Coupled response of stomatal and mesophyll conductance to light enhances photosynthesis of shade leaves under sunflecks.

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# Summary

* Light gradients within tree canopies play a major role in the distribution of plant resources that define the photosynthetic capacity of sun and shade leaves. However, biochemical and diffusional constraints on gas exchange in sun and shade leaves in response to light remain poorly quantified, but critical for predicting carbon and water exchange in canopies.
* To investigate the CO2 diffusion pathway of sun and shade leaves, leaf gas exchange was coupled concurrent measurements of carbon isotope discrimination to measure net leaf photosynthesis (*An*), stomatal conductance (gs) and mesophyll conductance (gm) in *Eucalyptus tereticornis* trees grown in the field in climate controlled whole tree chambers.
* Compared to sun leaves, shade leaves had lower *An*, gm, leaf nitrogen and photosynthetic biochemical parameters (Vcmax and Jmax), but gs was similar. When light intensity was temporarily increased for shade leaves to match that of sun leaves, both gs and gm increased, leading to increases in *An* greater than sun leaves.
* Here we show that dynamic physiological responses of shade leaves to altered light environments have important implications for up-scaling leaf level measurements and predicting whole canopy carbon gain. Despite exhibiting reduced photosynthetic biochemical capacity, the rapid up-regulation of gm with increased light enables shade leaves to respond quickly to sunflecks, possibly representing a new mechanism underpinning leaf gas exchange responses to light.

## Key words

*Eucalyptus tereticornis*, mesophyll conductance, photosynthesis, stomatal conductance, sunflecks

# Introduction

Light availability is one of the most important environmental drivers of leaf carbon (C) uptake in trees. Predicting C uptake of forests usually involves up-scaling leaf level measurements to assess whole canopy function. Due to the costs and limitations of efficient light harvesting within plant canopies, not all leaves are exposed to full sun (Niinemets, 2010), making simple up-scaling based on solar irradiance problematic. Incident photosynthetic photon flux density (PPFD) declines exponentially with cumulative leaf area index (ratio of leaf area to ground area), creating a steep light gradient from the canopy top to bottom (Monsi & Saeki, 2005). Consequently, structural and functional properties of leaves within canopies are modified to efficiently use light (Vogelman *et al.*, 1996; Niinemets & Valladares, 2004), as changing irradiance with canopy depth strongly affects rates of leaf photosynthesis (*An*) (Evans, 1995). To estimate whole canopy C gain it is thus necessary to account for the non-linear response of *An* to light by distinguishing between shaded and sunlit leaves (De Pury & Farquhar, 1997; Linderson *et al.*, 2012).

The distribution of resources required for *An*, including leaf nitrogen (N) and supply of water, are also partially defined by canopy light gradients. As *An* has a saturating response with light and maximum rates depend, in part, on N-rich photosynthetic machinery, it has been argued that leaf N should be proportional to PPFD along the canopy light gradient to maximize canopy C gain at a given total canopy N (Field, 1983; Field & Mooney, 1986; Peltoniemi *et al.*, 2012; Buckley *et al.*, 2013). Changes in chlorophyll per unit N, chlorophyll a:b ratios, electron transport capacity per unit chlorophyll and ratios of electron transport capacity to Rubisco activity can also occur in response to changes in irradiance of the growth environment (Evans & Poorter, 2001). Sun leaves frequently experience greater water limitations in the upper canopy, despite effective vascular systems developed for high radiation loads and transpiration (Sellin *et al.*, 2008; Niinemets, 2012). Higher rates of *An* and stomatal conductance (gs) in sun leaves can only be sustained if the leaf specific hydraulic conductance (Kl) is also large enough to avoid low leaf water potentials (Hubbard *et al.*, 2001). Optimal photosynthetic N investment in the upper canopy will be ineffective in enhancing *An* if water supply is insufficient (Niinemets, 2012; Peltoniemi *et al.*, 2012); thus Kl should also be higher in the upper canopy to supply sunlit leaves with sufficient water (Sellin & Kupper, 2007 ; Sellin *et al.*, 2008; Burgess *et al.*).

Rates of photosynthesis in C3 plants are limited by the [CO2] available for fixation by Rubisco within the chloroplast and this [CO2] is a function of the drawdown of CO2 from the atmosphere to the site of carboxylation (Warren, 2008). This drawdown consists of two major resistance pathways to CO2 diffusion, namely, the CO2 diffusion from the atmosphere through stomata into intercellular air spaces (stomatal conductance, gs) and the pathway from the intercellular air spaces into the chloroplast of the mesophyll cells (mesophyll conductance, gm). Based on optimality theory, regulation of gs within a tree canopy should act to efficiently utilize available supplies of light, N and water to maximize *An* (Peltoniemi *et al.*, 2012). This is because stomata are hypothesized to exhibit an optimal behaviour to maximize C gain while simultaneously minimizing water loss through transpiration (Cowan & Farquhar, 1977). Mesophyll conductance can also impose limitations on *An* that can be as large as gs (Warren, 2008; Ubierna & Marshall, 2011), reducing the efficiency of leaf N use in *An* (Niinemets, 2007), if gm constrains CO2 supply to the chloroplast. Part of the variation in photosynthetic capacity between sun and shade leaves may arise from differences in gm (Piel *et al.*, 2002; Warren *et al.*, 2007), yet the trade-offs that constrain this diffusion pathway are yet to be explicitly quantified. It is likely that leaf anatomical costs associated with minimizing the length and tortuosity of the gm diffusion pathway are necessary to maintain the benefits of a high gm (Hassiotou *et al.*, 2009). Stomatal and mesophyll conductance should not be considered independent of each other (Griffiths & Helliker, 2013), but a lack of empirical data currently hinders our ability to interpreting their coupled responses to *An* across sun and shade leaves.

Additionally, accounting for short term light fluctuations within a canopy, via sunflecks, makes assessing shade leaf behaviour difficult. How shade leaves utilize sunflecks for short term C gain depends on the combined response time of gs and gm and the underlying photosynthetic biochemistry acclimated to a low light environment (Pearcy, 1990; Tausz *et al.*, 2005). The utilization of sunflecks in shade leaves is first limited by delayed responses of stomata opening, which may take minutes, effectively limiting the maximum assimilation rate that can be achieved (Pearcy, 1990; Vico *et al.*, 2011; Way & Pearcy, 2012). Mesophyll conductance has been shown to respond to environmental factors (e.g. CO2, temperature or vapor pressure deficit) at timescales of minutes, possibly faster than gs (Flexas *et al.*, 2008 and references therein), yet the short term response to light availability is unclear. For example, gm was found to be independent of light intensity in wheat leaves (Tazoe *et al.*, 2009) but was responsive to light in tobacco (Flexas *et al.*, 2007). Anatomical parameters which regulate gm with changing growth irradiance such as chloroplast surface area (Terashima *et al.*, 2006) and mesophyll thickness (Boardman, 1977; Terashima *et al.*, 2001; Hanba *et al.*, 2002) are also unlikely to adjust during transient fluctuations in light. The physiological behaviour of shade leaves to maximize C gain must be assessed as both a degree of acclimation to local irradiance of the growth environment and as a potential response to transitory light availability.

Climate warming may also affect the physiological behaviour of leaves within a canopy. This is because leaves can be exposed to different heat, water and high light stresses as temperature and vapour pressure deficit (VPD) vary with canopy light availability (Baldocchi *et al.*, 2002; Niinemets & Valladares, 2004; Niinemets, 2007). How these stresses affect the diffusion of CO2, through either gs or gm, will have implications for up-scaling *An* for sun and shade leaves. Additionally, light-saturated rates of *An* are limited by the maximum rate of Rubisco carboxylation (Vcmax) or the maximum rate of photosynthetic electron transport (Jmax) across a range of temperatures, yet their temperature dependencies are not the same (Farquhar *et al.*, 1980; Medlyn *et al.*, 2002). How these parameters are differentially affected by warming may impact constraints of N distribution and leaf photosynthetic capacity across light gradients. The impacts of warming on plant physiological processes are vast, yet differentiating their impacts on leaf physiology within a canopy will be essential to evaluate whole tree responses to a changing climate.

In this study we use *Eucalyptus tereticornis* trees, planted outdoors in naturally sunlit climate controlled whole tree chambers with ambient and elevated temperature (ambient +3°C) treatments, to test whether the distribution of N and water supply and leaf physiological behaviour result in higher photosynthetic capacity in sun leaves compared to shade leaves. We further aimed to quantify the contraints on An in sun and shade leaves arising from biochemical photosynthetic capacity and the CO2 diffusion pathway via stomatal and mesophyll conductance. As leaves which developed in the shade were expected to have lower biochemical photosynthetic capacity and correspondingly lower diffusive conductance than sun leaves, we predicted that sunfleck simulations would increase *An* and gs to values lower than that of sun leaves. We further predicted that climate warming would decrease gs and leaf C gain in sun leaves more so thatn shade leaves during summer months, as increased evaporation demand from higher temperatures and irradiance lead to stomatal closure.

# Materials and Methods

## Whole tree chamber experimental design

Twelve *Eucalyptus tereticornis* Sm. seedlings, chosen from a single local Cumberland plain cohort, were planted in March 2013 into 12 whole-tree chambers (WTC) at the Hawkesbury Forest Experiment site near Richmond, New South Wales, Australia. Each chamber was 9 m tall, which accommodated growth of trees for 15 months. A detailed description of the WTC operation and design is available in Barton et al. (2010) and methods for this experiment in (Drake *et al.*, 2016). Six chambers were set to match outside ambient air temperatures (AT) while the remaining 6 experienced an elevated air temperature treatment of ambient +3°C (ET, Figure S1). The trees grew quickly and developed large canopies, with height growth reaching the top of the WTCs at the end of the experiment. Trees were watered weekly with 70 L from March 2013 to September 2013. From October 2013 to the end of the experiment trees were watered every 15 days with the mean monthly rainfall amount for Richmond, NSW. In February 2014 half of the chambers (3 each of AT and ET) were subjected to a drought treatment by withholding watering. Due to a limited range of data for the drought treatment only well-watered trees are reported, which reduces the sample size of WTC (*n*=6 to *n*=3) for the final 3 months of the experiment. This limited amount of data is attributed to small sample sizes as well as the difficulty in generating a sufficient CO2 drawdown inside the leaf cuvette, due to drought conditions, needed to accurately measure gm.

The top soils at this site, used in the chambers, are an alluvial formation of low-fertility sandy loam soils (380 and 108 mg kg-1 total N and phosphorus respectively) with low organic matter (0.7 %) and low water holding capacity. A root exclusion barrier extended from chamber walls to the hard layer (ca. 1 m) and roots were allowed to grow freely below the barrier.

Leaf gas exchange measurements were initiated in October 2013 when trees had both ample height growth and canopy development for realistic canopy light gradients to be measured. At this point, trees under AT treatment had a mean diameter of 28.2±1.1 mm, height of 348±15.1 cm and an leaf area of 3.9±0.1 m2. For ET treatments, trees had a mean diameter of 34.1±2.1 mm, height of 418.3±23.1 cm and an leaf area of 6.2±0.2 m2. Leaf area was calculated based on complete leaf counts and mean leaf size from a subsample (Drake *et al.*, 2016).

## Leaf gas exchange, couple with concurrent measurements of carbon isotope discrimination to estimate mesophyll conductance

Leaf gas exchange measurements were performed six times, beginning in October 2013 and monthly from December 2013 to April 2014. Measurements were taken on a representative sun and shade leaf for each tree during each measurement campaign. The newest fully expanded leaf from the branch apex was chosen for gas exchange measurements and sun leaves were measured in the upper third of the canopy. Here, shade leaves are defined as inner-canopy leaves developing on secondary branches in a low light environment. Shade leaves were always measured in the lower canopy, but leaves were sampled on subsequent higher branches across measurement campaigns to minimize confounding effects of leaf age. As shade leaves most likely developed more slowly this assured that older leaves in the bottom canopy were avoided.

Prior to gas exchange measurements photosynthetic photon flux density (PPFD) was recorded both as a point measurement at the individual leaf level and a spatially averaged measurement at the canopy position for each selected leaf. A hand-held quantum sensor (LI-COR, Lincoln, NE, USA) was used to record leaf level PPFD to ensure that chosen leaves were positioned in the desired light environment, either sun or shade. A ceptometer (AccuPAR LP-80, Decagon Devices, Pullman, USA) was then used to measure a spatially averaged PPFD at the canopy height of each chosen leaf type. Each ceptometer reading integrated an array of 80 sensors over a total length of 84 cm. Five ceptometer readings were recorded at different locations within the canopy, but at the same height and close to each selected leaf. The mean of these readings was assumed to represent the local light environment of sun and shade leaves for each tree. All measurements of PPFD and gas exchange were performed on sunny days between 10:00-14:30 h.

Concurrent gas exchange and C isotope discrimination measurements were conducted based on methods described in Tazoe et al. (2011) and Evans & von Caemmerer (2013). Leaf level gas exchange was measured with a standard (2 x 3 cm) leaf cuvette using a portable gas exchange system (LI-6400XT, LI-COR, Lincoln, NE, USA). This system was coupled with a tunable diode laser (TDL; TGA100,Campbell Scientific, Inc., Logan, UT, USA) for concurrent measurements of 13C isotope discrimination. The CO2 in the leaf cuvette was set at ambient atmospheric [CO2] (400 ppm) with a flow rate of 200 mol s-1. Two identical gas exchanges systems were run simultaneously, one in each of a randomly chosen WTC for each temperature treatment. Leaf temperatures were controlled at the current AT or ET WTC air temperature. PPFD in the cuvette was set to match the individual light environment of each leaf type (explained above). Sustained periods of high irradiance (sunflecks) were simulated for shade leaves by increasing the leaf cuvette PPFD (LI-COR red/blue light source) to match the light environment of the sun leaf in the same tree. The maximum sunfleck response of shade leaves was then recorded once CO2 and water vapour fluxes re-stabilized in the leaf cuvette (ca. 25 min).

Once CO2 and water vapour flux values were stable for each leaf measurement, the sample and reference gas lines were diverted to the TDL via T-junctions inserted into the reference gas tube and match valve outlet of the LI-6400XT. The gas streams were dried by passing through napion gas dryers in the respective gas lines, and then 12CO2 and 13CO2 concentrations were measured for each gas stream by the TDL. Reference, sample and two calibration gases were run on alternating 80 s loops (20 s each), one for each AT and ET leaf at a matched canopy position, for a total of 12 min. This allowed for 4-5 measurements per leaf and data were averaged over the last 10 s of reference line and sample line gas streams for calculations. The two calibration gases were drawn from compressed air tanks (330 and 740 ppm CO2) in order to correct for gain drift of the TDL on each measurement cycle. Photosynthesis, gs, transpiration, VPD and intercellular [CO2] (Ci) were auto-logged every 15 s for each gas exchange system over the 12 min interval.  
Mesophyll conductance was calculated from carbon isotope discrimination with equations and fractionation factors as presented in Evans & von Caemmerer (2013), including the ternary corrections proposed by Farquhar & Cernusak (2012), such that:

(1)

where o is the observed discrimination and i, gm , e and f are the contributions to fractionation if Ci = Cc, gm, respiration and photorespiration, respectively. For this study, the CO2 compensation point () and respiration during the day (Rd) parameters originally derived for tobacco plants (von Caemmerer *et al.*, 1994) were replaced with parameters derived for *Eucalyptus globulus* from Crous et al. (2012) when calculating gm. Full descriptions of the carbon isotope discrimination equations, with ternary corrections, are presented in Supporting Information Methods S1. The variation in o between sun and shade leaves and the simulated sunfleck were compared as a function of Ci:Ca. Once gm was calculated, the chloroplast CO2 partial pressure (Cc) and the drawdown of CO2 from the intercellular air spaces to the site of carboxylation were estimated from the relationship between gm and leaf photosynthesis rate (*An*) by:

(2)

## Biochemical parameters of photosynthesis

Photosynthetic CO2 response (ACi) curves were measured at 25 °C for one sun and shade leaf for each WTC, sampling in February 2014 when all tress were well-watered in each temperature treatment (*n*=6). Each ACi curve began at the reference [CO2] of 400 l l-1 and then consisted of 12 additional steps from [CO2] of 50 to 1800 l l-1 at 25 °C at saturating light (1800 mols m-1 s-1). From these curves the photosynthetic parameters, Jmax and Vcmax, were quantified using the biochemical model of (Farquhar *et al.*, 1980) and fit with the 'plantecophys' package (Duursma, 2015) in R (R Development Core Team, 2011) using default parameters.

## Leaf chemistry and hydraulic parameters

Following gas exchange measurements each leaf was collected, measured for leaf water potential (explained below), scanned for leaf area, oven-dried and weighed. These leaves were then milled and analyzed for leaf N content and 13C. Leaf samples were analysed on a Delta V Advantage coupled to a Flash HT and Conflo IV (Thermo Fisher Scientific, Bremen, Germany) in dual-reactor setup. Samples were flash combusted at 1000 °C and converted to CO2 and N2 and then subjected to stable isotope ratio mass spectrometry. Leaf N is reported on an area basis (Na, g m-2) and isotopic signatures of dry matter are reported relative to standard Vienna Pee Dee Belemnite.

Prior to the gas exchange measurements, predawn () leaf water potentials (MPa) were measured for a separate set of sun and shade leaves using a PMS 1505D pressure chamber (PMS Instruments, Albany, OR, USA). The leaf closest to the leaf used for gas exchange was sampled for measurement of before sunrise on the same day as gas exchange measurements. Following the gas exchange measurements, leaves used for gas exchange were immediately sampled for midday () leaf water potentials. All leaves were detached and immediately stored inside foil covered bags before water potential measurements were performed. Leaf water potentials and transpiration (E, mmol m-2 s-1) from gas exchange in the leaf cuvette were then used to calculate leaf-specific hydraulic conductance (Kl, mmol m-2 s-1 MPa) with the equation:

(3)

Leaf level instantaneous transpiration efficiency (ITE) was calculated as *An* divided by E. The g1 parameter, describing plant water-use strategy, was estimated from ITE vs. VPD response curves by fitting a rearranged optimal gs model for ITE (Medlyn *et al.*, 2011) using non-linear regression (see Duursma *et al.*, 2013). Small values of g1 indicate that transpiration is comparatively costly in C terms and reflecting conservative water use (increaed water-use efficiency), whereas large values imply a lower C cost and decreased water-use efficiency (Lin *et al.*, 2015).

## Data analysis

Differences in respones of dependent variables to either the warming treatment or leaf type were analysed by mixed-effects models in R (R Development Core Team, 2011) with WTC as a random effect. Explained variance (R2) of mixed models were computed as in (Nakagawa & Schielzeth, 2013), in which the marginal R2 represents variance explained by fixed factors and the conditional R2 by both fixed and random factors. Confidence intervals (95 %) of mixed effect linear models were generated using bootstrapping methods with 999 simulations, using the bootMer function in the 'lme4' package (Bates *et al.*, 2015). For non-linear relationships, confidence intervals were estimated by fitting a generalized additive model to the data with the 'mgcv' package, using WTC as a random effect. All tests of statistical significance were conducted at an of 0.05.

# Results

## Leaf resource distribution

Across six measurement campaigns over the 7 month period, PPFD was reduced on average by >75% in the shade (Figure 1). Leaf-specific hydraulic conductance (Kl) was similar across sun and shade leaves (Table 1). This was because neither leaf water potentials ( and , Table 1) nor transpiration rates (E, Table 2) differed between leaf types. Leaf Na was approximately 20% higher in sun leaves compared to shade leaves (Table 1). Leaf mass per area (LMA) was not different between leaf types (Table 1). No effect of the warming treatment was detected with PPFD, , , Kl, E, Na or LMA either within or across leaf types (P > 0.05).

## Photosynthetic capacity and leaf photosynthesis rates

The photosynthetic parameters Jmax and Vcmax were higher in sun compared to shade leaves (Table 1), as estimated from ACi curves (Figure 2a). Within leaf types, no effect of the warming treatment was detected on either parameter. Among the sampled leaves, Vcmax was positively related to leaf Na across leaf types and temperature treatments (P = 0.01, Figure 2b).

Mean *An* was significantly higher in sun compared to shade leaves (+23%), when measured at their local light environment and temperatures (Table 2). Additionally, leaf Na was positively related to *An* across gas exchange campaigns and leaf types measured under ambient light and temperature conditions (P < 0.001, Figure 2c). Following an increase in light intensity to match high-light conditions, *An* of shade leaves increased to values significantly greater than sun leaves at high light (P < 0.001, Table 2). No effect of the warming treatment was detected on *An* of sun leaves measured at high light or shade leaves at either low or high light. Photosynthesis within leaf types and warming treatments was similar through time and across the range of leaf temperatures measured (Figure S3a).

## Stomatal conductance and leaf water-use efficiency

On average, gs was 18% higher in shade compared to sun leaves under their local light environment (Table 2). Photosynthesis was positively correlated with gs in all leaves measured under high light conditions, however, gs and *An* were not correlated in shade leaves under low light (Figure 3a). Following increased PPFD, gs of shade leaves was significantly greater than both shade leaves at low light and sun leaves, pooled across all measurement dates (Figure 4a). No effect of the warming treatment was detected on gs within or across leaf types. Stomatal conductance within leaf types and treatments was similar through time and across the range of leaf temperatures measured (Figure S4b).

Measured under ambient light and temperature, leaf ITE was significantly greater in sun leaves than in shade leaves at low light (+21%, P = 0.001). Following an increase in PPFD to high-light conditions, ITE of shade leaves did not differ from shade leaves at low light and was therefore significantly lower than sun leaves (P < 0.001). Instantaneous transpiration efficiency in sun leaves was reduced in the warming treatment compared to ambient, but no warming effect was detected in shade leaves measured at low or high light (Table 2). The mean estimated g1 for sun leaves was 1.51±0.11 and for shade leaves measured at low and high light was 2.59±0.12 and 2.74±0.04. For all leaf types and light treatments there was a strong response of ITE to VPD and individual data points broadly corresponded to the fitted response curves from the optimal ITE model with a specified g1 value for each leaf type and treatment (Figure 5a). Within leaf types and light treatments the response of VPD to leaf temperature was similar across all measurement campaigns (Figure S4a).

Bulk-leaf 13C, as an index of integrated water-use efficiency (Marshall *et al.*, 2007), was significantly lower in shade leaves compared to sun leaves by ca. 2‰ (Table 1). No effects of the warming treatment on leaf 13C were detected. Leaf 13C and Na were positively correlated for all leaves (P<0.001, Figure 5b), with less negative 13C (higher water-use efficiency) and higher N investment in sun leaves than shade leaves.

## Leaf carbon isotope discrimination and mesophyll conductance

The observed carbon isotope discrimination () measured during photosynthesis was positively correlated with Ci:Ca for both leaf types (P < 0.001), with larger o detected for sun leaves and shade leaves at high light than shade leaves at low light (Figure S2). Carbon isotope discrimination associated with gm accounted for the majority of (69.7±0.4%) and varied little across measurement temperatures, leaf types, or warming treatments. The remainder consists of the contributions of gs, respiration and photorespiration to discrimination.

Mean gm was higher in sun compared to shade leaves (+27%) under their local light environment and temperatures (P < 0.001). Following the increase in PPFD from low to high light on the same leaf, gm values of shade leaves increased on average 55% after approximately 25 min (Figure 6). These measured values of gm for shade leaves at high light were also equivalent or greater than those of sun leaves (Table 2). Proportional increases in gm were matched by proportional increases in *An* from low to high light in shade leaves (Figure 4b,c). Photosynthesis scaled positively with increases in gm for all leaves, with similar intercepts but different slopes between leaf type and light treatment (P = 0.0186). The large increases in gm in shade leaves under high light likely resulted in the highest rates of *An* (Figure 3b). No differences in gm were detected with the warming treatment within leaf types. Mesophyll conductance did not vary across measurements campaigns within leaf types and light treatments (Figure S3b), but a weak negative relationship with increasing leaf temperature was detected with sun and shade leaves under their local light environment (P = 0.001 & 0.04, respectively).

## Variation in intercellular and chloroplastic CO2 concentrations

Higher gs in shade leaves under low and high light led to significant increases in Ci compared to sun leaves (Figure 7a). The chloroplast CO2 partial pressure was comparable between shade leaves when measured at both low and high light conditions (Figure 7c). In sun leaves Cc was significantly lower than shade leaves, consistent with a lower Ci. The drawdown of CO2 from intercellular spaces to the chloroplast, Ci-Cc, measures the coordination between gm and *An* (Von Caemmerer & Evans, 2014). This drawdown was similar between sun and shade leaves measured at their local light and temperature environment and increased marginally in shade leaves at high light (Figure 7c). This was the result of the proportional relationship between gm and *An* across all leaves. The CO2 drawdown from Ca to Ci and Ci to Cc were both relatively stable across the range of temperatures measured and gas exchange campaigns (Figure S4c and S3c, respectively).

# Discussion

Here we show that *An* in leaves within canopies of *Eucalyptus tereticornis* are limited by their local light environment, however, shade leaves increased rates of leaf C gain exceeding sun leaves when light availability increased. Although shade leaves in lower light environments exhibited relatively high gs and Ci, it was concomitant increases in gm under periods of high light availability that enabled up-regulation of *An*. Although we know shade leaves experience transient periods of sun and shade (Pearcy, 1990), a lack of empirical data within tree canopies currently impedes our ability to predict whole canopy C gain. These findings offer new insights into how aspects of leaf gas exchange physiology may be optimized differently in sun and shade leaves and reveal how the total leaf CO2 conductance pathway should be accounted for when testing optimizations of canopy C uptake and water use in future studies. Additionally, with measurements recorded across a large natural range of air temperatures only minimal effects a +3 °C warming treatment were detected on leaf physiology, owing to temperature acclimation (Aspinwall *et al.*, 2016).

## Resource distribution and photosynthetic capacity

The allocation of Na constrains *An* and is thus a key trait in determining the relative contribution of individual leaves to canopy C gain. Decreasing light availability should decrease the investment of N into photosynthetic enzymes within a canopy (Mooney & Gulmon, 1979). As a result, acclimation of photosynthetic capacity to irradiance is typically reflected in the key photosynthetic biochemical parameters Vcmax and Jmax (Farquhar *et al.*, 1980). Our data agree with these conventional conclusions as the distribution of Na, both measures of photosynthetic capacity and *An* were all reduced in shade leaves. Leaf mass per area, however, was not different between sun and shade leaves. This could be due to leaf formation under comparable light conditions or possible unmeasured differences in total non-structural carbohydrates contents between leaf types that masked differences in leaf thickness or density.

Photosynthesis is also limited by the ability to supply water to the upper canopy. Ultimately, the ability of tree hydraulic architecture to supply water to foliage across increasing pathlengths affects productivity and survival (Sellin *et al.*, 2008). Using a two-leaf model, Peltoniemi et al. (2012) theorizes that optimal N distribution will be proportional to light distribution only if Kl is also optimally distributed. In this study, variation in leaf N distribution and *An* rates were not associated with subsequent changes in Kl between sun and shade leaves. Thus, no direct relationship between water supply capacity and N distribution or *An* within the canopy were detected.

Unexpected higher gs in shade leaves compared to sun leaves led to decreased ITE in shade leaves throughout the experiment. From a canopy perspective this pattern in water-use efficiency initially appears to be detrimental to C gain as *An* in sun leaves was characterized by low gs and low Ci. Consistently lower leaf 13C in shade leaves also suggests that observed higher Ci and Cc in shade leaves was likely prevalent long term (Figure S2). Relative to the differences in *An* between leaf types, higher gs in shade leaves appears to result in inefficient water use. As whole canopy C gain integrates the efficiency of all leaves, this raises the question of why shade leaves maintained a lower ITE compared to sun leaves.

## Physiological behaviour of sun and shade leaves

The pattern of inefficient water use in shade leaves is important as we hypothesized that gs and *An* would be proportional across sun and shade leaves. In sun leaves, *An* and gs were strongly correlated, exhibiting behaviour broadly consistent with optimal stomatal theory. However, lower rates of *An* in shade leaves were not coupled with decreases in gs, leading to the observed decreases in ITE. This is significant as optimal stomatal regulation to balance C gain with water loss has been reported across a wide range of ecosystems and plant functional types; however, empirical data is often collected only on sun leaves (e.g. Prentice *et al.*, 2014; Lin *et al.*, 2015). As a result, the often used economic framework of balancing costs of using water versus N allocation to predict *An* (Wright *et al.*, 2003) may break down when considering all leaves within a tree canopy.

It is possible that reducing stomatal response time, by sustaining higher gs, is a strategy to take advantage of high light quickly in shade leaves (Tausz *et al.*, 2005). Evidence from this study supports this hypothesis, as shade leaves increased *An* to values equal or even outperforming sun leaves when subjected to a brief period of identical high-light intensity. Transpiration-induced cooling in shade leaves, by keeping stomata open, has also been suggested as an effective strategy to reduce sunfleck induced thermal load (Schymanski *et al.*, 2013). This is because rapid increases in leaf temperature with sunflecks have been shown to inhibit C gain (Leakey *et al.*, 2003). However, this response likely occurs at very high air temperatures and may not explain the observed gs in shade leaves across the large natural seasonal range of temperatures included in this study. How prevalent each of these strategies are within tree canopies is still unknown, as empirical studies assessing photosynthetic responses to sunflecks generally focus on seedlings (Küppers & Schneider, 1993; Pepin & Livingston, 1997; Leakey *et al.*, 2002) and understory plants, often in deep shade (Chazdon & Pearcy, 1991; Allen & Pearcy, 2000; Brantley & Young, 2009). though leaves within a forest canopy exhibited a similar uncoupling of *An* and gs across a light gradient (Tjoelker *et al.*, 1995). Thus, our findings highlight a critical need for empirical measurements of shade leaves under dynamic light environments in order to accurately scale C gain from leaf to canopy (see De Pury & Farquhar, 1997).

We found that *An* and gm scaled positively across leaf types and, unexpectedly, increased proportionately after leaf stability (~25 min) when light intensity was increased in shade leaves. Research has suggested that aquaporins can facilitate increases in the CO2 permeability of the cell membranes resulting in rapid modulation of gm (Hanba *et al.*, 2004; Heinen *et al.*, 2009; Li *et al.*, 2014). This provides a potential explanation for the observed increases in gm, but the impacts of aquaporins on gm are yet to be tested in leaves of tree species. Our findings support growing evidence that gm is highly variable and can respond to environmental variables (Flexas *et al.*, 2008). Here we provide empirical data showing gm not only varies within a canopy, but that the up-regulation of gm plays a critical role in the photosynthetic response of shade leaves to sunflecks.

If shade leaves "lie in wait" for sunflecks, then perhaps we should consider an alternate leaf economic strategy to maximize C gain, beyond conventional trade-offs associated with canopy resource distribution. This is because the role of gs in regulating photosynthetic induction impacts the capacity of a leaf to utilize sunflecks (Way & Pearcy, 2012). If the valuation of sunflecks as a C resource is large enough, then costs of sub-optimal stomatal behaviour could be offset over the leaf lifespan or across the entire canopy when considering both sun and shade leaf types. For example, the potential C gain in leaves where sunflecks constitute a large proportion of total daily PFFD may be large enough to accommodate the cost of decreases in ITE. However, accounting for the heterogeneous nature of light within a canopy remains a current challenge for empirical and modelling studies. Thus, models which predict leaf photosynthesis from N distribution within a canopy will be incomplete unless inclusion of canopy light extinction and the integration of sunflecks on shade leaves are included (De Pury & Farquhar, 1997).

## Conclusions

Here we show that dynamic physiological responses of shade leaves to altered light environments have important implications for up-scaling leaf level measurements to the canopy. Although resource allocation constrains leaf photosynthetic capacity it is the physiological behaviour of individual leaves which actually determine C gain. These findings suggest that current theories of leaf optimal behaviour should be extended to include dynamic light environments, which will have important implications for process-based models that predict canopy C gain from rates of leaf photosynthesis. Furthermore, the dynamic nature of gm cannot be simply parameterized in tree growth models and possibly should be excluded until it can be represented properly. Additional empirical data, across multiple tree species, are needed to determine both the mechanisms and the capacity of gm to opportunistically increase CO2 drawdown. To improve our ability to predict whole canopy C gain, future research should prioritize the incorporation of both sun and shade leaf physiology, which may be optimized differently.

# Tables

**Table 1**. *Eucalyptus tereticornis* leaf morphological and physiological traits of sun and shade leaves under ambient and elevated temperature treatments. Leaf mass per area, Na, 13C, pd, l and Kl values represent treatment mean (± 1 standard error) across six measurement campaigns. Values of Vcmax and Jmax are treatment mean (± 1 standard error) from ACi curves measured in each chamber at saturating light. Units of LMA and leaf Na are g m2, Kl is mmol m-2 s-1 MPa, is MPa and 13C is ‰. Different letters represent significant differences between leaf type and temperature treatments. The P value represents the overall effect between each unique combination of leaf type and temperature treatment for each trait.

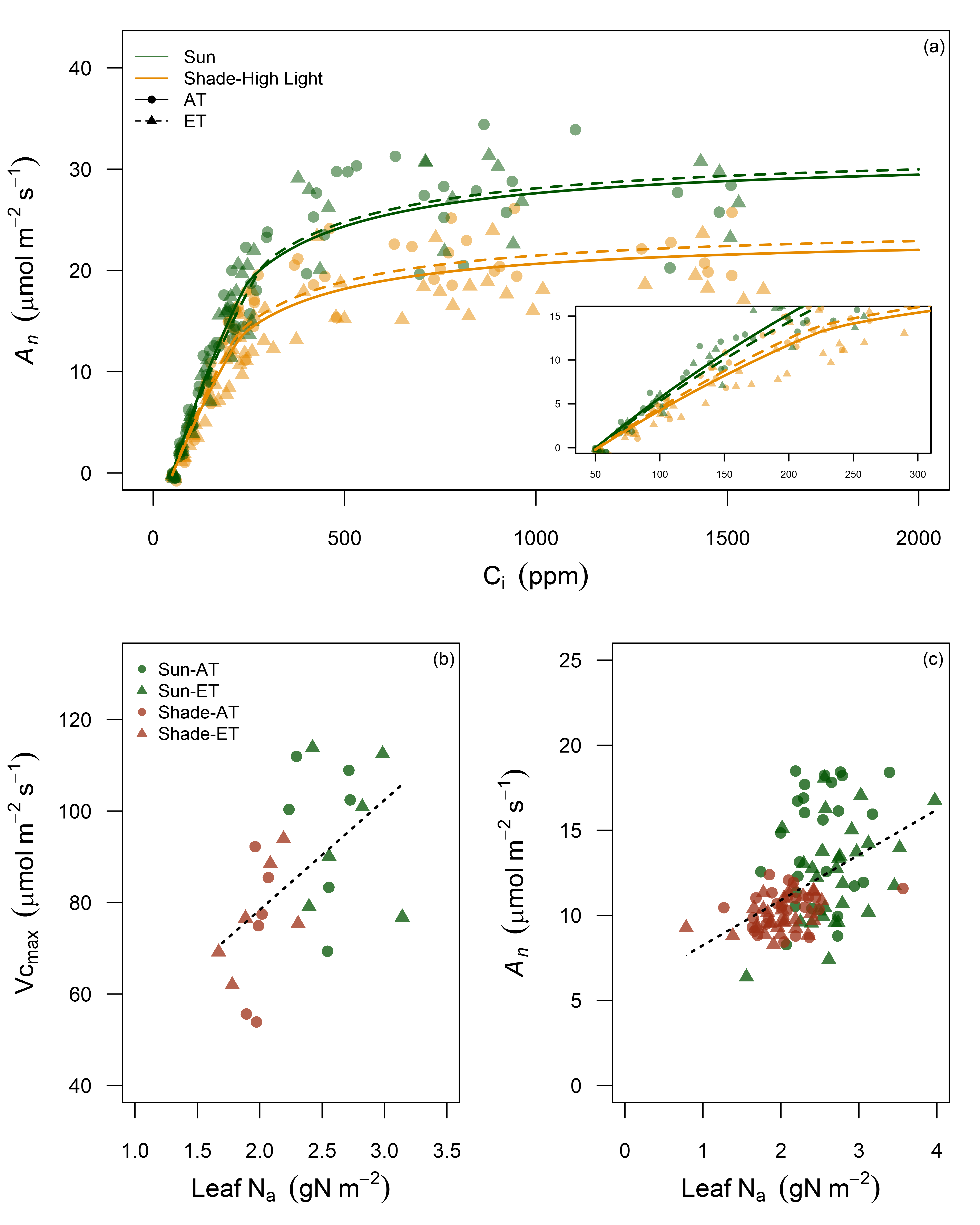
|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Leaf** | **Temperature** | **LMA** | **Na** | **Vcmax** | **Jmax** | **K** | **pre** | **l** | **13C** |
| Sun | AT | 114.1 (4.5) a | 2.63 (0.08) b | 96.3 (5.9) b | 146.1 (11.2) c | 1.69 (0.18) a | -0.32 (0.03) a | -1.60 (0.10) a | -28.1 (0.18) b |
|  | ET | 109.9 (4.8) a | 2.60 (0.09) b | 84.8 (10.5) b | 130.3 (11.6) bc | 1.79 (0.15) a | -0.32 (0.02) a | -1.70 (0.09) a | -28.3 (0.17) b |
| Shade | AT | 118.3 (4.4) a | 2.13 (0.07) a | 84.0 (3.5) ab | 112.7 (5.2) ab | 1.70 (0.13) a | -0.27 (0.02) a | -1.50 (0.09) a | -29.9 (0.17) a |
|  | ET | 113.1 (4.3) a | 1.88 (0.06) a | 66.8 (5.0) a | 95.6 (5.9) a | 1.78 (0.14) a | -0.30 (0.02) a | -1.60 (0.11) a | -30.4 (0.22) a |
| P value |  | 0.781 | 0.001 | 0.028 | 0.002 | 0.973 | 0.3486 | 0.6385 | 0.001 |

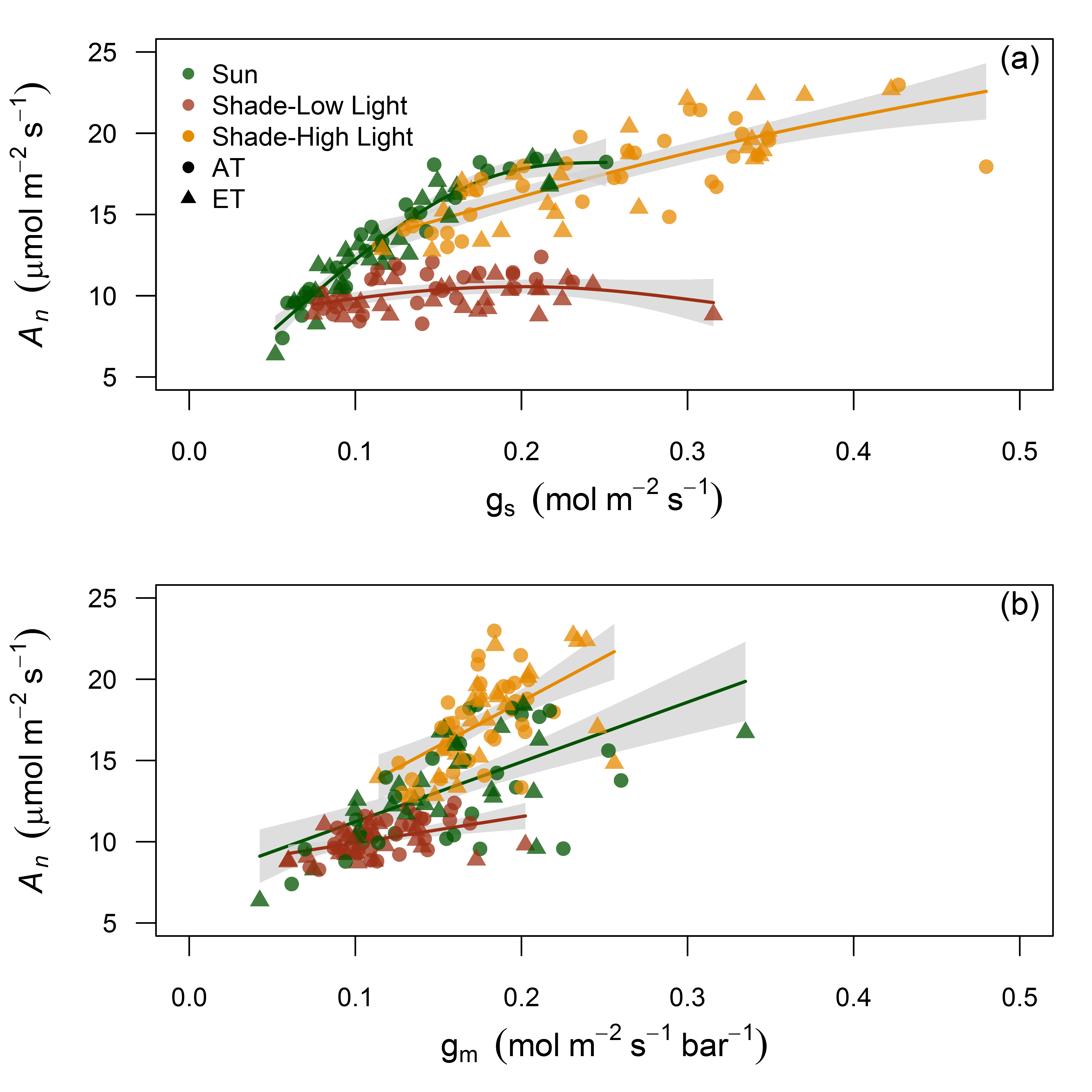
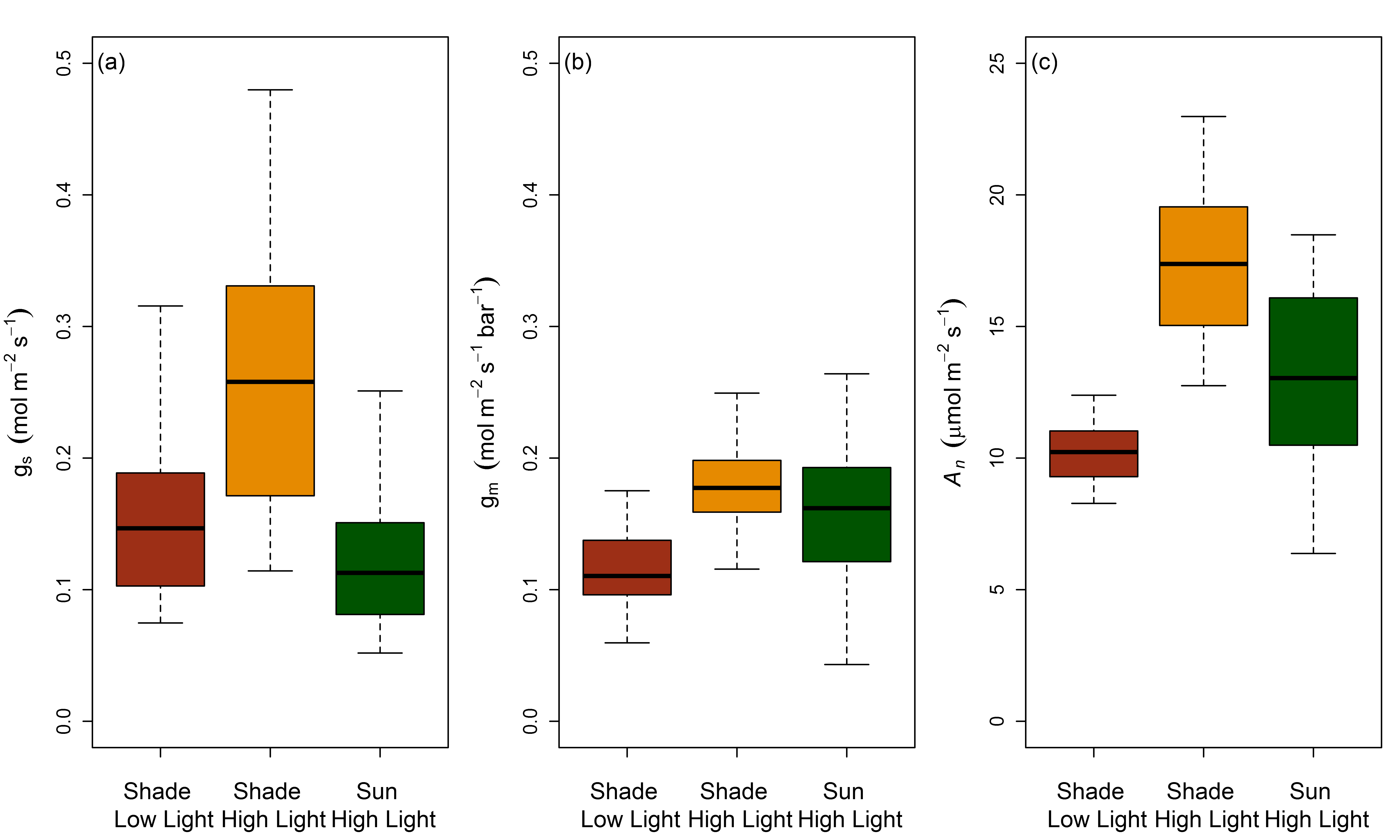
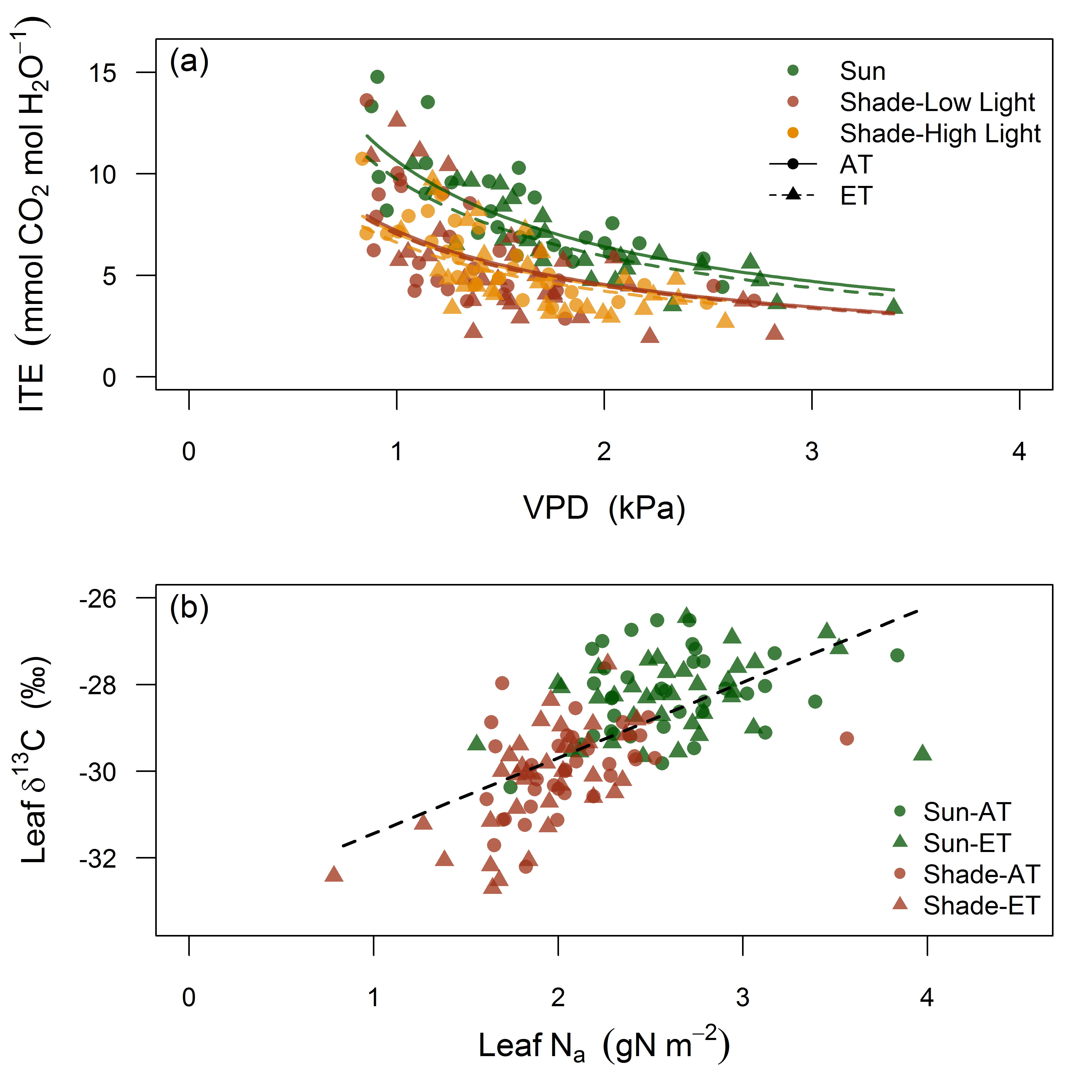
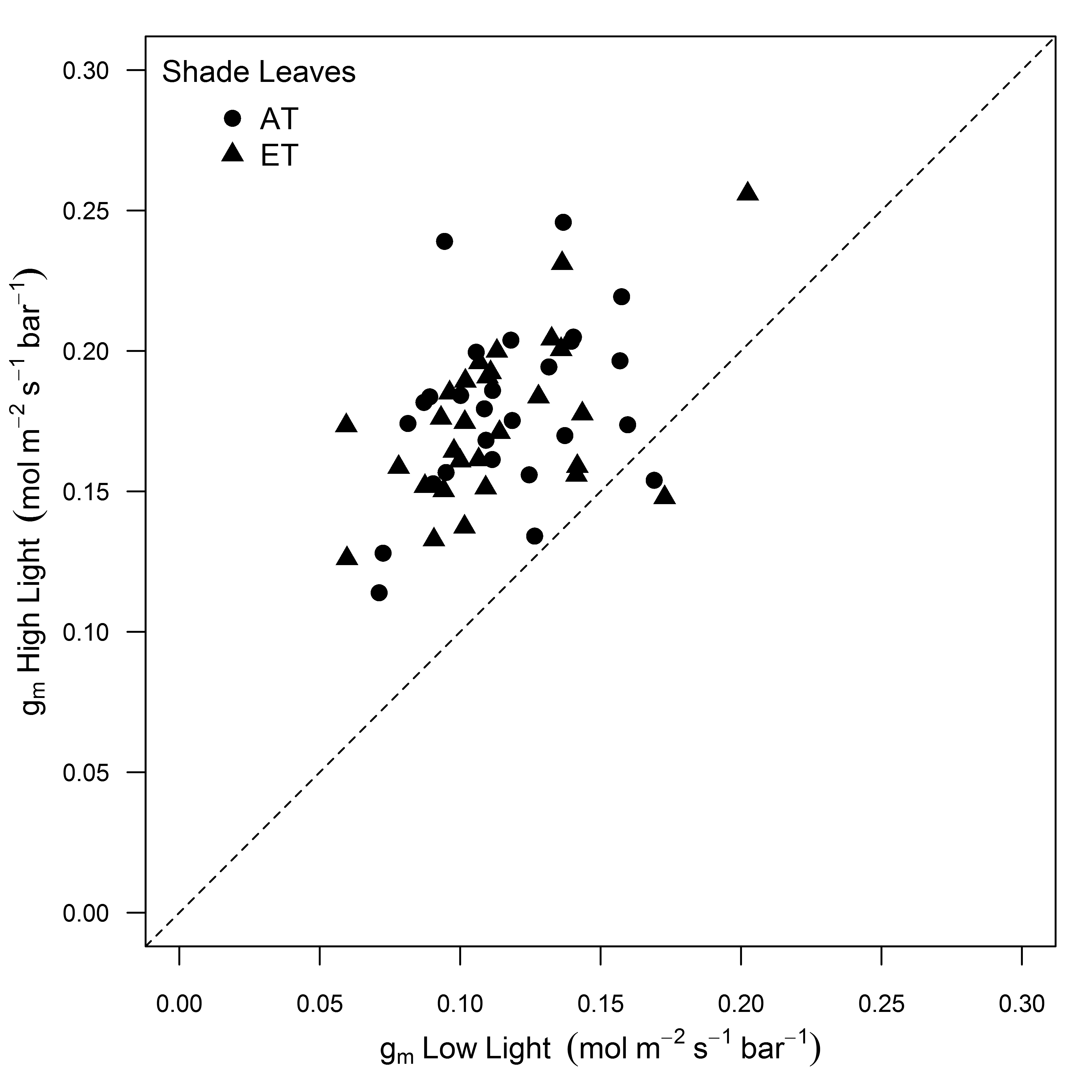
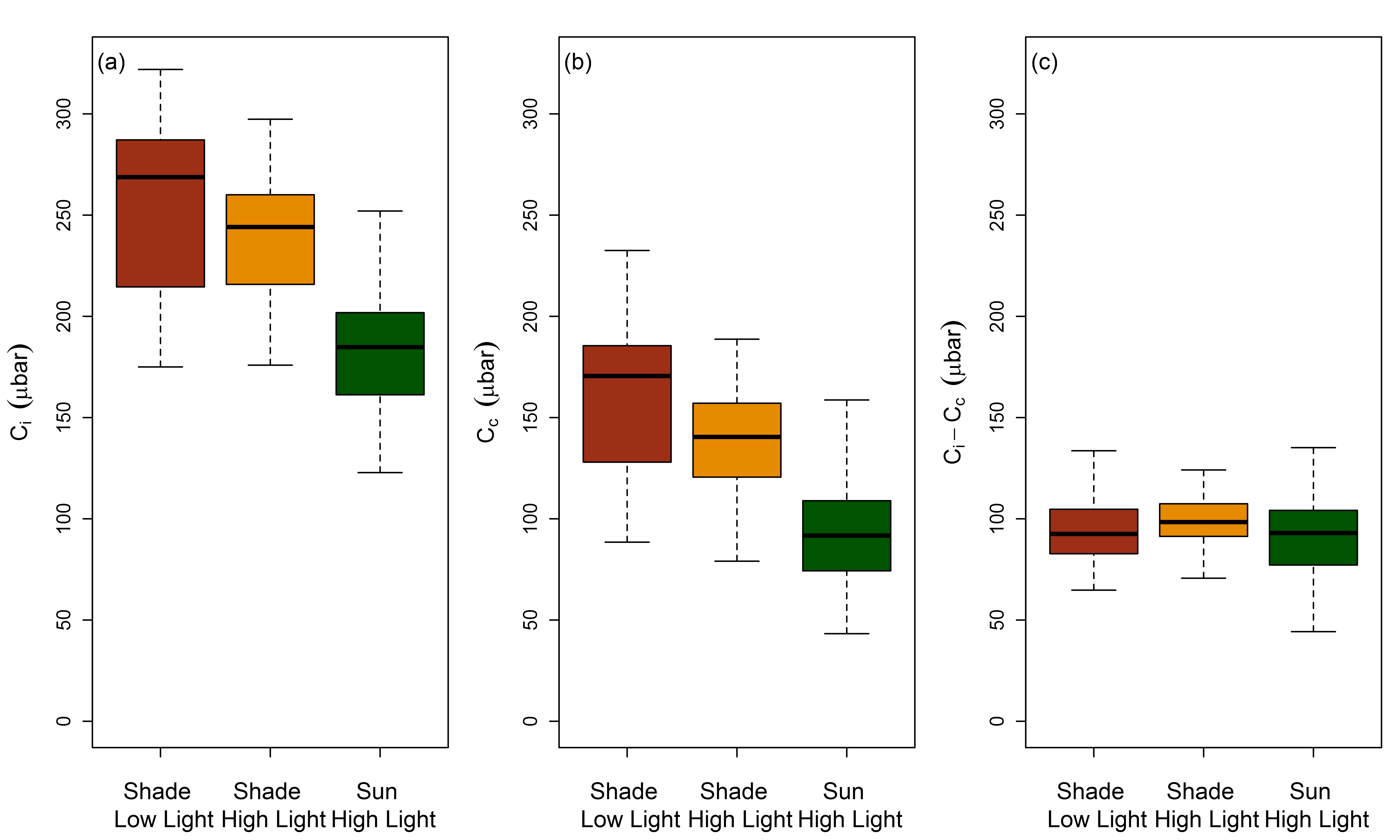
**Table 2**. *Eucalyptus tereticornis* leaf gas exchange parameters for sun and shade leaves under ambient and elevated temperature treatments. Each value reflects the mean (± 1 standard error) for each treatment across six gas exchange campaigns. Units for *An* and E are mol m-2 s-1, for gs are mol m-2 s-1, for gm are mol m-2 s-1 bar-1 and for VPD is kPa. Different letters represent significant differences between leaf type, light environment and temperature treatments. The P value represents the overall effect between each unique combination of leaf type, light environment and temperature treatment for each parameter.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Leaf** | **Light** | **Temperature** | ***An*** | **gs** | **gm** | **ITE** | **E** | **VPD** | **Ci** | **Cc** |
| Sun | High | AT | 13.5 (0.3) b | 0.122 (0.005) a | 0.163 (0.005) c | 8.26 (0.48) b | 1.78 (0.07) a | 1.60 (0.04) ab | 179.8 ( 3.2) a | 92.2 ( 2.9) a |
|  |  | ET | 13.1 (0.3) b | 0.123 (0.005) a | 0.153 (0.007) bc | 6.57 (0.39) ab | 2.21 (0.09) a | 1.90 (0.05) b | 187.9 ( 2.9) a | 92.2 ( 2.8) a |
| Shade | Low | AT | 10.4 (0.1) a | 0.150 (0.005) a | 0.117 (0.004) ab | 6.24 (0.50) a | 1.93 (0.07) a | 1.40 (0.04) a | 255.4 ( 3.8) b | 160.0 ( 4.1) c |
|  |  | ET | 10.0 (0.1) a | 0.146 (0.005) a | 0.116 (0.004) a | 5.43 (0.51) a | 2.23 (0.09) a | 1.60 (0.05) a | 253.8 ( 4.1) b | 160.3 ( 3.5) bc |
|  | High | AT | 18.1 (0.3) c | 0.255 (0.007) b | 0.184 (0.003) c | 5.85 (0.33) a | 3.42 (0.12) b | 1.40 (0.04) a | 237.4 ( 2.2) b | 137.4 ( 1.9) b |
|  |  | ET | 16.7 (0.2) c | 0.246 (0.009) b | 0.177 (0.003) c | 5.02 (0.35) a | 3.81 (0.15) b | 1.70 (0.04) ab | 238.1 ( 3.2) b | 141.7 ( 2.8) bc |
| P value |  |  | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.005 | 0.001 | 0.001 |

# Figures

  
**Figure 1**. Bars represent the local light environment for sun and shade leaves during six gas exchange campaigns from October 2013 to April 2014. Means ± 1 standard error represent integrated PPFD, measured with a ceptometer, at the canopy height of each selected leaf. Each date represents the starting date for each measurement campaign. Points represent the mean (± 1 standard error) daily maximum air temperature during each campaign period.



**Figure 2**. (a) ACi curves for sun and shade leaves grown under elevated (ET) and ambient (AT) temperature treatments. ACi curves were measured once on all trees, in February 2014, at 25°C and at saturating light (1800 mols m-1 s-1). (b) The relationship between Vcmax and mean leaf Na for each chamber, including sun leaves and shade leaves at low light. (c) The relationship between *An* and leaf Na for sun and shade leaves measured under their ambient light and temperature conditions. For (b,c) the dashed line represents the significant linear model fit for all leaves, with a marginal and conditional R2 of 0.28 and 0.35 for (b) and 0.24 and 0.33 for (c).  
  
**Figure 3**. The relationship between *An* to gs (a) and gm (b) for sun leaves measured at high light and shade leaves measured at both low and high light under their respective elevated and ambient temperature treatments across six measurement campaigns. Lines represent either smoothed regressions from a generalized additive model fit (a) or linear model fits (b). Grey areas are 95% confidence intervals for the mean.  
  
**Figure 4**. Box plots of measured gs (a), gm (b) and *An* (c) of sun leaves and shade leaves at both low and high light pooled across six measurement dates.  
  
**Figure 5**. (a) The relationship between instantaneous transpiration efficiency (ITE) and VPD for sun leaves and shade leaves at both low and high light with elevated and ambient temperature treatments. (b) The relationship between leaf 13C and leaf Na for sun leaves at high light and shade leaves at low light. For (a) VPD is the leaf to air pressure difference inside the gas exchange cuvette and lines represent predictions from the optimal ITE model with a g1 value for each leaf type and treatment. For (b) the dashed line represents the significant linear model fit across all leaves with a marginal and conditional R2 of 0.41 and 0.45, respectively.  
  
**Figure 6**. The change in measured gm for individual shade leaves following an increase in PPFD to match the light environment of full sun leaves in the same tree measured across six measurement dates. Measurements of gm were recorded once CO2 and water vapour fluxes were stable in the leaf cuvette, which took approximately 25 minutes after light intensity was increased. The dashed line is the 1:1 relationship.  
  
**Figure 7**. Boxplots of (a) intercellular CO2 concentration (Ci), (b) CO2 concentration in the chloroplasts (Cc) and (c) CO2 drawdown from substomatal cavities to sites of carboxylation of sun leaves and shade leaves at both low and high light (Ci-Cc).

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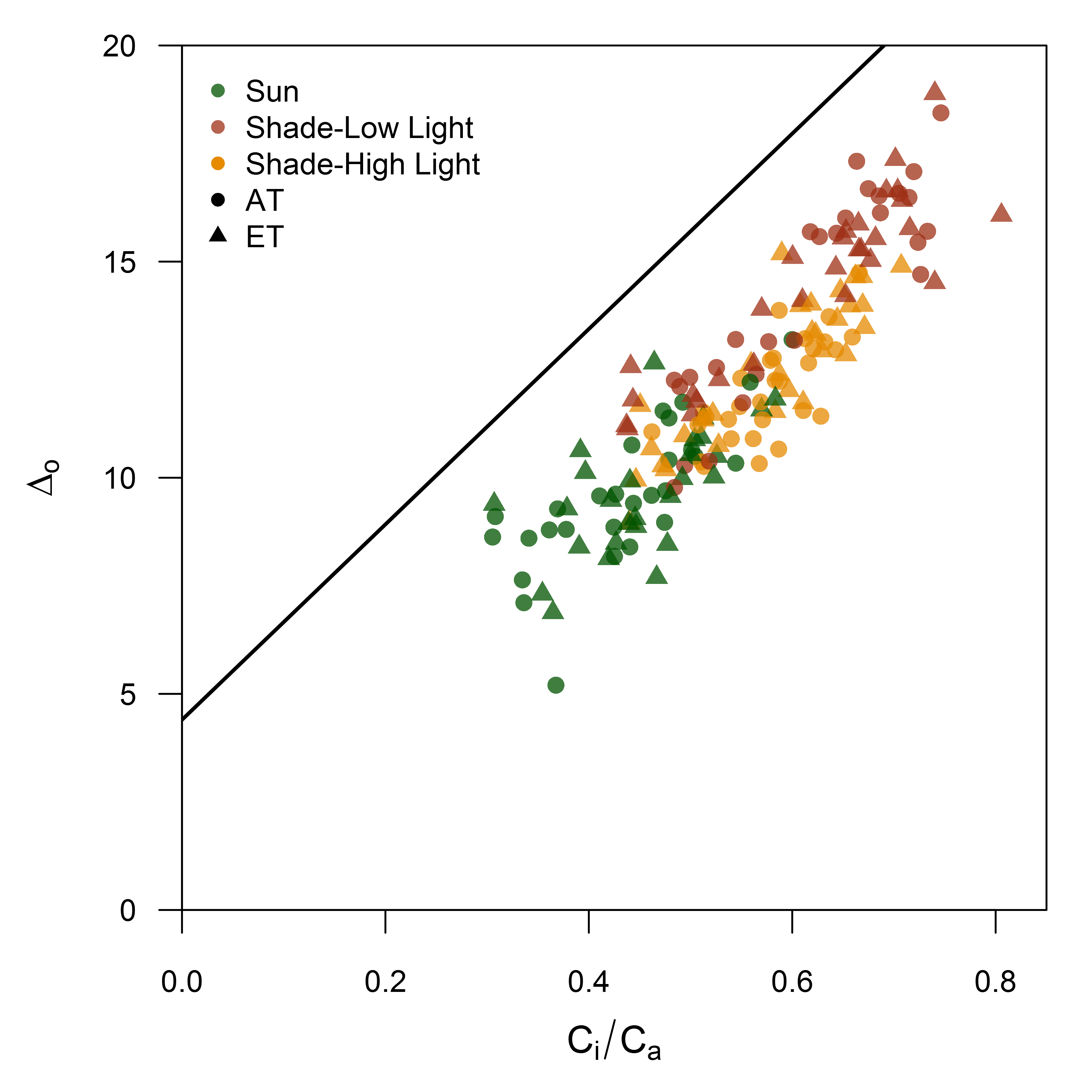
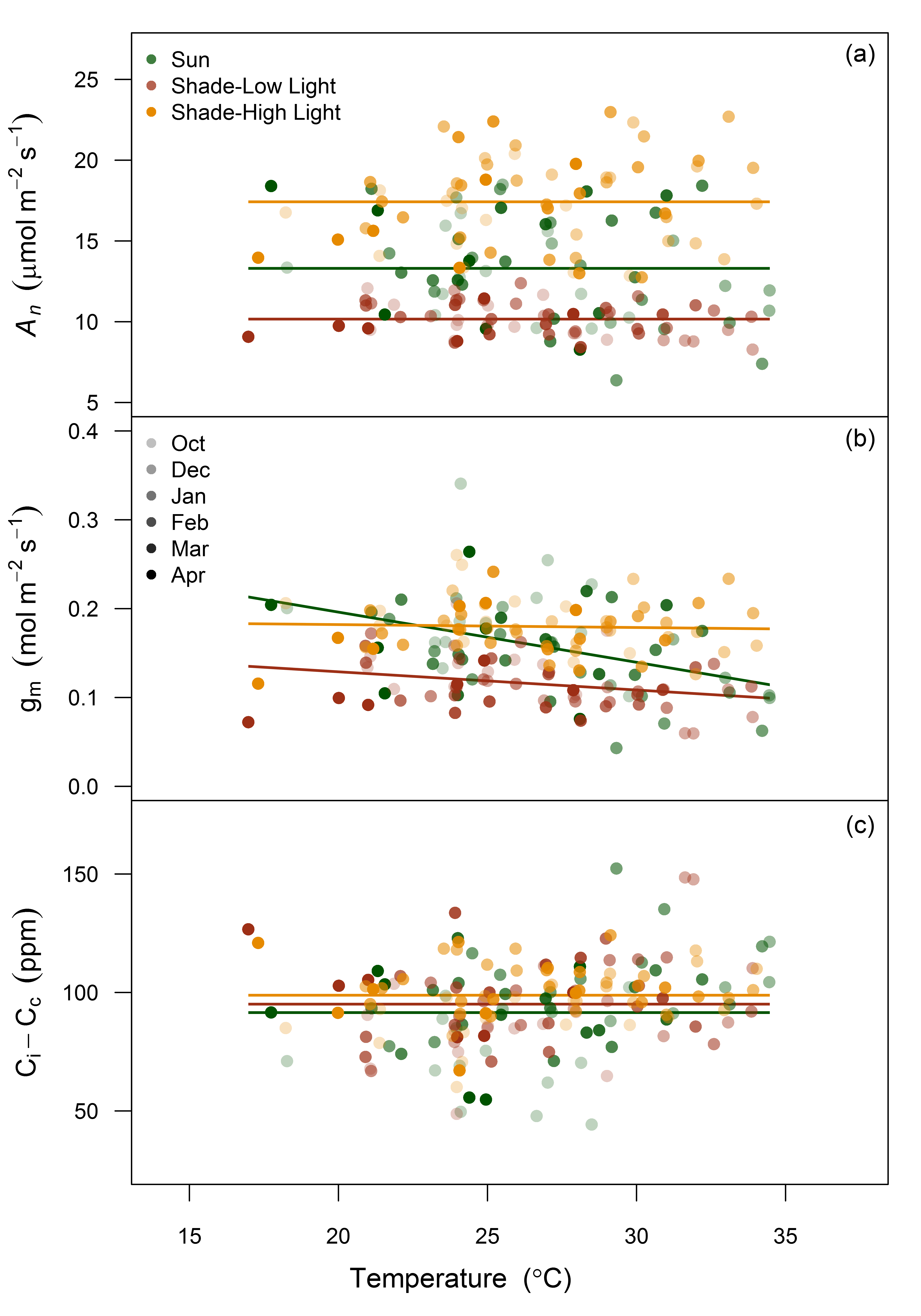
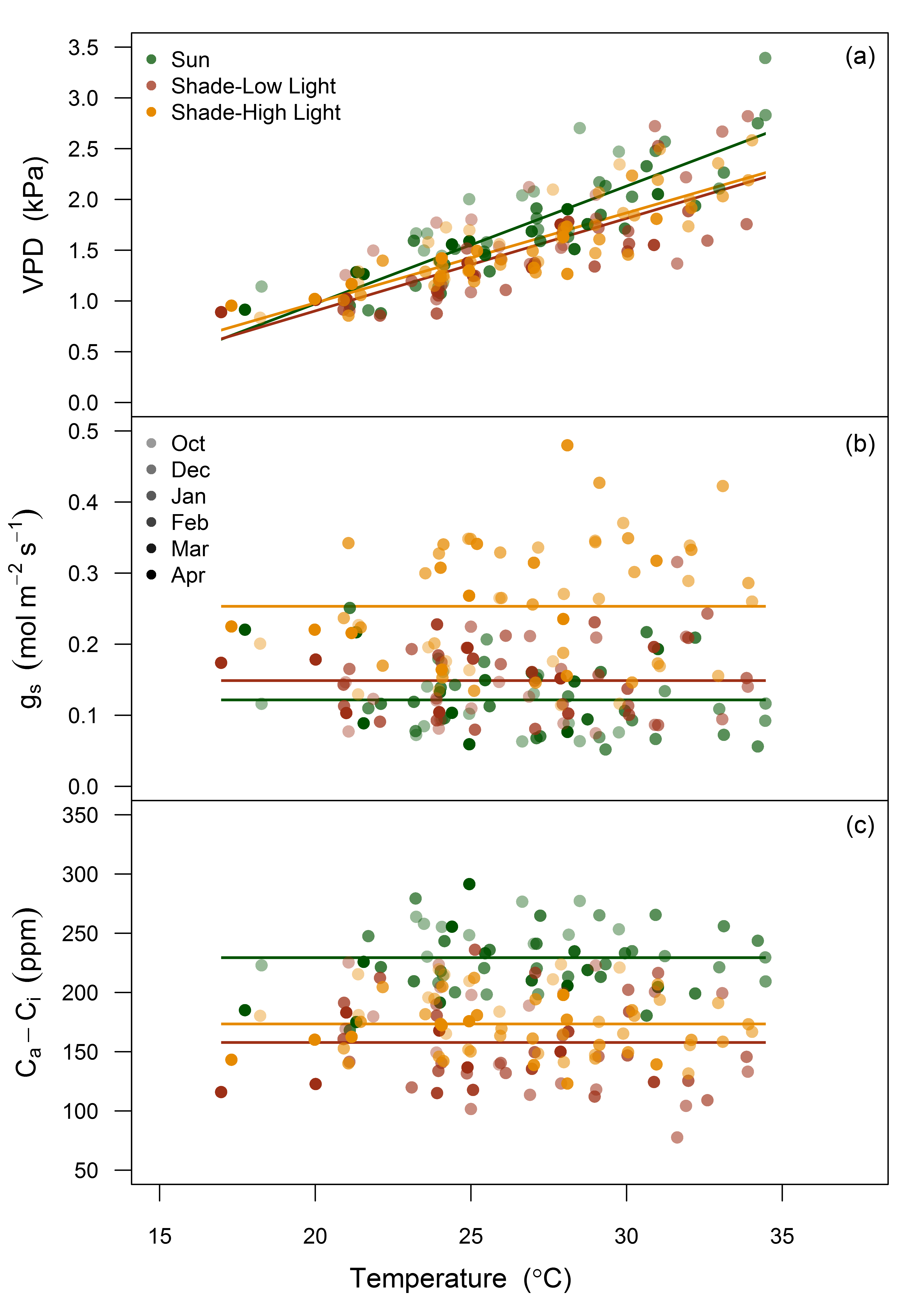
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### Author Contributions

CC contributed to the design of the research, data analysis, collection, interpretation and writing the manuscript. MT contributed to the design of the research, interpretation and writing the manuscript. SC contributed to the design of the research, performance of the research and interpretation. RD contributed to the design of the research, data analysis, interpretation and writing the manuscript.

# Supporting Information

## Figures

  
**Figure S1**. Daily maximum and minimum temperature (a), daily maximum VPD (b) and total daily PPFD (c) for each chamber across the experiment duration.  
  
**Figure S2**. Relationship between the observed discrimination of 13CO2 measured during photosynthesis () and measured Ci/Ca for sun leaves measured at high light and shade leaves measured at both low and high light. The solid line represents the theoretical line for C3 plants from Evans et al. (1986).  
  
**Figure S3**. Response of *An* (a), gm (b) and Ci-Cc to leaf temperature for sun leaves and shade leaves at low and high light. Shaded symbols represent each monthly measurement campaign. Solid lines, colored by leaf and light type, are fitted line for the relationship with each parameter and leaf temperature across all measurement campaigns. All parameters with no relationship are fitted with zero slope and the overall mean value for each treatment combination. Weak negative relationships with gm and increasing leaf temperature were detected with sun and shade leaves under their local light environment (R2 = 0.16 and 0.08, respectively).  
  
**Figure S4**. Response of VPD (a), gs (b) and Ca-Ci to leaf temperature for sun leaves and shade leaves at low and high light. Shaded symbols represents each monthly measurement campaign. Solid lines, colored by leaf and light type, are fitted line for the relationship with each parameter and leaf temperature across all measurement campaigns. All parameters with no relationship are fitted with zero slope and the overall mean value for each treatment combination. Leaf VPD inside the gas exchange cuvette was positively correlated with increasing leaf temperature for sun leaves and shade leaves at low and high light (R2 = 0.73, 0.58 and 0.72, respectively).

## Methods S1

### Description of the calculation of gm from carbon isotope discrimination during C3 photosynthesis

Using online C isotope discrimination measurements, the difference between the observed discrimination and what is predicted for light saturated gas exchange is proportional to gm (Griffiths & Helliker, 2013). First, leaf C isotope discrimination was calculated by comparing the isotopic composition of the reference gas entering the leaf cuvette (13Ce) with the sample gas (13Co) such that:

(1)

where Rs is the isotopic ratio of the sample and Rstnd is the isotopic ratio of the standard Vienna Pee Dee Belemnite (VPDP). Next, the observed discrimination (o) is calculated from Evans et al. (1986):

(2)

where:

(3)

and is the ratio of the CO2 entering the well mixed leaf cuvette to the CO2 draw down in the gas stream by the leaf.

Second, C isotope discrimination during C3 photosynthesis () is the resultant discrimination from CO2 diffusion from the atmosphere to the site of carboxylation, consisting of a series of fractionation steps described in Evans et al. (1986). In this experiment, a modified form of the equation presented in Evans & von Caemmerer (2013) with ternary effect corrections by Farquhar & Cernusak (2012) was used such that:

(4)

where o is the observed discrimination and i, gm , e and f are the contributions to fractionation if Ci = Cc, gm, respiration and photorespiration, respectively. The equations for each are as follows:

(5)

(6)

(7)

(8)

where the different fractionation factors include; diffusion through water (ai, 1.8‰), Rubisco carboxylation (b, 29‰), the photorespiratory fractionation (f, 16.2‰) and the combined fractionation through the boundary layer and the stomata (a'). a' is defined by:

(9)

where Cs is the CO2 partial pressure at the leaf surface, ab is the fractionation from boundary layer diffusion (2.9‰) and a is the fractionation due to diffusion in air (4.4‰) (Evans *et al.*, 1986). Ca and Ci are the atmospheric and intercellular partial pressures and is the compensation point in the absence of mitochondrial respiration in the light (Rd). In this experiment both and Rd were derived using a standard Arrhenius function with parameters for *Eucalyptus globulus* from Crous et al. (2012). The ternary effect corrections (t) are described by:

(10)

where E denotes the transpiration rate and is the total conductance to CO2 diffusion to both the boundary layer and stomatal conductance.

The gm can then be calculated as:

(11)

Here, gm is expressed in units of mol m-2 s-1 bar-1 to be consistent with Evans & von Caemmerer (2013). As the pressure term is nearly equal to unity, suitable comparisons between gm and gs can be made.

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