ijk]} = \alpha + \beta_1 b_{jk} + \beta_2 [N]_{a[ijk]} + \beta_3 [P]_{a[ijk]} + a_k + a_{jk} + \varepsilon_{ijk}. \quad (2)$$

Here response variable  $A_{\max, a[ijk]}$  denotes the maximum rate of area-based photosynthesis for observation  $i$  of species  $j$  at site  $k$  with  $b$  being a categorical variable taking a base value of 0 for species in plots classified as  $\mathbb{F}$  and a value of 1 for  $\mathbb{S}$ . The term  $a_k$  is a random intercept and allows for

variation among sites. The term  $a_{jk}$  allows for interspecific variation at the same site. The term  $\varepsilon_{ijk}$  is the residual (unexplained) error and represents the within-site variation, i.e. variation among plants of the same species and measurement error. Each of the variation terms is assumed to be normally distributed with mean zero. With the independent covariates centred (i.e. zeroed on the population mean), the fitted intercept term  $\alpha$  thus represents the predicted forest tree  $A_{\max, a}$  at the  $(\mathbb{F} + \mathbb{S})$  population mean  $[N]_a$  and  $[P]_a$ . The term  $\beta_1 b$  represents the difference in predicted  $A_{\max, a}$  between the two  $\nabla$  values (in this case  $A_{\max, a}[\mathbb{S}] - A_{\max, a}[\mathbb{F}]$ ). The predicted  $\mathbb{S}$  tree  $A_{\max, a}$  at the population mean  $[N]_a$  and  $[P]_a$  values is therefore  $\alpha + \beta_1$ .



**Figure 2.** Scatterplots of the relationships between leaf phosphorus and leaf nitrogen (a) on an area basis and (b) on a mass basis. Plot (c) shows the relationship between leaf nitrogen on an area basis and leaf mass per unit area; plot (d) shows the equivalent relationship for leaf phosphorus. Each point corresponds to a single tree and vegetation types are distinguished by colour: green for  $\mathbb{F}$  and brown for  $\mathbb{S}$ . SMA-fitted lines are shown for the two vegetation types only where the bivariate relationship proved significant  $p < 0.05$ . Pearson correlations testing the assumption of linearity are given in Table S4 together with the likelihood ratio and Wald statistics testing the  $H_0$  of common slope, elevation and axis shift for the two  $\mathbb{V}$  classes. Intercept, slope and  $r^2$  values for the SMA-fitted lines are given in Table 3. In plot (a) a third fitted line (grey, dashed) displays a slope based on a mean N:P ratio of 18.8 typical for tropical forests as reported by Reich et al. (2009) and passing through the origin. In plot (b) there is a common slope to the  $[P]_m \leftrightarrow [N]_m$  relationship for both vegetation types (black line). In reviewing residual plots of initial SMA fits (not shown), four data points were identified as outliers (crossed circles). The four outliers have been excluded from the rerun SMA fits shown here.

## 2.5 Plant functional types

$\mathbb{F}$  species were assigned to one of four plant functional types ( $\Phi$ ) depending on their adult stature and light requirements for recruitment (Veenendaal et al., 1996). Three of the authors (D. M. Crayn, A. Ford and D. J. Metcalfe), each with an extensive knowledge of Australian tropical forest trees, made independent  $\Phi$  assignments before the combined results were consolidated and minor discrepancies resolved. The  $\Phi$  descriptions are provided in Table S2 and the relevant species designations in Table S1. All of the tropical moist forest species in this study are obligate evergreen.

## 3 Results

### 3.1 Key leaf traits: forest versus savanna trees

There was a tenfold range across the data-set in photosynthetic capacity per unit leaf area ( $A_{\max, a}$ ) from 4.9 to  $52.0 \mu\text{mol m}^{-2} \text{s}^{-1}$  (Fig. 1a). Mean values (treating each sampled tree as an independent variable) differed among sites ( $p < 0.0001$ ) and were significantly higher in the  $\mathbb{S}$  plots (Fig. 1b;  $p < 0.0001$ ). When expressed per unit leaf dried mass, photosynthetic capacity ( $A_{\max, m}$ ) was also highly variable with significant plot-to-plot differences (Fig. 1c;  $p < 0.0001$ ). Overall there was, however, no difference in mean  $A_{\max, m}$  between  $\mathbb{F}$  and  $\mathbb{S}$  (Fig. 1d;  $p = 0.11$ ). There were striking intersite differences in leaf mass per unit area ( $M_a$ ; Fig. 1e) which was highly variable, spanning a fivefold range from lowest to highest observations. Overall,  $M_a$  was

higher for  $\mathbb{S}$  than for  $\mathbb{F}$  (Fig. 1f;  $p < 0.0001$ ). That contrast in  $M_a$  derived chiefly from variable leaf dry matter content ratios ( $\xi$ ) with a threefold variation in  $\xi$  observed. Of note were pronounced differences among sites (Fig. 1g;  $p < 0.0001$ ) and, like  $M_a$ , higher mean values for  $\mathbb{S}$  than for  $\mathbb{F}$  (Fig. 1h;  $p = 0.0035$ ). By contrast, there was no difference between  $\mathbb{S}$  and  $\mathbb{F}$  for measures of leaf thickness ( $d$ ) (Fig. 1j;  $p = 0.70$ ) which was also much less variable.

Both area- and mass-based leaf nitrogen levels were highly variable and this was most pronounced within the  $\mathbb{F}$  plots. On an area basis, differences among sites (Fig. 1m;  $p < 0.0001$ ) produced higher mean  $[N]_a$  values for  $\mathbb{S}$  than for  $\mathbb{F}$  (Fig. 1n;  $p = 0.0002$ ) with this intersite N variability even more pronounced on a mass basis (Fig. 1o;  $p < 0.0001$ ). Overall, mean  $[N]_m$  was higher for  $\mathbb{F}$  than for  $\mathbb{S}$  (Fig. 1p;  $p < 0.0001$ ). Broadly similar trends were observed for total leaf phosphorus with higher mean  $[P]_a$  for  $\mathbb{S}$  versus  $\mathbb{F}$  (Fig. 1r;  $p = 0.003$ ), with that ranking also reversed when expressed on a mass basis (Fig. 1t;  $p = 0.0004$ ). Foliar ratios of  $[N]:[P]$  ranged from 10.1 (*Neisosperma poweri*, KBL-01) to 39.1 (*Symplocos hayesii*, KBL-03) but, on average, did not differ across plots (Fig. 1k;  $p = 0.29$ ) and showed no systematic differences between  $\mathbb{F}$  and  $\mathbb{S}$  (Fig. 1l;  $p = 0.74$ ).

Considering the data-set as a whole (i.e.  $\mathbb{F}$  and  $\mathbb{S}$  trees combined), significant correlations of  $A_{\max, a}$  with environmental variables such as elevation, temperature and soil cation status were found. However, these are mirrored by significant correlations of the same sign for both leaf  $[P]_a$  and  $[N]_a$  (Table S3). In investigating the underlying sources of our dataset's tree-to-tree variation in photosynthetic properties, we therefore focussed (using the mixed-effects model) on associated tree-to-tree variations in leaf-based nitrogen and phosphorus concentrations; checking for any edaphic or climatic effect beyond that through an examination of model residuals in relation to the site-associated climate and soil covariates.

### 3.2 Leaf nutrient relationships

There was a strong positive linear relationship between leaf  $[P]_a$  and  $[N]_a$  for both  $\mathbb{F}$  and  $\mathbb{S}$  (Fig. 2a), but with a steeper slope observed for  $\mathbb{S}$ . The shallower slope for  $\mathbb{F}$  differs ( $p = 0.031$ ) from the mean relationship for tropical forests as suggested by Reich et al. (2009), depicted by the dotted line passing through the origin in Fig. 2a (slope =  $10^3/18.8$ ). When expressed on a mass basis, there was a single, common  $P \leftrightarrow N$  relationship for both  $\mathbb{V}$ s (Fig. 2b). Leaf nutrient investment on an area basis showed positive relationships with  $M_a$  for  $\mathbb{F}$  only (Fig. 2c, d).

To test for differences in the photosynthesis  $\leftrightarrow$  nutrient relationships between the two  $\mathbb{V}$ s, a series of SMA analyses was undertaken with photosynthetic capacity ( $A_{\max}$ ) as the response variable and leaf chemistry ( $[N]$  and  $[P]$ ) as the explanatory bivariate (Table 3). For the combined data-set, linear relationships were strong for both nutrients irrespective

of whether variables were expressed on a mass or area basis ( $r$  values ranging from 0.63 to 0.70; Table S4).

The  $A_{\max, a} \leftrightarrow [N]_a$  association as shown in Fig. 3a suggests two important differences between the two  $\mathbb{V}$ s. First, across the (pooled) data-set the lowest 0.3 fraction of  $[N]_a$  is confined to  $\mathbb{F}$ -associated trees (as can also be inferred from Figs. 1 and 2). Second, for the lowest  $[N]_a$  for  $\mathbb{S}$ -associated trees (ca.  $1.6 \text{ g m}^{-2}$ ), similar  $A_{\max, a}$  values are observed for both  $\mathbb{S}$  and  $\mathbb{F}$ , but as  $[N]_a$  increases beyond that point  $A_{\max, a}$  for  $\mathbb{S}$  rises with a sensitivity nearly 3 times that observed for  $\mathbb{F}$ . There was no difference between the two  $\mathbb{V}$ s in either the slope or the intercept of the  $A_{\max, a} \leftrightarrow M_a$  association (Table S4) and a single line ( $r^2 = 0.3$ ) describes the common positive relationship (Fig. 3c).

### 3.3 Nutrient use efficiency and leaf structure

Elevated rates of photosynthesis per unit N yielded higher photosynthetic use efficiencies ( $A_N$ ) for  $\mathbb{S}$  species (Fig. 4a). Of the  $\mathbb{F}$  trees only the tall pioneers showed an equivalent  $A_N$  to the  $\mathbb{S}$  species and there was a significant difference between tall pioneers and shade-tolerant species. Very similar patterns were observed for  $A_P$  (Fig. 4b).

The higher  $M_a$  values for the  $\mathbb{S}$  trees (Fig. 1f) suggested underlying differences in leaf structure between the two  $\mathbb{V}$ s and the range of  $M_a$  values for separate  $\Phi$  classes showed distributions centred at different points along the  $M_a$  axis (Fig. S1). Whilst we found positive relationships for  $M_a$  with  $d$  and  $\rho$ , the slopes of those relationships were  $\mathbb{V}$ -dependent (Fig. 5a, b) and the association was much stronger for the  $\mathbb{S}$  group. Over common ranges of  $M_a$ , the  $\mathbb{F}$  trees displayed the thicker leaves (measured fresh) – a result heavily influenced by the upper canopy group. Indeed,  $M_a$  was seldom greater than  $75 \text{ g m}^{-2}$  for either the small pioneer or sub-canopy classes but, for any given  $M_a$ , the ratio of leaf dry mass to water content ( $\varphi$ , as an index of sclerophylly) was much higher for the small pioneers (Fig. 5c). The slope of the relationship  $\varphi \leftrightarrow M_a$  also differed among the  $\Phi$  classes ( $p < 0.0001$ ) – being shallowest for the  $\mathbb{S}$  trees (an increased ratio of 0.005 per unit  $M_a$ ) and steepest for the small pioneers (an increase of 0.019). Such structural differences among classes of  $\mathbb{V}$  and  $\Phi$  appeared unrelated, however, to our measure of photosynthetic N allocation:  $A_N$  was independent of  $d$  ( $p = 0.46$ ) and an overall correlation with  $M_a$  ( $p = 0.0009$ ) disappeared upon controlling for  $\mathbb{V}$  and  $\Phi$  (Fig. 5d).

### 3.4 Modelling photosynthetic capacity

In attempting to model variation in  $A_{\max, a}$  the starting, or maximal, fixed component of our linear mixed-effects model (model 1; Table 4) included, along with a  $\mathbb{V}$ -dependent term, those continuous variables spanning leaf morphology and chemistry suggested by pair-wise correlation plots in Fig. S2. The optimal fixed term, on AIC and likelihood ratio criteria, was provided by model 4: with vegetation type a

**Table 3.** Coefficients for SMA bivariate relationships. Vegetation contrasts: forest and savanna;  $n$ , number of observations;  $r^2$ , correlation coefficient and associated  $p$  value; intercept; slope and 95 % confidence interval (CI).

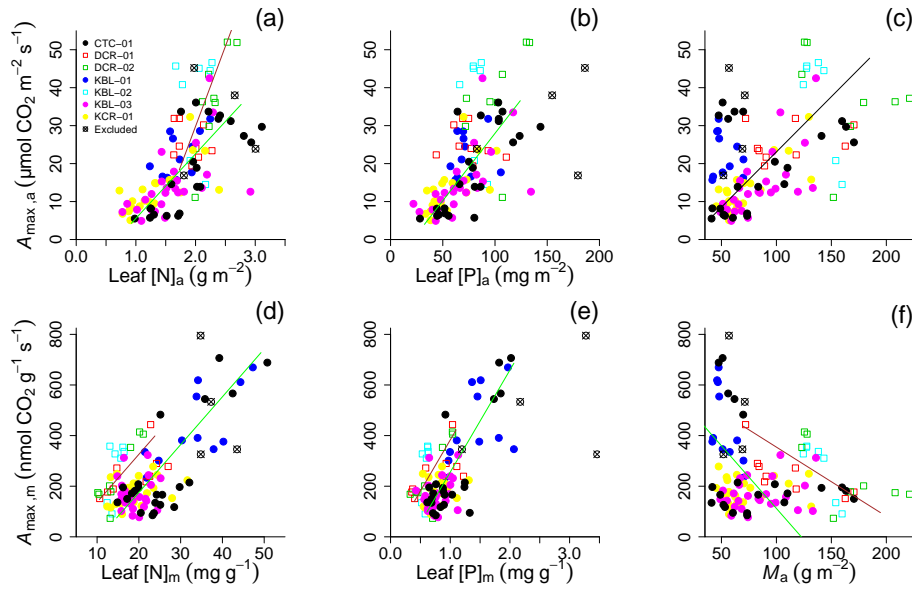
| Response         | Bivariate        | Vegetation class | $n$ | $r^2$ | $p$      | Intercept | Slope  | Slope:<br>low 95 % CI | Slope:<br>high 95 % CI |
|------------------|------------------|------------------|-----|-------|----------|-----------|--------|-----------------------|------------------------|
| [P] <sub>a</sub> | [N] <sub>a</sub> | Forest           | 81  | 0.82  | < 0.0001 | -11.01    | 47.92  | 43.58                 | 52.68                  |
|                  |                  | Savanna          | 24  | 0.51  | < 0.0001 | -70.96    | 75.86  | 55.87                 | 102.99                 |
| [P] <sub>m</sub> | [N] <sub>m</sub> | All              | 105 | 0.81  | < 0.0001 | -0.097    | 0.046  | 0.042                 | 0.050                  |
| [N] <sub>a</sub> | $M_a$            | Forest           | 81  | 0.43  | < 0.0001 | 0.299     | 0.018  | 0.015                 | 0.021                  |
|                  |                  | Savanna          | 24  | 0.08  | 0.1848   |           |        |                       |                        |
| [P] <sub>a</sub> | $M_a$            | Forest           | 81  | 0.38  | < 0.0001 | 3.31      | 0.84   | 0.71                  | 1.00                   |
|                  |                  | Savanna          | 24  | 0.00  | 0.8207   |           |        |                       |                        |
| $A_{\max,a}$     | [N] <sub>a</sub> | Forest           | 81  | 0.47  | < 0.0001 | -11.43    | 17.01  | 14.46                 | 20.00                  |
|                  |                  | Savanna          | 24  | 0.17  | 0.0442   | -54.48    | 42.15  | 28.47                 | 62.40                  |
| $A_{\max,a}$     | [P] <sub>a</sub> | Forest           | 81  | 0.47  | < 0.0001 | -7.52     | 0.35   | 0.30                  | 0.42                   |
|                  |                  | Savanna          | 24  | 0.09  | 0.1522   |           |        |                       |                        |
| $A_{\max,a}$     | $M_a$            | All              | 105 | 0.30  | < 0.0001 | -6.03     | 0.29   | 0.25                  | 0.34                   |
| $A_{\max,m}$     | [N] <sub>m</sub> | Forest           | 81  | 0.63  | < 0.0001 | -192.81   | 18.47  | 16.12                 | 21.16                  |
|                  |                  | Savanna          | 24  | 0.31  | 0.0049   | -100.47   | 21.87  | 15.26                 | 31.35                  |
| $A_{\max,m}$     | [P] <sub>m</sub> | Forest           | 81  | 0.61  | < 0.0001 | -148.85   | 404.67 | 352.06                | 465.15                 |
|                  |                  | Savanna          | 24  | 0.30  | 0.0061   | -14.60    | 394.68 | 274.50                | 567.47                 |
| $A_{\max,m}$     | $M_a$            | Forest           | 81  | 0.08  | 0.0132   | 607.15    | -4.95  | -6.13                 | -4.00                  |
|                  |                  | Savanna          | 24  | 0.30  | 0.0056   | 628.00    | -2.73  | -3.93                 | -1.90                  |
| $V_{c\max,a}$    | [N] <sub>a</sub> | Forest           | 81  | 0.41  | < 0.0001 | -50.19    | 59.99  | 50.57                 | 71.17                  |
|                  |                  | Savanna          | 24  | 0.23  | 0.0168   | -183.24   | 142.76 | 97.82                 | 208.35                 |
| $V_{c\max,m}$    | [N] <sub>m</sub> | Forest           | 81  | 0.66  | < 0.0001 | -0.94     | 0.071  | 0.063                 | 0.081                  |
|                  |                  | Savanna          | 24  | 0.35  | 0.0025   | -0.35     | 0.075  | 0.053                 | 0.107                  |
| $V_{c\max,a}$    | [P] <sub>a</sub> | Forest           | 81  | 0.41  | < 0.0001 | -36.40    | 1.25   | 1.06                  | 1.48                   |
|                  |                  | Savanna          | 24  | 0.17  | 0.0471   | -49.69    | 1.88   | 1.27                  | 2.79                   |
| $V_{c\max,m}$    | [P] <sub>m</sub> | Forest           | 81  | 0.65  | < 0.0001 | -0.77     | 1.56   | 1.37                  | 1.78                   |
|                  |                  | Savanna          | 24  | 0.35  | 0.0022   | -0.05     | 1.36   | 0.96                  | 1.92                   |
| $J_{\max,a}$     | [N] <sub>a</sub> | Forest           | 81  | 0.51  | < 0.0001 | -52.66    | 76.12  | 65.16                 | 88.92                  |
|                  |                  | Savanna          | 24  | 0.15  | 0.0660   |           |        |                       |                        |
| $J_{\max,m}$     | [N] <sub>m</sub> | Forest           | 81  | 0.65  | < 0.0001 | -0.89     | 0.083  | 0.073                 | 0.095                  |
|                  |                  | Savanna          | 24  | 0.37  | 0.0017   | -0.38     | 0.094  | 0.066                 | 0.133                  |
| $J_{\max,a}$     | [P] <sub>a</sub> | Forest           | 81  | 0.53  | < 0.0001 | -35.17    | 1.59   | 1.36                  | 1.85                   |
|                  |                  | Savanna          | 24  | 0.08  | 0.1873   |           |        |                       |                        |
| $J_{\max,m}$     | [P] <sub>m</sub> | Forest           | 81  | 0.65  | < 0.0001 | -0.69     | 1.82   | 1.59                  | 2.07                   |
|                  |                  | Savanna          | 24  | 0.33  | 0.0033   | -0.01     | 1.69   | 1.19                  | 2.41                   |
| $\varphi$        | $M_a$            | Forest           | 85  | 0.40  | < 0.0001 | -0.063    | 0.009  | 0.007                 | 0.010                  |
|                  |                  | Savanna          | 24  | 0.30  | 0.0056   | 0.086     | 0.005  | 0.003                 | 0.007                  |
| $d$              | $M_a$            | Forest           | 82  | 0.26  | < 0.0001 | 107.77    | 3.91   | 3.23                  | 4.72                   |
|                  |                  | Savanna          | 24  | 0.74  | < 0.0001 | 152.77    | 1.86   | 1.48                  | 2.32                   |
| $\rho$           | $M_a$            | Forest           | 82  | 0.45  | < 0.0001 | 0.040     | 0.0020 | 0.0017                | 0.0024                 |
|                  |                  | Savanna          | 24  | 0.66  | < 0.0001 | 0.141     | 0.0014 | 0.0011                | 0.0018                 |
| $A_N$            | $M_a$            | Forest           | 81  | 0.00  | 0.6122   |           |        |                       |                        |
|                  |                  | Savanna          | 24  | 0.00  | 0.9268   |           |        |                       |                        |

fitted categorical variable (through the  $\beta_1 b$  term) along with the continuous variables [N]<sub>a</sub> and [P]<sub>a</sub>. Model performance was not improved by adding interaction terms (see model variants 8–12; Table 4). Also of note is model 6, which in dropping the vegetation term ( $b$ ) produces a significantly inferior model ( $p = 0.002$ ). That is to say, we could not account for the intrinsically higher area-based photosynthetic capacities of  $\mathbb{S}$ -affiliated trees (Fig. 1b) through systematic

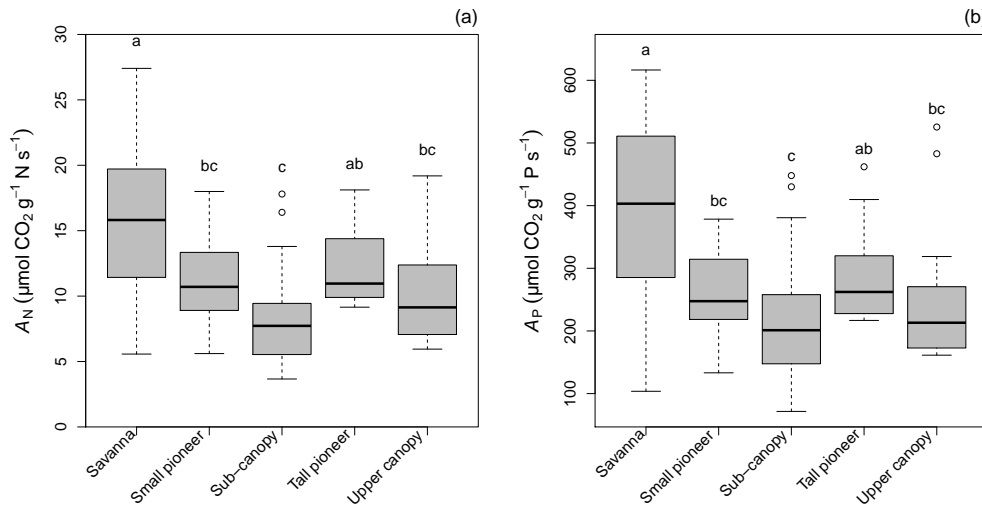
$\mathbb{F} - \mathbb{S}$  differences in any of our measured foliar traits. Comparisons against a model variant (model 7; Table 4), excluding the vegetation term, but reinstating available traits relating to leaf chemistry and structure confirmed that vegetation type could not be substituted in this way.

The full model, fixed and random terms combined, explained 82 % of variation in the observed values of  $A_{\max,a}$  and with all four forest  $\Phi$  values reasonably well predicted





**Figure 3.** Top panels (plots a, b and c): scatterplots of the area-based relationships between photosynthetic capacity ( $A_{max,a}$ ) and (a) leaf nitrogen, (b) leaf phosphorus, and (c) leaf mass per unit area ( $M_a$ ). Bottom panels (plots d, e and f): the equivalent plots are expressed per unit leaf dried mass. Each point represents a single leaf; dots denote  $\mathbb{F}$  sites and square symbols denote  $\mathbb{S}$  sites; individual sites are distinguished by colour: CTC-01 black, DCR-01 red, DCR-02 green, KBL-01 royal blue, KBL-02 turquoise, KBL-03 pink, and KCR-01 yellow. SMA-fitted lines are shown where significant:  $\mathbb{F}$  (green),  $\mathbb{S}$  (brown). Pearson correlations testing the assumption of linearity are given in Table S4 together with likelihood ratio and Wald statistics testing the  $H_0$  of common slope, elevation and axis shift for the two  $\mathbb{V}$  classes. In plot (c) there was no difference in slope between the two  $\mathbb{V}$ s and so a common line is fitted (black). SMA intercept, slope and  $r^2$  values are given in Table 3.



**Figure 4.** Boxplots of photosynthetic N use efficiency ( $A_N$ ) and P use efficiency ( $A_P$ ) by  $\phi$ . Boxes which share the same letter correspond to means that were not significantly different (Tukey’s HSD on ranked values). Boxplot construction is explained in Fig. 1.

(Fig. 6a). A plot of model residuals against fitted values raised no concerns for the model assumptions (Fig. S3). These model results also suggest, other things being equal, that photosynthetic capacities are intrinsically higher for  $\mathbb{S}$  than for  $\mathbb{F}$  species (Fig. 1b) – with estimated values in the data-set trait means of 29 and  $18 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  (Table 5). Despite the relatively low  $t$  value for the fitted  $[P]_a$

term, the predictive power of the overall model was improved by retaining  $[P]_a$  as a fixed term (compare models 4 and 5 in Table 4). The greater significance attached by the final model to the  $[N]_a$  term is confirmed when the two slope coefficients are standardised to allow for the difference in underlying units:  $\beta'_2 [N]_a = 0.294$  and  $\beta'_3 [P]_a = 0.172$  (interpreted as

**Table 4.** Stepwise selection process for the fixed component of the linear mixed-effect model: photosynthetic capacity ( $A_{\max,a}$ ) as response variable. Categorical variable  $b$  has two levels: forest and savanna for the contrasting vegetation types. Continuous explanatory variables are  $[N]_a$ ,  $[P]_a$ , leaf mass per unit area ( $M_a$ ), leaf dry matter content ( $\xi$ ) and leaf thickness ( $d$ ). The effect of dropping sequential terms was tested by comparing the nested model variants. Model variants were all run using the maximum likelihood method; the model's random component was identical in all variants. Test parameters and statistics are  $df$ , degrees of freedom; AIC, Akaike information criteria; BIC, Bayesian information criteria; logLik, maximum likelihood; the likelihood ratio statistic and associated  $p$  value. Models with the same degrees of freedom are not nested one in the other.

| Model | Fixed component   | $df$ | AIC    | BIC    | logLik  | Test     | L. ratio | $p$ value    |
|-------|---|------|--------|--------|---------|----------|----------|--------------|
| 1     | $b + [N]_a + [P]_a + M_a + d + \xi$   | 11   | 735.51 | 765.12 | -356.76 |          |          |              |
| 2     | $b + [N]_a + [P]_a + M_a + d$   | 10   | 733.52 | 760.44 | -356.76 | 1 vs. 2  | 0.011    | 0.915        |
| 3     | $b + [N]_a + [P]_a + M_a$   | 9    | 731.94 | 756.16 | -356.97 | 2 vs. 3  | 0.417    | 0.519        |
| 4     | $b + [N]_a + [P]_a$   | 8    | 730.58 | 752.11 | -357.29 | 3 vs. 4  | 0.640    | 0.424        |
| 5     | $b + [N]_a$   | 7    | 732.96 | 751.80 | -359.48 | 4 vs. 5  | 4.383    | <b>0.036</b> |
| 6     | $[N]_a + [P]_a$   | 7    | 738.39 | 757.23 | -362.20 | 4 vs. 6  | 9.814    | <b>0.002</b> |
| 7     | $[N]_a + [P]_a + M_a + d + \xi$   | 10   | 742.94 | 769.86 | -361.47 | 1 vs. 7  | 9.432    | <b>0.002</b> |
| 8     | $b + [N]_a + [P]_a + b : [N]_a + b : [P]_a + [N]_a : [P]_a + b : [N]_a : [P]_a$ | 12   | 734.73 | 767.02 | -355.36 | 4 vs. 8  | 3.852    | 0.426        |
| 9     | $b + [N]_a + [P]_a + b : [N]_a + b : [P]_a$                                     | 10   | 733.15 | 760.07 | -356.58 | 7 vs. 9  | 2.426    | 0.297        |
| 10    | $b + [N]_a + [P]_a + b : [N]_a$   | 9    | 731.37 | 755.59 | -356.68 | 8 vs. 10 | 0.213    | 0.645        |
| 11    | $b + [N]_a + [P]_a + b : [P]_a$   | 9    | 731.49 | 755.71 | -356.75 | 8 vs. 11 | 0.339    | 0.561        |
| 12    | $b + [N]_a + [P]_a + [N]_a : [P]_a$   | 9    | 732.53 | 756.75 | -357.26 | 4 vs. 12 | 0.050    | 0.823        |

the relative effect on  $A_{\max,a}$  of 1 standard deviation change in the independent variable).

Model output indicated that, after controlling for vegetation type ( $b$ ) and leaf nutrient levels, less than 10% of variation in  $A_{\max,a}$  was attributable to site effects. The environmental influence on photosynthetic capacity noted above (Table S3) was, however, adequately captured by our mixed model's fixed term (which incorporates leaf N and P), as shown by the absence of any relationship between model residuals and those same site variables relating to climate and soil conditions (Table S5, Fig. S4).

Broadly similar results were obtained when the mixed modelling approach was repeated for mass-based leaf traits (Table S6). The fixed component of the final parsimonious model again included vegetation type ( $b$ ),  $[N]_m$  and  $[P]_m$ , but this time with a significant  $N \times P$  interaction. The preferred random term was unchanged from that presented above.

### 3.5 Plant functional types

The area-based model's nested random component, which recognises the grouping of species within sites, allows the variance of the response ( $A_{\max,a}$ ) to be partitioned among the available terms. The fraction attributable to variance among plots (9%) is dwarfed by that among species (71%). Variation in  $A_{\max,a}$  around the population mean was therefore influenced much more by a tree's taxonomy than the plot in which it was growing. One factor that may help explain this interspecific variation is plant functional type ( $\Phi$ , related to a tree's growth strategy and light requirements as described in Table S2). We examined model output for any  $\Phi$ -related pattern in random intercepts for the different species. We found that tall pioneers displayed higher intercepts than subcanopy species ( $p = 0.0326$ ) as is shown in Fig. 6b. Thus, at any

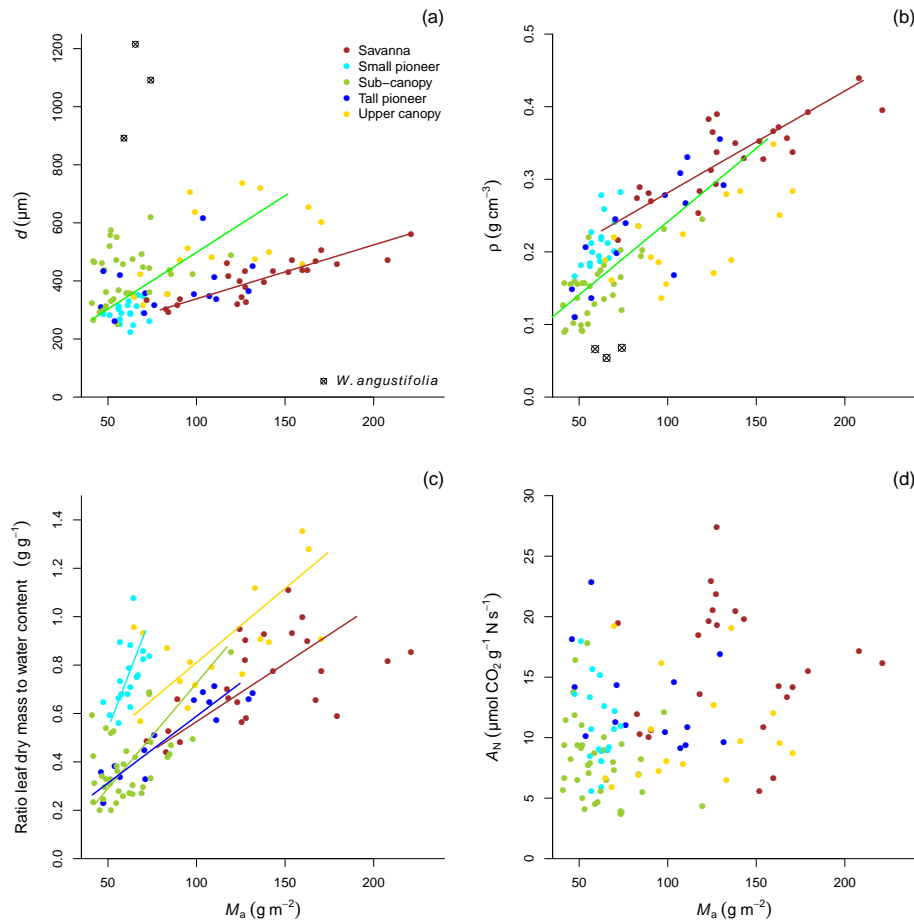
given  $[N]_a$  and  $[P]_a$  tall pioneers typically achieved a higher  $A_{\max,a}$  than shade-tolerant forest trees – as confirmed by their higher  $A_N$  and  $A_P$  (Fig. 4). Small pioneers and shade-tolerant canopy species were intermediate between these two extremes and showed intercepts close to the population mean.

## 4 Discussion

The main aim of this study was to compare photosynthetic traits for the tree species typical of adjacent tropical moist forest and savanna plots – a dynamic boundary potentially sensitive to changes in global climate (Sitch et al., 2008; Booth et al., 2012; Gloor et al., 2012; Huntingford et al., 2013). Our findings include higher photosynthetic capacity and nutrient use efficiencies for the savanna species, but our prediction of a primary photosynthetic role for P rather than N across the forest sites was not supported. Our preferred area-based model retained only three fixed terms, vegetation type, leaf N and P, yet accounted for 82% of variation in  $A_{\max,a}$ . Model output revealed a stronger relationship of  $A \leftrightarrow N$  than of  $A \leftrightarrow P$  and found the variability among species much more pronounced than among sites. For  $\mathbb{F}$  there was qualified support for the expectation that pioneer species would show higher photosynthetic traits of  $A_{\max,a}$  and  $A_N$  compared to late successional shade-tolerant species (Raaimakers et al., 1995).

### 4.1 Forest and savanna comparisons

Values reported here for key leaf traits such as  $A_{\max,a}$ ,  $M_a$  and levels of foliar N and P fell within previously published ranges for  $\mathbb{F}$  and  $\mathbb{S}$  trees (e.g. Medina, 1984; Prior et al.,



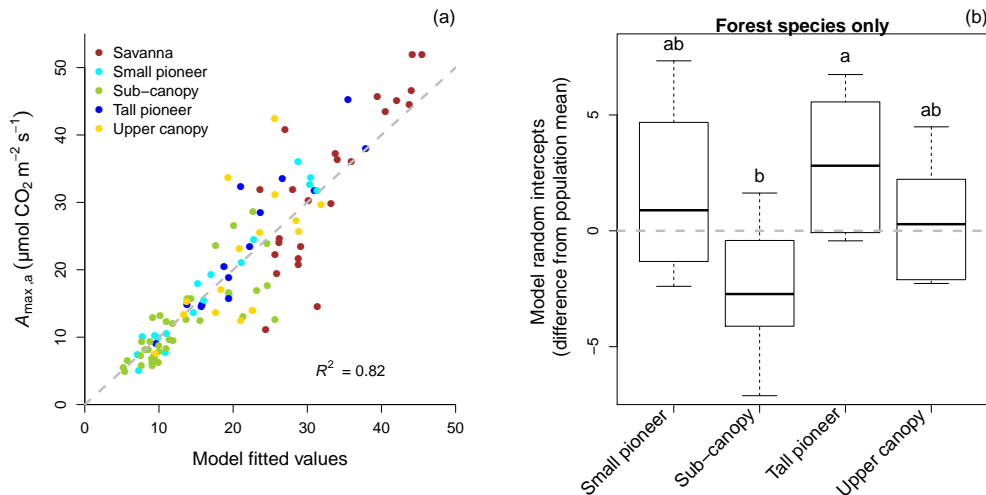
**Figure 5.** Scatterplots of the relationship with leaf mass per unit area for (a) leaf thickness (measured fresh), (b) leaf density (derived as  $M_a/d$ ), (c) the ratio of leaf dry mass to water content and (d) photosynthetic N use efficiency. Each point represents one tree and separate  $\phi$  values are distinguished by colour. SMA-fitted lines are shown in the top panel for the two vegetation types:  $\mathbb{F}$  in green and  $\mathbb{S}$  in brown. Outlying values for *Wilkiea angustifolia* (crossed circles) were excluded from the SMA analyses of plots (a) and (b). In plot (c) a separate fitted line is shown for each  $\phi$ . Pearson's correlations testing the assumption of linearity are given in Table S4 together with the likelihood ratio and Wald statistics testing the  $H_0$  of common slope, elevation and axis shift for the two  $\mathbb{V}$  classes. SMA intercept, slope and  $r^2$  values are given in Table 3. There was no relationship  $A_N \leftrightarrow M_a$  for individual levels of  $\mathbb{V}$  or  $\phi$ .

2005; Harrison et al., 2009; Cernusak et al., 2011). There were, however, significant differences among sites and between  $\mathbb{F}$  and  $\mathbb{S}$  in all these traits (Fig. 1). In particular, a recently cyclone-affected  $\mathbb{F}$  site south of Ravenshoe (KBL-01) stood out as high in leaf nutrients and photosynthetic capacity when expressed on a mass basis. Due to lower  $M_a$ , however, that prominence was all but removed when area-based traits were examined.

Our study included measurements of 30 tree species across seven sites; these sites and species were viewed as representative of wider populations and our modelling treatment of those terms therefore focused on their influence on the variance of the photosynthetic response rather than mean values. The linear mixed-effects model (Table 5), through its random component of species nested within sites, showed that most of the variance in the data occurred among species (71%). Once levels of leaf N and P had been included in the model,

variation among sites represented less than 10% of total variation. This corresponds with the findings of other Australian studies where within-site variation has proved much larger than that across sites (e.g. Wright et al., 2004; Asner et al., 2009). For this study, it could be argued, however, that the climatic and topographical ranges spanned by the seven sites (Table 2) were rather modest – mean annual precipitation, for example, is nowhere lower than 1.3 m and the range in mean annual temperatures is only 6°C.

Lower mass-based leaf nutrient values for  $\mathbb{S}$  species have traditionally been linked to their higher  $M_a$  associated with contrasts in leaf longevity and economic strategy. In the Australian literature, these species are widely described as sclerophyllous, characterised by tough leaves and adaptations to limit water loss. We argue, however, that on theoretical grounds it is area- rather than mass-based concentrations of N (and presumably also P, where relevant for photosynthetic



**Figure 6.** Output from linear mixed-effects model (Eq. 2): (a) scatterplot of observed photosynthetic capacity ( $A_{\max, a}$ ) against the model-fitted values as an indication of goodness of fit and (b) boxplot of model random intercepts ( $A_{\max, a} \leftrightarrow [N]_a$ ) by  $\phi$  for the  $\mathbb{F}$  subset; boxes which share the same letter correspond to means that were not significantly different (Tukey's HSD on ranked values). Boxplot construction is explained in Fig. 1.

**Table 5.** Output of the linear mixed-effects model (Eq. 2): fixed effects (top) and random effects (bottom). The top section shows fixed-effect parameter estimates and associated standard error (SE), degrees of freedom, test statistic and associated  $p$  value. The final “optimal” model is compared against a simpler “null” model that includes only vegetation type ( $b$ ) in the fixed component, but has an identical random term of species nested within site. Continuous explanatory variables were centred on their respective means (i.e. zero reset to the trait average).

| Fixed effect                            | Estimate                 | Final model |        |           |           |            | Null model |    |           |           |  |
|---|--------------------------|-------------|--------|-----------|-----------|------------|------------|----|-----------|-----------|--|
|   |                          | SE          | df     | $t$ value | $p$ value | Estimate   | SE         | df | $t$ value | $p$ value |  |
| Forest (if other variables were zero)   | 18.06                    | 1.57        | 73     | 11.537    | < 0.0001  | 17.08      | 2.47       | 75 | 6.925     | < 0.0001  |  |
| Savanna (vegetation contrast)           | $\beta_1$ 11.18          | 3.08        | 5      | 2.076     | 0.0151    | 14.15      | 4.54       | 5  | 3.119     | 0.0263    |  |
| Leaf $[N]_a$                            | $\beta_2$ 6.66           | 2.07        | 73     | 3.472     | 0.0020    |            |            |    |           |           |  |
| Leaf $[P]_a$                            | $\beta_3$ 0.07           | 0.03        | 73     | 1.618     | 0.0502    |            |            |    |           |           |  |
| Random effect                           | Variance                 | % of total  |        | Variance  |           | % of total |            |    |           |           |  |
| Intercept variance: among sites         | $a_k$ 3.56               | 9.4%        | 12.06  | 13.9%     |           |            |            |    |           |           |  |
| Intercept variance: among species       | $a_{j k}$ 26.77          | 70.8%       | 66.39  | 76.2%     |           |            |            |    |           |           |  |
| Residual (within species, within sites) | $\varepsilon_{ijk}$ 7.49 | 19.8%       | 8.64   | 9.9%      |           |            |            |    |           |           |  |
|   | 37.82                    | 100.0%      | 87.10  | 100.0%    |           |            |            |    |           |           |  |
| AIC                                     |                          |             | 726.7  |           | 746.5     |            |            |    |           |           |  |
| Likelihood ratio test                   |                          |             | -355.4 |           | -367.2    |            |            |    |           |           |  |

carbon gain) that should be modulated by differences in water availability (Buckley et al., 2002). With declining precipitation, therefore, an increase in area-based photosynthetically important nutrients (in our case  $\mathbb{S} > \mathbb{F}$ ) seems to be the general case (Buckley et al., 2002; Cernusak et al., 2011; Domingues et al., 2014; Schrodtt et al., 2014). It is non-systematic variations in  $M_a$  with precipitation, in turn probably attributable to differences in rainfall seasonality, that produce contradictions in mass-based  $N \leftrightarrow$  precipitation relationships (Schrodtt et al., 2014).

## 4.2 Linking leaf structure to metabolism

At the leaf level,  $A_N$  is dependent upon a number of factors including N allocation, conductance and Rubisco kinetics and no single cause has been found to explain observed interspecific differences (Hikosaka, 2004; Hikosaka and Shigeno, 2009). The idea that species with high  $M_a$  exhibit low  $A_N$  due to greater structural investment (e.g. Takashima et al., 2004) has been countered by later studies that found no relationship between  $A_N$  and the proportion of leaf N allocated to cell walls (Harrison et al., 2009; Hikosaka and Shigeno, 2009). Indeed, our general positive association between area-based photosynthetic capacity and  $M_a$  – also observed by Domingues et al. (2014) – challenges the general notion

that thick sclerophyllous leaves should be characterised by low photosynthetic rates and/or low photosynthetic nutrient use efficiencies (Wright et al., 2004; Westoby and Wright, 2006). Certainly, it has long been known that typically sclerophyllous eucalypt species can have exceptionally high photosynthetic rates (Larcher, 1969), with Denton et al. (2007) also finding very high nutrient use efficiencies for numerous xeromorphic Proteaceae species that exhibit some of the very highest  $M_a$  values worldwide. Maximov (1929) noted that “the drier the habitat, the smaller and more leathery the leaves, and the higher their rate of transpiration”.

Interestingly, our best-fit photosynthesis model was not improved by the inclusion of morphological traits such as  $M_a$ , leaf thickness or the ratio of leaf dry to fresh mass. Although  $M_a$  was much higher for the S plots, there was no difference in leaf thickness between S and F sites ( $p = 0.95$ ), suggesting that most of the difference in  $M_a$  between the two vegetation types was attributable to a higher leaf density for S. But, as noted above, with no adverse effects on photosynthetic nutrient use efficiencies.

### 4.3 The role of phosphorus

It has long been considered that vegetation differentiation in Australia is strongly influenced by edaphic constraints and specifically soil P status (Webb, 1968; Russell-Smith et al., 2004). The widely observed positive correlation of leaf  $[N] \leftrightarrow [P]$  (e.g. Wright et al., 2001) is evident here as well (Fig. 2a), but the slope of the relationship differed between F and S. Despite their situation in the Atherton basalt province (Whitehead et al., 2007), the mean foliar N:P ratios for all of the sites visited in this study were far above thresholds believed to constitute P deficiency (Townsend et al., 2007; Cernusak et al., 2010). This is particularly striking since the forests studied here, even after excluding the sub-canopy trees, had median  $[N]_a$  of only  $1.63 \text{ g m}^{-2}$ . Such N levels are low compared to other tropical forests for which extensive data have recently become available – see Table 2 of Domingues et al. (2014). Values here are lower, for example, than Cameroon ( $2.12 \text{ g m}^{-2}$ ) and lower even than for trees growing on soils of low nutrient availability in the Amazon Basin ( $1.90 \text{ g m}^{-2}$ ). Foliar P levels, however, were lower still despite concentrations of total soil extractable P ( $P_{ex}$ ) for our forest plots being relatively high ( $165\text{--}958 \mu\text{g g}^{-1}$ ; Table 2). For what have been classed “high nutrient” soils in the Amazon Basin, for example, Fyllas et al. (2009) reported median foliar P values of  $1.11 \text{ mg g}^{-1}$  and  $0.11 \text{ g m}^{-2}$  with equivalent soil  $P_{ex}$  ranging from  $52$  to  $422 \mu\text{g g}^{-1}$  (Quesada et al., 2010). In our study, however, upper canopy forest trees displayed median P values of only  $0.76 \text{ mg g}^{-1}$  and  $0.08 \text{ g m}^{-2}$ , much closer to Amazon forest trees growing on “low nutrient status” soils for which soil  $P_{ex}$  ranges from  $14$  to  $87 \mu\text{g g}^{-1}$  (Quesada et al., 2010) with foliar P median values of  $0.7 \text{ mg g}^{-1}$  and  $0.06 \text{ g m}^{-2}$  (Fyllas et al., 2009).

This apparent “inability” of Australian forest trees to utilise high soil P availabilities could perhaps be related to their unique evolutionary history. Essentially of Gondwanan origin (Crisp et al., 1999), today’s forests represent remnants of more temperate moist forests that covered much of the continent until the mid-Miocene (Adam, 1992). Presumably arising from a flora already adapted to the characteristically P-limited soils of much of Australia (McKenzie et al., 2004), it may be that many of the species occurring within the Australian tropical forest region suffer from an “evolutionary hangover” lacking the ability to utilise high levels of soil P even where available. There is in addition, especially for the lowlands, a considerable Asia-derived element in the Australian tropical forest flora (Sniderman and Jordan, 2011; Crayn et al., 2014), as many soils of the Asian lowland tropical forest region are also of relatively low nutrient status (Acres et al., 1975; Tessins and Jusop, 1983; Ohta and Efendi, 1992; Banin et al., 2014). By comparison, despite the generally lower P status of the savanna soils (Table 2), the savanna trees in our study had a slightly higher median  $[P]_a$  than those of the forest ( $S = 0.08 \text{ g m}^{-2}$  and  $F = 0.06 \text{ g m}^{-2}$ ) and this was true also for  $[N]_a$  ( $S = 2.09 \text{ g m}^{-2}$  and  $F = 1.62 \text{ g m}^{-2}$ ). This finding for the Australian species contrasts with previous work in western Africa and Cameroon where area-based N and P concentrations were lower for savanna than for forest species (Domingues et al., 2014; Schrodt et al., 2014).

Despite these differences in area-based nutrient concentrations, there are notable consistencies between our results and the African studies mentioned above. First, albeit with different model constructs, there is clear evidence of a role for both N and P in the modulation of photosynthetic rates in the field. Second, other things being equal, it seems that savanna trees have higher N use efficiency than their forest counterparts. This higher  $A_N$  (Fig. 4) may reflect differences in leaf construction linked to the higher light environment. Earlier studies have suggested that lower  $A_N$  values for sclerophytes may be caused by limitations to internal conductance caused by leaf structural factors linked to greater leaf longevity (e.g. Warren, 2008). Mesophyll conductance ( $g_m$ ) is, however, the complex and variable product of at least three phases acting in series (Flexas et al., 2008): conductance through intercellular air spaces ( $g_{ias}$ ), through cell walls ( $g_w$ ) and through the liquid and membrane phases inside cells ( $g_{liq}$ ). The most important constraint on  $g_m$  is thought to be  $g_{liq}$ , which is the phase least affected by leaf structure.

Overall, our results suggest a complex effect of P on photosynthetic capacity for these Australian tree species. Foliar  $[P]_a$  was only marginally significant in the preferred linear mixed-effects model (Table 5), but its inclusion improved the overall predictive power. When examined on a mass basis, P did, however, appear more critical and with a N  $\times$  P interaction term also included in the optimal model (Table S6). This mass- versus area-based inconsistency in the apparent importance of P as a modulator of photosynthetic rates was also

noted by Domingues et al. (2014), who likewise found their mass-based models to include a  $N \times P$  interaction term not present in the area-based version. The sudden appearance of apparently significant terms when transforming area-based entities to a mass basis is, however, to be expected (Lloyd et al., 2013).

#### 4.4 Describing trait variation using plant functional types

Where possible in the  $\mathbb{F}$  sites, tree species were selected in order to provide a contrast of light environment as described in the assigned categories of plant functional type ( $\Phi$ ). Such categorisation is often problematic and especially in the setting of boundaries from one group to another (e.g. Poorter, 1999). For Australian tropical moist forests, Webb developed a classification system of 20 structural vegetation types along climatic and edaphic gradients (1968). Faced with such complexity and subjectivity, many authors have instead argued for a spectrum of vegetation types or habits (e.g. Coste et al., 2005). The current study used  $\Phi$  to attempt to explain residual patterns in the data after controlling for  $\mathbb{V}$  (Fig. 6b). As hypothesised, there was evidence that pioneer trees of the  $\mathbb{F}$  showed higher photosynthetic capacity and nutrient use efficiency than those shade-tolerant species which persist in the understory (Fig. 4).

## 5 Conclusions

Comparing tree species of neighbouring forest and savanna sites in Far North Queensland, Australia, we found higher photosynthetic capacity for savanna species linked to greater nitrogen use efficiency. Higher leaf mass per unit area for the savanna trees derived from greater leaf density rather than thickness, but did not inhibit photosynthetic capacity or  $A_N$ . Our mixed-effects model accounted for 82 % of variation in observed photosynthetic response and confirmed the importance of the  $A \leftrightarrow N$  relationship. The model, whilst retaining leaf  $P$  as a key explanatory term, did not support the prediction of a dominant role for  $P$  rather than  $N$  in determining rates of photosynthesis for Australian tropical forest species.

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