Analysis of lighting conditions of indoor living walls: Effects on CO2 removal

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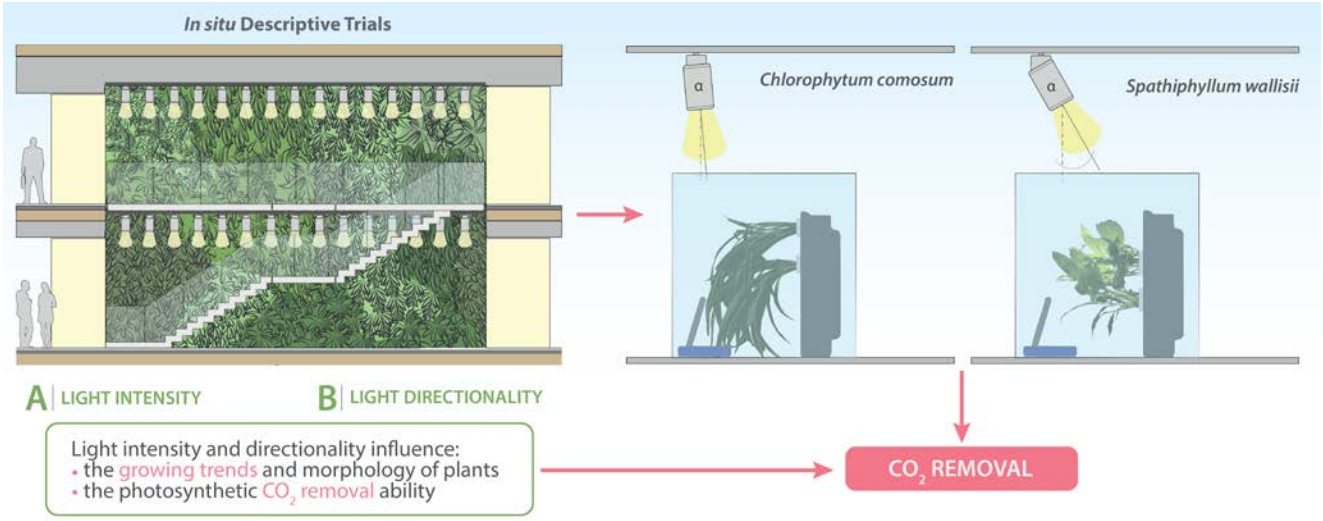
Abstract

Vertical greening systems, or living walls, are becoming increasingly used indoors for improving the sustainability of buildings, including for the mitigation of excess CO_2 levels, derived from human respiration. However, light provision within indoor environments is often insufficient for the efficient functioning of many plant species, leading to low photosynthetic CO_2 removal rates, and the need for supplementary light sources. In this study, we investigated the performance of supplementary lighting employed for indoor living wall systems, and whether optimised lighting conditions could lead to improved CO_2 removal. *In situ* trials with several medium-large indoor living walls were performed to sample the lighting scenarios currently employed. We concluded that the majority of plants in existing systems were exposed to suboptimal lighting and will have a net-zero CO_2 removal efficiency. Sealed chamber experiments using two common living wall plant species were conducted to explore the effect of varying lighting conditions on CO_2 removal efficiency. Comparisons on optimal and "best case" *in situ* conditions were carried out, showing that CO_2 removal efficiency was significantly correlated with both leaf and stem angles, which suggest phototropism may influence *in situ* CO_2 removal. After a ten-day experimental period, the highest CO_2 removal efficiency for both test plant species was observed at 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ light flux density (~10500 lux) at 15° from the vertical growing surface. Our results indicate that most current lighting systems are inadequate for healthy plant photosynthesis and CO_2 removal, and that modified lighting systems could improve this performance. The estimation of the CO_2 removal ability of a 5 m^2 passive living wall decreases from an ACH of 0.21 h^{-1}, achieved in an optimal light exposure condition, to only 0.03 h^{-1} when plants are exposed to sub-optimal conditions. To reduce maintenance costs, technical guidelines for indoor living wall lighting should be established, and lighting suppliers should recognise the developing niche market for specialised indoor living wall lighting.

Graphical Abstract



Keywords:

Green Building, Sustainability, Green wall, Phytoremediation, Indoor air quality.

Highlights:

- *In situ* living walls require optimized lighting conditions for high CO_2 removal efficiency.
- Light intensity and directionality influence the CO_2 removal efficiency of indoor living walls.
- Phytosystem selection and design stands to significantly improve indoor CO_2 removal efficiencies.

1. Introduction

Densification of cities has led a growing proportion of society becoming urban dwellers, spending approximately 90 % of their time indoors (Klepeis et al., 2001; Liu et al., 2019). Population exposure to many air pollutants is thus increasingly determined by their concentrations within the indoor environment (Molloy et al., 2012; Riviere, 2010), with indoor air quality increasingly recognised as a significant health concern. Carbon dioxide (CO_2), derived mainly from occupant respiration, is a major determinant for the control of indoor environmental air quality. Even if CO_2 is considered a non-toxic compound at ambient concentrations and there is little evidence of clinical issues on human cognitive performances at high concentrations (Du et al., 2020; Fisk et al., 2019), many guidelines consider it as a metric of poor ventilation and indoor air quality. Indeed, the monitoring of indoor CO_2 concentration is adopted as marker for heating, ventilation and air conditioning (HVAC) systems operation in order to maintain adequate indoor air quality and thermal comfort standards in public buildings (Franco and Schito, 2020). Human respiration is considered as a significant source of CO_2 in non-industrial indoor environment (Azuma et al., 2018; Shen et al., 2020) and its concentration along with indoor temperature are used as parameters to operate the automatic control of HVAC systems through the regulation of ventilation rates (Li et al., 2020). However, they use considerable electrical energy, especially when the ambient air requires substantial heating or cooling prior to entering the indoor environment (Ben-David and Waring, 2016). Thus, there is a need to explore alternative, low-energy-use systems for the maintenance of CO_2 concentrations in indoor environments.

Vertical greening systems, also referred to as green walls or living walls, may be an effective nature-based solution to improve indoor environments and reduce the costs associated with HVAC systems (Irga et al., 2017; Pearlmutter et al., 2020). Living walls are characterised by infrastructure that enables ornamental plant species to be grown on, or within, indoor and outdoor wall spaces (Newton et al., 2007). The innate biophilic qualities of these systems are often desirable for indoor environments due to their therapeutic psychological effect of building occupants (Bringslimark et al., 2009; Montacchini et al., 2017; Tifferet and Vilnai-Yavetz, 2017; van den Berg et al., 2016). However, a commercially underappreciated aspect of living walls is their ability to remove indoor air contaminants such as volatile organic compounds, particulate matter and CO_2 (Aydogan and Montoya, 2011; Gubb et al., 2018; Moya et al., 2018; Oh et al., 2011; Pettit et al., 2018; Soreanu et al., 2013; Wolverton et al., 1989). Through photosynthesis, living walls are able to effectively reduce the concentrations of CO_2 from indoor environments, however lighting conditions have a strong influence on the efficacy of this process (Torpy et al., 2017).

Indoor living walls are often situated in areas where they have the greatest aesthetic impact on building occupants such as hallways, conference rooms or as a backdrop to building lobbies. Consequently, these locations often do not allow for adequate natural sunlight at the plant surfaces (Tan et al., 2017), and therefore, many systems are illuminated with supplementary artificial lighting. As light is a fundamental requirement for photosynthesis, the provision of sufficient lighting is essential to maintain plant health and facilitate CO_2 removal (Pennisi and van Iersel, 2012). Currently, there has been little research into the provision of optimal lighting for medium to large scale indoor living wall installations (Egea et al., 2014; Kaltsidi et al., 2020; Tan et al., 2017).

Various qualitative and quantitative aspects of light affect the photosynthetic activity and photomorphogenesis of indoor plants (Cope et al., 2014). Both light intensity (photon flux density) and photoperiod play a vital role in light-sensing and light-acclimatory processes, both of which regulate key physical and chemical plant mechanisms such as disease defense signaling (Karpinski et al., 2003) and photosynthesis. Within the indoor environment, light intensities and duration are often designed for human comfort during occupation periods, with light intensities of 500 to 1000 lux (equivalent to photosynthetic photon flux densities of ~10 – 50 $\mu mol \cdot m^{-2} \cdot s^{-1}$) being commonly used (European committee for standardization, 2011). These levels are significantly lower than the photosynthetic requirements of many plant species (Kim et al., 2012; Torpy et al., 2014), and often do not align with natural diurnal cycles.

Furthermore, the absorption of light and the resulting photosynthetic response are determined by the interaction between light directionality, and leaf orientation (Posada et al., 2012). Many plants are able to adapt to dynamic lighting conditions by changing the orientation of their leaves through phototropism, thus maximizing the light irradiance at the leaf surface (Goyal et al., 2013), however there is no existing literature describing the influence of phototropism and the effect of current commercial lighting systems on CO_2 removal for indoor living walls.

The current study seeks to establish a rationale for the development of technical guidelines for lighting designs for indoor living walls through manipulative laboratory experiments informed by *in situ* observations of current lighting conditions, that aimed to: (i) assess the influence of varying light intensities and light angles on CO_2 reduction by living walls containing two common indoor plant species, and (ii) explore the effect of living wall phototropism on CO_2 removal under varied lighting conditions, reflective of *in situ* conditions.

2. Materials and Methods

2.1. In situ *living wall lighting assessment*

Prior to conducting manipulative laboratory experiments, the lighting conditions of four indoor living walls (LW 1 - 4) from multi-story commercial buildings in the Greater Sydney area were assessed *in situ* (Supplementary Table 1). Indoor living walls one and two (LW 1 & LW 2) each had vertical surface areas of 60 m^2 and were comprised of 240 individual botanical biofilter modules (0.25 m^2), while living walls three and four (LW 3 & LW 4) had vertical surface areas of 27 and 16.25 m^2 and contained 108 and 65 individual botanical biofilter modules respectively (Fig. 2).

Botanical biofilter modules used in the commercial systems were made from recycled low-density polyethylene, containing a coconut husk-based growth substrate and designed with 16 front-facing holes into which the following plant species were grown: *Chlorophytum comosum, Spathiphyllum wallisii, Epipremnum aureum, Philodendron xanadu, Peperomia obtusifolia, Nephrolepis exaltata, Neomarica gracilis* and *Gibasis* sp.. The four living walls were selected as they were all installed in environments lacking exposure to natural light and were thus reliant wholly on artificial lighting.

At LW 1, 2 and 4, lighting was supplied by adjustable LED spotlights (COB LED spotlight, model PLD-TL-40W-F1, 130 x 200 cm, 40 W, 60° beam angle, 3000 K warm white, produced by the Huizhou Plamd Lighting Technology Co., China), installed above the living walls at a distance of 0.8 – 1 m from the planted surfaces and 0.2 m from one another. Lighting at LW 3 was supplied by in-ceiling LED downlights, 1 m from the planted surfaces, and 1 m from one another. The intensity of photosynthetically active light (photosynthetically active radiation (PAR); λ = 400 – 700 nm) was measured with a Li-250A light meter (Li-Cor Biosciences, USA) at a distance of 0.5 m from the living wall surface (in front of plant foliage). Light intensity was measured at the wall surface either at 0.5 or 1 m vertical intervals, dependent on wall design (Fig. 2).

Lighting devices at LW 1 and 2 were photographed using a Nikon D3200 camera (ISO 100, f. 3.8, t 1/100) to establish the lighting profile and average inclination of luminaries (light angle) relative to the front surface of the walls. Images were taken from the left and right sides of the walls, at a height equal to the luminaries' position. Only LW 1 and 2 were considered for light angle evaluation as they utilised a consistent number of luminaries and represented a larger and more comprehensive lighting design than LW 3 and 4.

Image analysis was performed using Adobe Photoshop CC (Adobe Systems) and AutoCAD 2019 software (Autodesk Inc., USA) to determine the inclination angle between the vertical and the luminary's axis for 50 luminaries (Supplementary Fig. 1). Each luminaire was isolated from photographs using Adobe Photoshop CC's (1) [Polygonal Lasso] tool to draw straight-edged segments of the selected luminaire's border, (2) the [Select > Inverse] tool was used to select the background pixels and (3) the [Crop] tool was used to delete background pixels. Luminaries were imported into the AutoCAD environment featuring a re-created layout setting of LW 1 and 2 for each lighting device. Finally, the [Measure > Angle] tool was used to calculate the luminaire's inclination angle.

2.2. Plant module experimental set up

Chlorophytum comosum and *Spathiphyllum wallisii* were the plant species selected for manipulative examination in this study, as they are frequently used in indoor living wall applications (Egea et al., 2014; Pérez-Urrestarazu et al., 2016), were the most prevalent species in *in situ* observations, and have previously been recommended for the phytomitigation of indoor air pollution (Torpy et al., 2017; Wolverton et al., 1989). While the light requirements of individual plant species differ (Niinemets, 2006), both *C. comosum* and *S. wallisii* are capable of tolerating low light conditions (Torpy et al., 2017), making them ideal for current indoor living wall designs.

Eight individual plants of each species were housed in open-ended PVC pipes (cassettes: 90 mm external diameter and 120 mm in length) containing coco-husk substrate, similar to the substrate used *in situ*, as described previously (Pettit et al., 2018). Plant replicates were adapted to a horizontal growth position at ambient light intensities (~ 6 – 7 $\mu mol \cdot m^{-2} \cdot s^{-1}$; ~235 lux) within a laboratory environment for seven days (temperature 22.0 ± 2.3 °C and relative humidity 65.8 ± 15.8 %). Plants were watered to field capacity weekly and allowed to drain for two days prior to testing. To ensure the plant cassette arrangements were representative of a vertical wall, cassettes

were housed in a frame made of rotary molded polyethylene (500 x 500 x 130 mm;; Supplementary Fig. 2).

During experiments, the rear of the plant cassettes were covered with plastic film to limit respiratory emissions from non-green tissues and microorganisms associated with the growth substrate that would be unrepresentative of living walls with an enclosed growth substrate. (Gubb et al., 2018). Additionally, *C. comosum* plants were arranged in the upper-central module holes (Supplementary Fig. 2). As the experimental test chamber cannot facilitate wall-mounted modules, this arrangement was used to minimise leaf contact with the chamber floor to prevent unrepresentative leaf angles ("floor drag"). Living wall frames with single plant species (henceforth, plant modules) were used to perform subsequent CO_2 removal assessments.

2.3. Sealed chamber experiments

2.3.1 Preliminary study: non-photoadapted CO_2 removal

To determine the effect of lighting conditions on plant specific CO_2 drawdown, a preliminary study was conducted to assess the optimal lighting conditions for each plant species (Supplementary Table 1). Plants were placed in a sealed chamber and CO_2 drawdown was monitored under varying conditions. As the plants were given no time to adapt their physiology to the lighting conditions in each treatment, the preliminary study was termed "*non-photoadapted CO_2 removal*". The results from this study were applied over a 10-day period, in which plant species could adjust their physiology to the lighting conditions (*photoadaptation*), similar to how *in situ* plants would. Prior to CO_2 drawdown assessments, total plant leaf area was determined using plant images in AutoCAD.

CO_2 drawdown assessments for both plant species were conducted in sealed Perspex chambers (216 L), fitted with an 80 mm electric fan (12 V) for air circulation. Lighting was provided by a Parscan circular LED spotlight (12 LEDs, 30 W, 3000K warm white; ERCO Lighting Pty. Ltd., Australia) and an Opton square LED spotlight (6 LEDs, 25 W, 3500K warm white; ERCO Lighting Pty. Ltd., Australia), both equipped with a spherulite optical polymer flood lens (ERCO Lighting Pty. Ltd., Australia). Both luminaries were adjustable through 0° - 90° tilt, light housings were rotatable through 360°, and the luminous flux was dimmable (Parscan luminous flux 200 – 6600 lm; Opton luminous flux 200 – 4920 lm). These light systems were selected due to their similarities to luminaries employed *in situ,* light manipulation capabilities, low energy consumption, and low radiant heat output (Morrow, 2008; Ouzounis et al., 2015; Pattison et al., 2018; Yeh and Chung, 2009). Frames were constructed to house luminaries where both spotlights were mounted on a single linear light track power supply (ERCO 3C/DALI, Jadecross, Australia) and positioned adjacent to the test chambers.

Single-species plant modules containing eight plants (Supplementary Fig. 2) were placed within the chamber where light angles and intensities were set vertically (Fig. 1). Four light inclinations (0°, 15°, 30° and 45° from solar apex) were tested in combination with five light intensities (50, 75, 100, 150, and 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$; ~ 1946, 2919, 3893, 5839, and 7785 lux), providing assessments of CO_2 removal for both plant species under 20 lighting scenarios.

Fig. 1. Lighting design for angle and intensity used in Experiment 1 for *Spathiphyllum wallisii* and *Chlorophytum comosum*. Species depicted in Fig. is *S. wallisii*.

As indoor CO_2 concentrations trigger many heating, ventilation and air conditioning (HVAC) systems to increase ventilation rates when indoor CO_2 concentrations reach ~1000 ppm (Lawrence et al., 2018), we assessed CO_2 drawdown from a starting concentration of ~1000ppm, generated by respiration until chamber concentrations reached this threshold (mean starting concentrations of CO2 were 985ppm ± 90ppm). CO_2 drawdown was measured using an infrared gas analyzer (IAQ-CALC 7525, Tsi Inc., USA; Range 0 – 5000ppm, Accuracy ± 3% or 50ppm, Resolution 1ppm, Response Time 20 seconds) which was sealed within the chamber to monitor the concentration of CO_2 at one-minute intervals over a period of 40-minutes. This instrument was brand new with factory calibration at the time of these trials. Instrument specifications were: CO_2 Range 0 – 5000 ppm, Accuracy ± 3% or 50 ppm, Resolution 1 ppm, Response Time 20 seconds. These experiments were performed in triplicate with ~5-minute intervals between testing to return chamber CO_2 concentrations to ambient laboratory conditions (baseline global CO_2 concentration of ~410 ppm).

Sampling was repeated three times (sample triplicate), with lighting conditions maintained between measurements by measuring the light intensity across plantlet canopies, averaged across four points. Light measurements were taken 150 mm from the module using a LI-250A light meter (Li-Cor Biosciences, USA). Light intensity adjustments between treatments were achieved through modulation of the light dimmers and repositioning of the frame, as necessary.

CO_2 removal efficiency was calculated as percentage removal over the 40-minute period from the 1000 ppm starting concentration after stabilisation. This method accounted for variations in starting CO_2 concentrations among replicates (n = 3). All CO_2 removal data was corrected *post hoc* for chamber leakage (ie. CO_2 decay from the empty chamber without plants), calculated to be 1.24 ± 0.387 % (mean ± SEM) over the 40-minute testing period. Chamber design did not allow for manipulation of temperature and humidity, however these factors did not vary significantly throughout the 40 min experiments.

The results from this experiment informed the optimal lighting angles and intensities required for heightened photosynthetic performance to be assessed in comparison with the conditions observed *in situ*.

2.3.2 CO_2 removal efficiency and phototropic adaptation study

To determine how prolonged exposure at the optimal light angles and intensities identified during the *in situ* field assessments and laboratory experiments influences CO_2 removal efficiency and plant morphology (phototropism), single-species plant modules were exposed to the following treatments continuously for ten days (Supplementary Table 1):

1. 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (~5250 lux) at 15°; this was the highest light intensity detected in the *in situ* field assessments, and the most common light angle observed in *in situ* systems,
2. 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (~10500 lux) at 15°; this was the optimum lighting combination detected in the laboratory study for non-photoadapted *C. comosum*,
3. 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (~10500 lux) at 45°; this was the optimum lighting combination detected in the laboratory study for non-photoadapted *S. wallisii*.

Single-species plant modules containing four plants were assessed in triplicate with a photoperiod of ten hours per day, using the above experimental set up. CO_2 removal was measured daily, and daily movements in leaf and stem angles were measured by taking photographs of four leaves per plant, which were then isolated from the photobank and adjusted to a reference axial system (*xy*) using Adobe Photoshop (Adobe Inc., USA) (Supplementary Fig. 3). Variation in leaf and stem angle relative to the axis was measured using AutoCAD 2019 (Autodesk Inc., USA; Fig. 5).

A pilot study conducted by the authors indicated that phototropism would be complete after ten days, with negligible leaf/stem angle movement observed after this time thus this trial was performed for 10 days.

2.4. Statistical analysis

Non-photoadapted CO_2 removal was assessed using multiple linear regression to quantify linear associations with plant species, light intensity, and light angle.

To assess whether the observed, linear changes in photoadapted CO_2 removal efficiency through time were significant, a series of linear regression models were generated separately for each plant species and the three, light angle-intensity combination treatments (six in total). Similar models for species and light treatment were conducted to assess whether leaf and stem angle position changed linearly through time (nine total: 6 x leaf angle, 3 x stem angle).

To determine whether photoadapted CO_2 removal efficiency, leaf or stem position on the final day differed significantly between plant species and amongst light treatments, analyses of variance (ANOVA) with Tukey HSD *post hoc* tests were employed independently (three in total). A rank transformation was applied *a priori* to leaf/stem angle data for the ANOVAs only as the data violated parametric data analysis assumptions. As such, these analyses compare differences in median leaf/stem angles.

To investigate whether CO_2 removal efficiency was associated with phototropism, multiple Pearson's correlations were computed between both absolute leaf and stem angle positions, and the net daily movements in these parameters, across the ten-day period. These were performed separately by plant species, both across and within the three light treatments (fifteen in total).

All analyses and graphs were generated using R Project v3.6.2 (Team, 2019) and using the following packages; "car" (Fox and Weisberg, 2019), "dplyr" (Wickham et al., 2019), "ggplot2" (Wickham, 2016), "ggpubr" (Kassambara, 2019), "multcomp" (Hothorn et al., 2008), and "xlsx" (Dragulescu et al., n.d.).

3. Results

3.1 In situ *living wall lighting conditions*

Field measurements of light intensity for *in situ* commercial living walls from the Greater Sydney area are presented in Fig. 2. All *in situ* living walls demonstrated non-uniform light distributions across their plant foliage, due to insufficient light provision in both intensity and direction. Additionally, sub-optimal lighting conditions due to inefficient plantscape design and infrastructure was observed (Fig. 2). Luminaries were observed to create shade zones, and larger branching plant species (such as *Philodendron xanadu* and *Nephrolepis exaltata*) were observed blocking light to smaller, non-branching species below (such as *Epipremnum aureum, Spathiphyllum wallisii* and *Peperomia obtusifolia*).

Luminary angles of 11–50° were observed *in situ* at LW 1 and LW 2 no luminaries produced light at angles of between 0–10°, and only 16 % of luminaries were positioned at angles greater than 50° (Supplementary Fig. 1).

Of the four living walls measured, no lighting infrastructure was able to achieve light intensities at the plant foliage of 200 µmol·m^{-2}·s^{-1} (Supplementary Table 2). In all cases, most plants were exposed to light levels similar to ambient indoor lighting (≤ 10 µmol·m^{-2}·s^{-1} and 11–49 µmol·m^{-2}·s^{-1} for 35.6 % and 51.8 %, respectively).

Fig. 2. Lightmap of the four Living Walls (LW 1 – 4). Light measurements were taken at 1 m intervals for LW 1-3, and at 0.5 m intervals for LW 4 due to the relative complexity in both design and plant composition. The number within each square represents the average light intensity (µmol·m^{-2}·s^{-1}) available at the plant canopy for each 1 m^2 area of living wall (0.5 m^2 for LW 4). No access was available for light measurements at LW 2 for the upper 20 m^2 due to infrastructure limitations.

3.2 Non-photoadapted plant CO_2 removal

The relationship between non-photoadapted net CO_2 removal over the 40-minute time period, and the combined effects light intensity and angle, was significant in multiple linear regression for both *C. comosum* ($F(7,52) = 46.390$, $p < 0.001$, $R^2 = 0.86$) and *S. wallisii* ($F(7,52) = 37.420$, $p < 0.001$, $R^2 = 0.83$).

As expected, higher light intensities displayed significant, positive effects on net CO_2 removal for both plant species ($p < 0.01$ in all cases; Supplementary Table 3). For *C. comosum*, light intensities of 75, 100, 150 and 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ were associated with a mean increase in net CO_2 removal of 6.8, 11.2, 17.7, and 19.4 % relative to 50 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively. *S. wallisii* featured similar associations with intensity, where 75, 100, 150 and 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of light were associated with a relative mean increase in CO_2 removal of 4.1, 8.2, 13.1, and 16.7 %, respectively.

For *C. comosum*, there was no difference in net CO_2 removal between light angles of 0 and 15° from the vertical ($p = 0.144$; Supplementary Table 3). Greater angles of 30 and 45° both lead to lower mean net CO_2 removal efficiencies of 4.1 and 6.8 %, relative to 0°, respectively ($p = 0.002$ and $p < 0.001$, respectively). Contrastingly, *S. wallisii* displayed significantly higher net CO_2 removal for all light angles, where inclinations of 15, 30 and 45° from the vertical were associated with a mean increase in net CO_2 removal of 6.1, 4.0, and 5.4 %, relative to 0°, respectively ($p < 0.001$ in all cases; Supplementary Table 3).

Overall, the greatest mean CO_2 removal was observed under the maximum tested light intensity of 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for both *C. comosum* and *S. wallisii* at 31.72 ± 3.74 and 30.00 ± 1.14 % (mean ± SD) respectively, and at light angles of 15° and 45° respectively (Fig. 3, Supplementary Fig. 4).

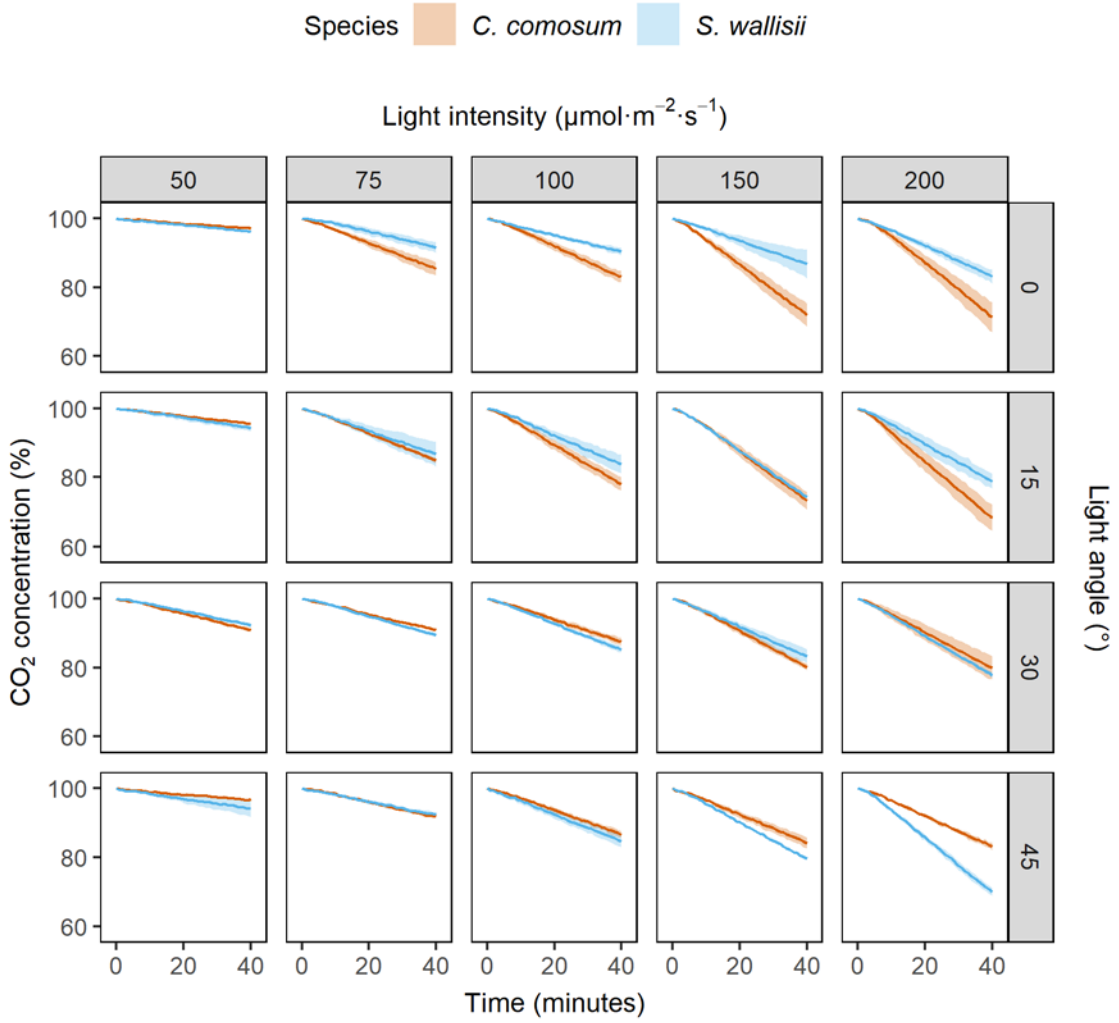


Fig. 3. Mean CO_2 removal concentration (%) from input concentration (~1000 ppm) over 40-minute period for *C. comosum* (orange) and *S. wallisii* (blue) plant species under various intensities and angles of light. Shaded areas represent SDs (n = 3). CO_2 concentration (%) is expressed as a proportion of the inlet CO_2 at the end of the 40-minute test period.

3.3 Photoadapted CO_2 removal and phototropism

3.3.1 CO_2 draw down performance

Linear regression models of CO_2 removal efficiency across the ten day adaptation periods revealed non-significant relationships for all light treatments except for the 200 µmol·m^{-2}·s^{-1} at 15° treatment (Fig. 4), where both models for *C. comosum* and *S. wallisii* were significant ($F(1,31) = 15.890$, $p < 0.001$, $R^2 = 0.34$ and $F(1,31) = 13.500$, $p = 0.001$, $R^2 = 0.28$ respectively). These models show contrasting directional influence of time on CO_2 removal efficiency, where for each additional day, CO_2 removal efficiency decreased on average by 0.92 % for *C. comosum*, whilst it increased by 0.33 % for *S. wallisii* (Supplementary Table 4).

The interaction between species and light treatment had a significant effect on final (day ten) photo-adapted CO_2 removal efficiencies ($F(2,12) = 29.120$, $p < 0.001$), indicating that treatment effects were not equivalent for the two species (Fig. 4).

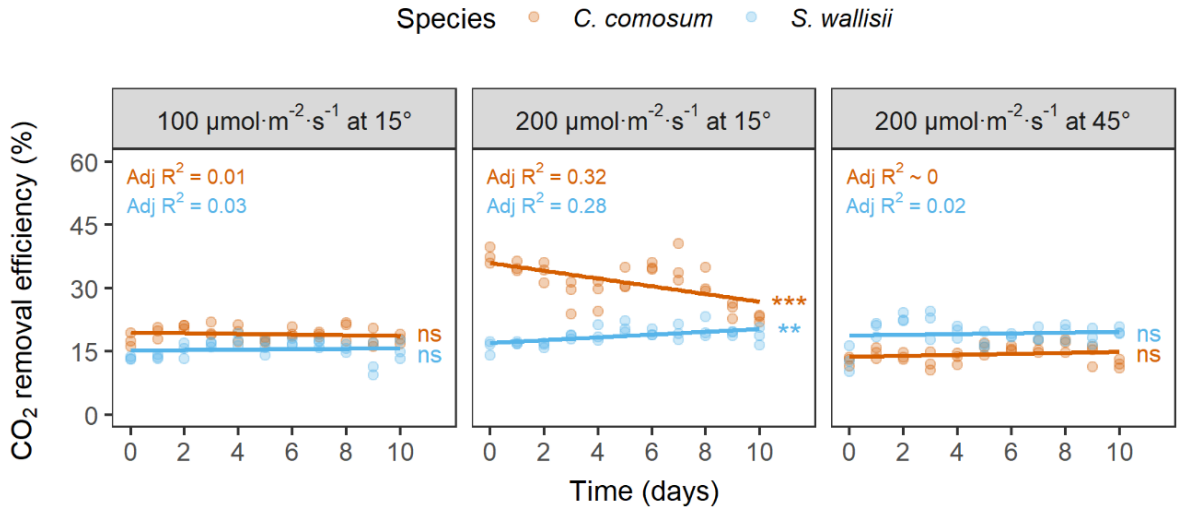


Fig. 4. Linear regression models of CO_2 removal efficiency time series in *C. comosum* (orange) and *S. wallisii* (blue) species under the three-light angle-intensity treatments. Replicates depict experiments performed in triplicate on single plant modules. Lines of best fit represent fitted models of daily CO_2 removal efficiency through time, where asterisks denote significant relationships (* p<0.05; ** p<0.01; *** p<0.001).

3.3.2 Physiological phototropism

Linear regression models of leaf angle changes with time revealed significant relationships for all light treatments for both plant species ($F(1,130) = 4.623$-42.860, $p < 0.05$ in all cases, $R^2 = 0.03$-0.25), although with contrasting directional trends. *C. comosum* demonstrated an average daily 0.88 to 1.12° decrease in leaf angle from the vertical across treatments, whereas *S. wallisii* demonstrated a 4.2 to 5.2° increase (Figs. 5 and 6, Supplementary Table 5). Additionally, linear regression models of *S. wallisii* stem angle changes over time were also significant across all treatments ($F(1,130) = 56.770$-144.900, $p < 0.001$ in all cases, $R^2 = 0.30$-0.53), where stem angle increased on average by 1.5–2.4° per day (Figs. 5 and 6, Supplementary Table 5).

The final leaf position at day ten differed significantly amongst the three light treatments ($F(2,63) = 8.564$, $p < 0.001$), which was driven by a single comparison between the 100 µmol·m^{-2}·s^{-1} at 15° and 200 µmol·m^{-2}·s^{-1} at 15° treatments ($p_{adj} = 0.048$). Here, higher leaf angle positions were observed under the 200 µmol·m^{-2}·s^{-1} at 15° treatment for both species (Fig. 6). The final leaf position of *S. wallisii* was significantly greater than that of *C. comosum* across treatments ($F(2,63) = 148.308$, $p < 0.001$), ranging on average between 29 to 71° and -17.8 to -30.5°, respectively (Fig. 6). There was no significant interaction between treatment and species ($F(2,63) = 0.276$, $p = 0.760$).

The final stem angle position in *S. wallisii* differed significantly across treatments ($F(2,30) = 24.416$, $p < 0.001$), where all treatment comparisons were significant ($p_{adj} < 0.05$ in all cases). The final stem angle for the 200 µmol·m^{-2}·s^{-1} at 15° treatment was closest to the vertical at 8.25 ± 7.41° (mean ±

SD), followed by the 100 µmol·m^{-2}·s^{-1} at 15° and 200 µmol·m^{-2}·s^{-1} at 45° treatments at 14.00 ± 12.99° and 23.50 ± 3.87° respectively.

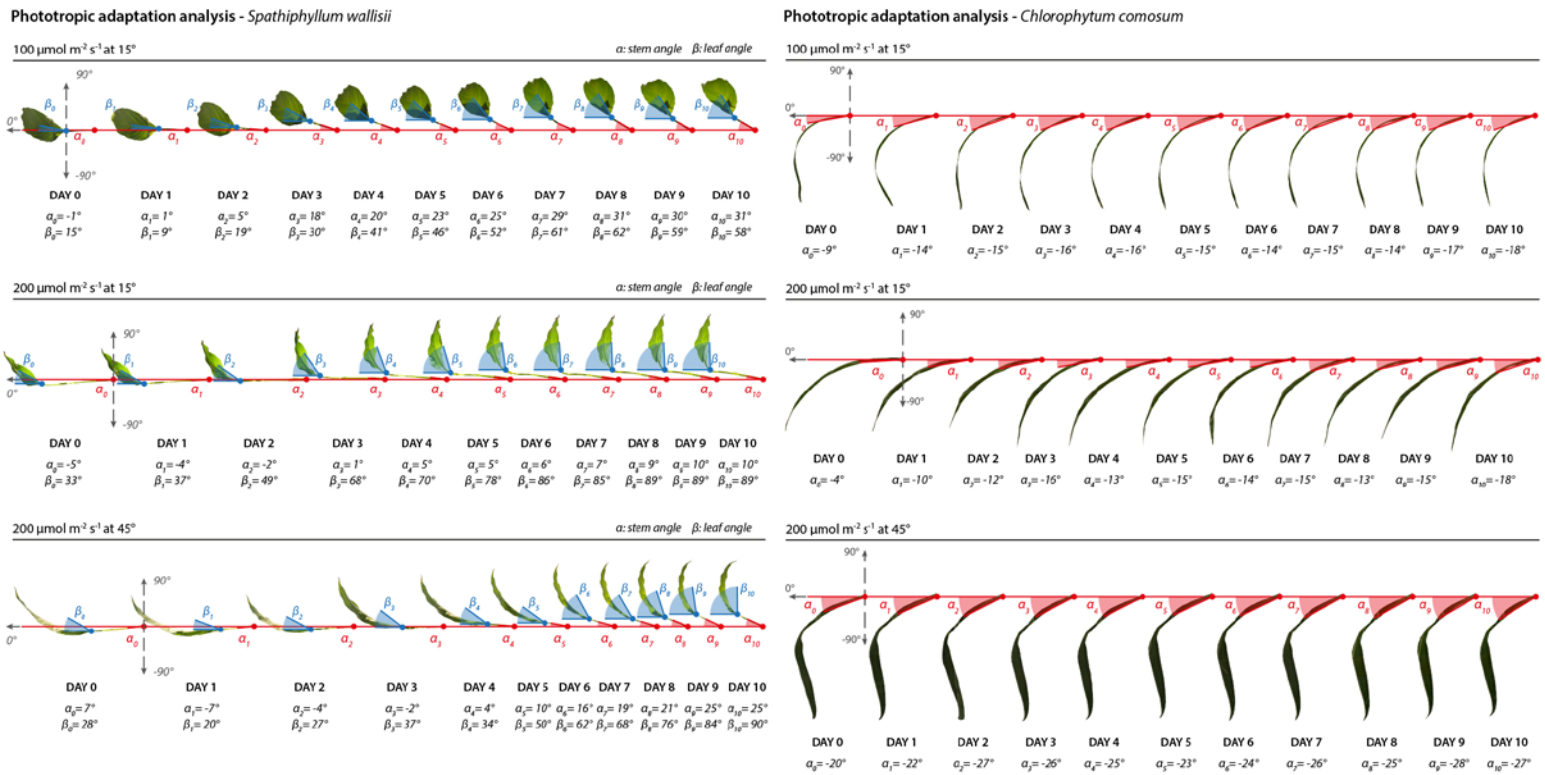


Fig. 5. Leaf movement analysis of *S. wallissi* (left) and *C. comosum* (right) through time under the three light angle-intensity treatments. Single representative replicates are shown here (n = 4 were used in the trial), where α denotes average leaf angle and β denotes average stem and leaf angle, respectively.

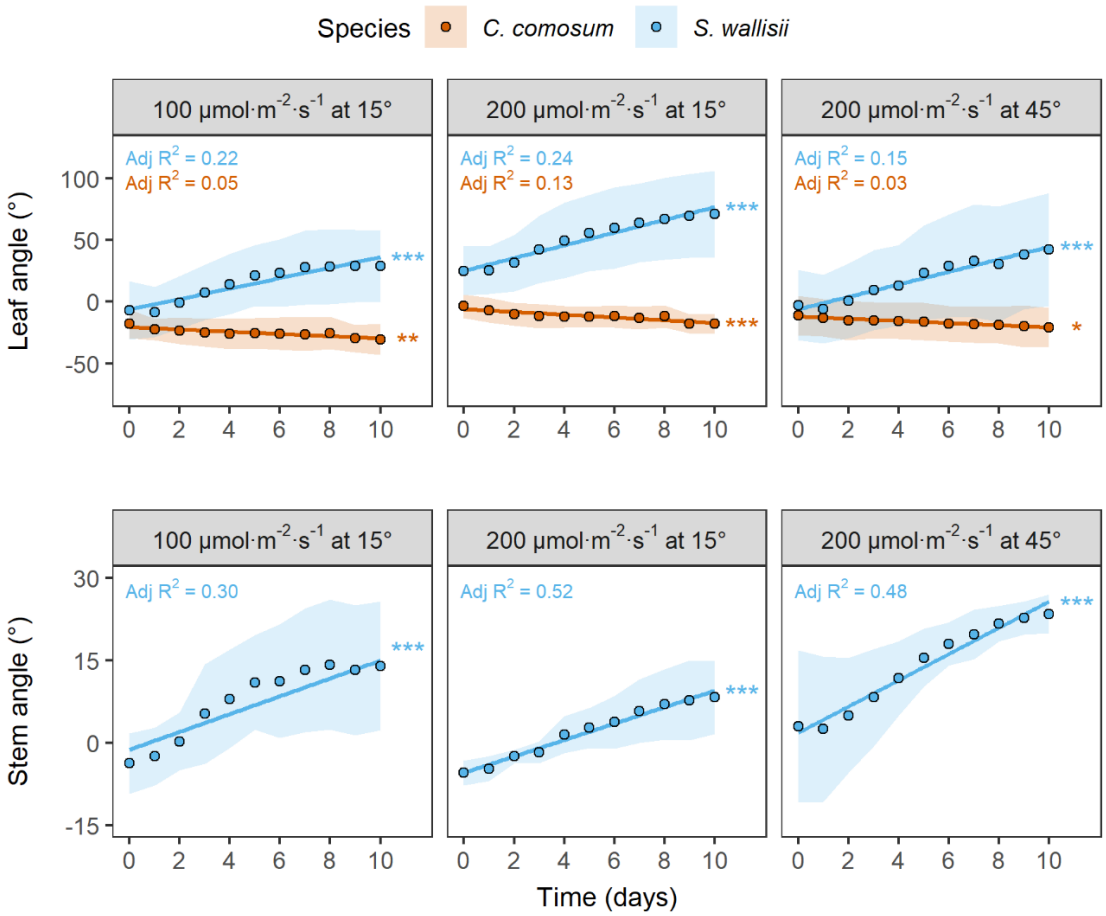


Fig. 6. Linear regression models of leaf positions for both *C. comosum* (orange) and *S. wallisii* (blue) (top subplots) and stem positions for *S. wallisii* (bottom subplots) across a 10-day trial under the three light angle-intensity treatments. Points represent the mean leaf/stem angles from the vertical for each day, where the shaded areas depict the SDs (n = 4). Lines of best fit depict fitted models where asterisks denote significant regressions (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$).

Leaf position and net daily phototrophic movement had a small effect on CO_2 removal efficiency, with fairly weak correlations observed for both plant species (*C. comosum* leaf position: r = 0.258, $p < 0.001$; *C. comosum* leaf movement: r = -0.027, $p = 0.594$; *S. wallisii* leaf position: r = 0.198, $p < 0.001$; *S. wallisii* leaf movement: r = 0.168, $p = 0.001$). *S. wallisii* stem position and movement was also weakly correlated with CO_2 removal efficiency (*S. wallisii* stem position: r = 0.137, $p = 0.006$; *S. wallisii* stem movement: r = 0.158, $p = 0.002$).

Interestingly, light treatment specific correlations between leaf position and CO_2 removal efficiency yielded comparatively higher correlations for both plant species under the 200 µmol·m^{-2}·s^{-1} at 15° treatment compared to the other two treatments (200 µmol·m^{-2}·s^{-1} at 15° leaf position: r = 0.304-0.323, $p < 0.001$; 100 µmol·m^{-2}·s^{-1} at 15° and 200 µmol·m^{-2}·s^{-1} at 45° leaf positions: r = -0.036-0.109, $p = 0.214$-0.679; Fig. 7). This same trend was also observed for stem position in *S. wallisii* (200 µmol·m^{-2}·s^{-1} at 15° leaf position: r = 0.437, $p < 0.001$; 100 µmol·m^{-2}·s^{-1} at 15° and 200 µmol·m^{-2}·s^{-1} at 45° leaf positions: r = 0.001-0.155, $p = 0.076$-0.991; Fig. 7).

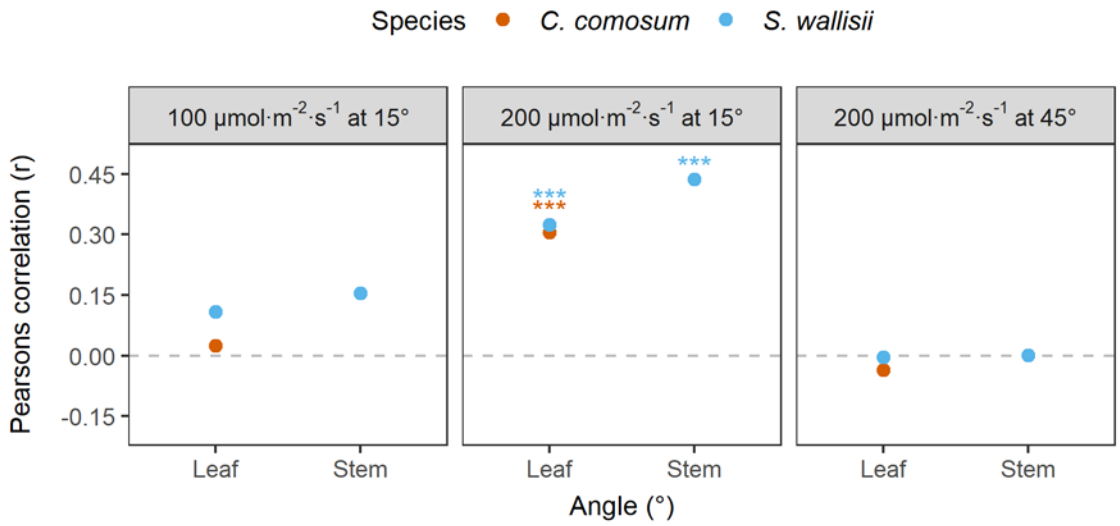


Fig. 7. Pearson correlations between CO_2 removal efficiency, and the leaf/stem angle positions throughout the ten-day testing period for each light angle-intensity treatment and plant species. Note, no stem measurements exist for *C. comosum* due to the physiological nature of the species.

4. Discussion

The angle of incident light, light intensity and photoperiod all influence the photosynthesis and photomorphogenesis of plants, affecting plant metabolism and developmental morphology (Folta and Childers, 2008; Morrow, 2008). The indoor environment often provides light that is considerably different to the lighting requirements of most species of plants. Currently, the scientific literature pertaining to optimal lighting for indoor greenery is sparse (Gunawardena and Steemers, 2019; Kaltsidi et al., 2020; Moya et al., 2018). Consequently, commercial suppliers of living wall systems often follow the recommendations provided by lighting suppliers and indoor horticultural practices, which may be based on conditions for human habitability rather than plant health.

In this study, we highlight the reduced efficiency for indoor CO_2 removal under current lighting conditions and demonstrate the practical and ideal lighting conditions for heightened CO_2 removal. By extension, our work also provides direction that may assist in determining the suitability of a given light treatment for plant health, using CO_2 drawdown as a surrogate for photosynthesis and plant metabolic activity.

The lighting conditions observed for the *in situ* living walls in this study featured relatively low light intensities at a range of inclinations, where ~87 % of all sampled living walls received > 49 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Fig. 2) at angles of between 11 and 50° (Supplementary Fig. and Table 1). Experimentally, these conditions were associated with a mean chamber CO_2 removal efficiency of between 1.68 and 7.95 % of ~1000 ppm over 40-minutes (Fig. 3). Non-photoadapted removal efficiencies for *C. comosum* and *S. wallisii* were greatest at a light intensity of 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and inclinations of 15 and 45° from the vertical respectively, reaching ~30 % CO_2 removal over 40-minutes (Fig. 3, Supplementary Fig. 4). For comparability with existing practices used for indoor environmental quality maintenance in buildings, we have used the CO_2 draw down rates calculated

in the current work to estimate the ventilation equivalence that might be possible with the use of indoor living walls using optimised lighting systems *in situ*. The best performing treatment we found was *C. comosum* at the 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ light flux density at 15° from the vertical growing surface. Assuming this CO_2 removal was constant per plant, the extrapolated effects from a reasonably-sized, 5 m^2 passive living wall containing 400 plants in a typical 40 m^3 office can be estimated. Such a system could reduce a 1000 ppm CO_2 concentration to roughly 872 ppm, which has a ventilation equivalence based solely on CO_2 removal to an ACH of 0.21 h^{-1}, assuming an ambient CO_2 concentration of 410 ppm. As stated previously, this light level will be difficult to achieve in practice: an equivalent sized living wall receiving up to 50 $\mu mol \cdot m^{-2} \cdot s^{-1}$ light flux density will achieve an estimated ACH of only 0.03 h^{-1}.

While no *in situ* living walls received a light intensity of 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$, ~5 % of the sampled walls achieved intensities between 100 and 199 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Fig. 2 and Supplementary Table 2). If changes to plantscape design or lighting infrastructure could support an average light intensity greater than 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$, it may be plausible to increase the rate of elevated indoor CO_2 removal by 1.5–7-fold (Fig. 3), and thus reduce building reliance on HVAC ventilation by some degree, if adequately sized living walls can be used. Our findings confirm the positive correlation between light intensity and CO_2 assimilation rates by ornamental plants observed in previous studies (Cetin and Sevik, 2016; Gubb et al., 2018; Oh et al., 2011) and highlight the need for technical guidelines to be established for the lighting of indoor living walls.

Previous studies highlight the strong influence of the angular distribution of light incident at the leaf surface on the internal absorption profiles and photosynthetic capacity of a plant (Brodersen and Vogelmann, 2010; Smith et al., 1997). In low-light environments such as those optimised for human occupation, light intensity and directionality affect the penetration of light through leaf tissues, limiting the effective rate of photosynthesis (Brodersen et al., 2007). Plants respond to this through phototropic and spectral signaling, where leaves will respond to light stimuli by changing their structural features to more efficiently perform their function (Smith et al., 1997). Further, phototropism can act synergistically or antagonistically with gravitropic effects to enhance or reduce plant growth behaviours such as light or gravitational sensing, transduction of signals, and differential growth of organs and tissues (Correll and Kiss, 2002). Previous studies have demonstrated that leaf orientation is critical to leaf-level light and that some plant species modify their morphology to increase the light quantity received [9]. In living wall systems, plants are orientated with their apical stems parallel to the ground as opposed to a natural vertical orientation, and thus plant morphology must respond in accordance with gravitropic and spectral signals. During laboratory testing, *S. wallisii* leaves and stems sought to be closer to the light source in all three treatments, while *C. comosum* displayed a downwards trend in response to the light sources over the ten-day testing periods (Fig. 5). Differences in plant physiology are likely the key factor in this finding, where *C. comosum* lacks the stem structural integrity to facilitate an increase in inclination over time, leading to a response dominated by gravitropism. However, despite the variance in phototropism between species, both plant species displayed effective CO_2 removal efficiencies over the ten-day test period.

Contrary to our hypothesis, the absolute position of plant leaves and stems and net morphological changes appeared to have weak associations with CO_2 removal efficiency. However, morphological

movement did appear to induce some sort of photosynthetic response in specific treatments (Fig. 7). Under 200 µmol·m^{-2}·s^{-1} at 15° lighting conditions, *S. wallisii* exhibited significant leaf/stem movement in a vertical plane, seeking the light source, of +15° and +56° (leaf and stem respectively; Figs. 4 and 5), which exhibited comparatively strong correlations (r = 0.323 and 0.437, respectively; Fig. 7) with a CO_2 removal efficiency increase of 0.33 % per day (Fig. 4). Similarly, *C. comosum,* under the same conditions, exhibited significant downwards leaf movement (away from the light source) of -14° (Figs 4 and 5), which was also significantly correlated (r = 0.304), compared to the other treatments (Fig. 7), with a daily CO_2 removal efficiency reduction of 0.92 % (Fig. 4). While there were significant differences observed between species under this treatment, both completed the ten-day period with a CO_2 removal efficiency of ~18 %, which was higher than 100 µmol·m^{-2}·s^{-1} at 15° and 200 µmol·m^{-2}·s^{-1} at 45°. These findings indicate phototropism should be considered in the decision making process of plantscape design, and could be utilised to optimise light capture, prevent light stress, or to balance the effects of other abiotic factors (Goyal et al., 2013; Ouzounis et al., 2015), although decisions will inevitably be species specific.

Neither species displayed significant changes in CO_2 removal efficiency under the 100 µmol·m^{-2}·s^{-1} at 15° and 200 µmol·m^{-2}·s^{-1} at 45° lighting conditions over the ten-day period (Fig. 4). These findings indicate these treatments had a generally equivalent effect on final CO_2 removal efficiency, independent of plant species. Variations in plant species performance (Fig. 4) could again be attributed to various physiological characteristics, however it is likely that these results speak to the robust nature of these species and further validates their popularity for species selection in living walls.

Brodensen and Vogelmann (2010) notes that at the leaf surface, only illuminated tissues are capable of photosynthesis. As light intensity measurements were taken only across the top of the plant foliage, variations in single leaf light exposure attributed to inclination and orientation may have been overlooked in the current work. nevertheless, from the work conducted, it is evident that light inclination is an important factor in living wall performance and should be considered in future designs or retrofits, such as optimisation of individual species placement to suit the available light.

In many current photosystems used for indoor living walls, static lighting at fixed light inclinations is employed, typically placed ~0.8 – 1 m from the foliage. This 'one size fits all' approach has proven to be suitable for maintaining plant survival between maintenance periods, however it provides little in the way of optimised, plant specific lighting, especially if photosynthetic activity is to be harnessed for indoor environmental quality improvement. Our observations indicate that some living walls are constructed with little forethought for the morphology of specific plant species, giving the impression of a 'set and forget' installation with a reliance on plant cycling and maintenance. In some instances, this approach creates shaded areas across the wall surface, where scrambling plant species such as *Philodendron xanadu* and *Nephrolepis exaltata* block plants below from adequate lighting (Fig. 2). This can be overcome only if regular and costly maintenance is performed.

From the *in situ* measurements performed, up to ~63 % of plant foliage was exposed to light levels less than 10 µmol·m^{-2}·s^{-1} (Supplementary Table 2). Previous literature has demonstrated that light intensities below 10–15 µmol·m^{-2}·s^{-1} may lead to increased ambient CO_2 concentrations through

plant respiration (Torpy et al., 2014; Treesubsuntorn and Thiravetyan, 2018), and that light levels of 250 $\mu mol \cdot m^{-2} \cdot s^{-1}$ are optimal for highly efficient living walls (Torpy et al., 2014). It is entirely possible that at the low light levels recorded, the overall effectiveness of living walls could be CO_2 neutral, with plant species exposed to insufficient lighting contributing to indoor CO_2 concentrations.

Insufficient lighting (i.e. below the light compensation point, where plant photosynthetic CO_2 drawdown is greater than respiratory CO_2 emission) provided to living walls may indeed contribute to elevated CO_2 concentrations of an indoor space. Although there is little literature to suggest that this occurs *in situ,* it might be prudent to assess the costs associated with this inefficiency. Maintenance costs are thought to be the bottleneck in the widespread implementation of air phytoremediation technology worldwide (Perini and Rosasco, 2013), where it is common for maintenance to be conducted purely for 'plant health management'. With insufficient lighting, ornamental plants are able to sustain biomass, but are unable to properly utilise certain biological functions such as disease defenses (Karpinski et al., 2003), which in turn leads to the deterioration of plant health, and subsequent increases in the maintenance required. For improved economic management and implementation, designs with sufficient lighting systems for living walls are required. While current systems can provide adequate lighting to limited regions of living walls (Fig. 2), there are opportunities in the interior plantscape industry for the development of lighting to provide a more adequate range of illumination.

Recently, light emitting diodes (LEDs) have increased in popularity amongst indoor horticulture applications due to their reduced pricing, operational costs, longevity and energy consumption (Yeh and Chung, 2009). LEDs demonstrate remarkable promise as supplementary lighting in terms of luminous flux control due to their low radiant heat output and wavelength specificity (Kaltsidi et al., 2020). While some capital costs of LEDs may be high, they are characterised by long lifetimes (Pattison et al., 2018) and are more versatile than current indoor lighting systems (Rehman et al., 2017). They can be easily adjusted to increase photosynthetic photon flux density (PPFD: the proportion of the light spectrum usable by photosynthetic tissues) at the leaf surface, without creating an undesirable glare to building occupants. Additionally, plantscape design is a currently underutilised aspect of indoor living walls, with many suppliers basing plant species placement solely on aesthetics, as opposed to optimal lighting. For example, of the walls observed in this paper, branching species such as *Philodendron Xanadu* and *Nephrolepis exaltata* should be placed towards the base of the LW, to reduce plant-shading. Moreover, plant species with relatively low light compensation points such as *Peperomia obtusifolia* (13 $\mu mol \cdot m^{-2} \cdot s^{-1}$; Torpy et al., 2014), may be situated where light intensities are sufficient to ensure photosynthesis. To this extent, future studies that incorporate any form of *in situ* living wall analysis should take note of the plantscape design employed and monitor the light distribution across the wall.

5. Conclusion

As living walls have become more common for indoor air quality improvement, technical guidelines for lighting design should be developed to promote plant health, enhance phytoremediation potential, and reduce maintenance costs. A systemic design approach that considers plant species responses to supplementary lighting variations would facilitate an understanding of how and where

plants should be placed across vertical greening infrastructure to receive optimal lighting conditions.

The current study demonstrates that living wall lighting systems are a crucial yet often neglected consideration to enhance the removal of CO_2 from indoor air. This study simulates the current removal efficiencies of living wall systems to remove CO_2 under commonly used *in situ* conditions (50 $\mu mol \cdot m^{-2} \cdot s^{-1}$) to be low. Due to the lack of homogenously distributed light observed at the four living walls tested, the shortcomings of the lighting systems employed are clear. To address these shortcomings, commercial suppliers should invest in better lighting systems to increase photosynthesis and reduce maintenance costs associated with plant care and replacement.

This study found the highest CO_2 removal efficiency for both plant species to be in the 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at 15° treatment. This, coupled with the enhanced phototropic movements observed, suggests that phototropism at specific light angles may play a significant role in increasing the CO_2 removal efficiency for some plant species. However, achieving these light intensities requires retrofitting lighting systems with a lower impact light such as LEDs. If commercial suppliers can deliver consistent light intensities of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$, the final challenge for optimised CO_2 removal will be morphological considerations for plantscape design. The intensity and directionality of light will influence the growing trends and morphology of branching species, leading to increased maintenance work when excessive shading occurs (as observed in this study). For this reason, further analysis on plant species growth under *in situ* conditions, and extended light exposure, may facilitate the design of an appropriate vegetation framework for indoor living walls.

The authors recommend that living wall providers undertake research and development to incorporate not only comprehensive lighting systems, but also a plant-scape design optimised for lighting. This will facilitate the development of more efficient living walls for indoor air pollution removal, rather than those that prioritise aesthetics or ease of access.

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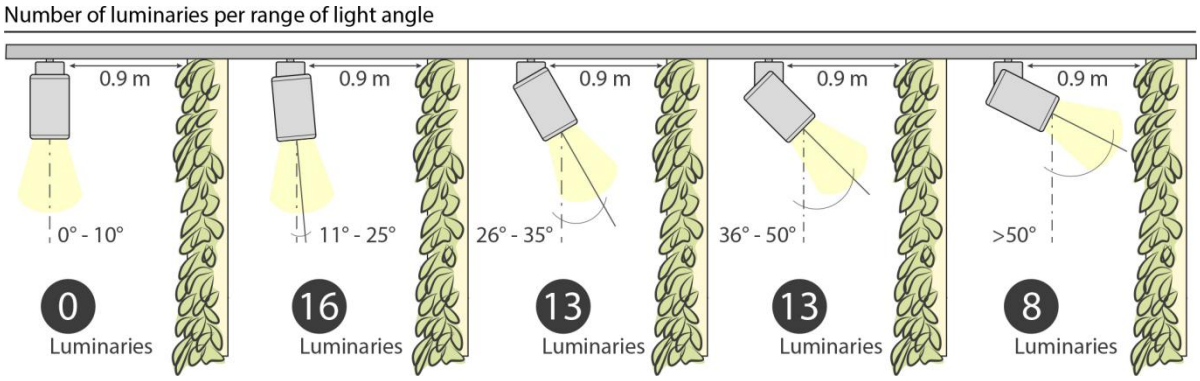
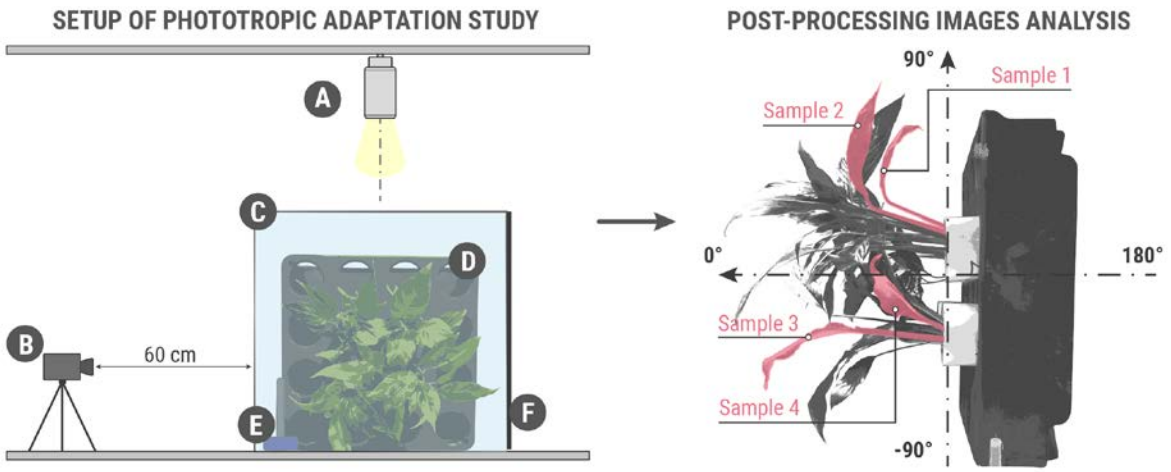
Supplementary materials



Supplementary Fig. 1. Range of luminary angles as observed for the 50 units isolated from on-site image assessment of LW 1 and LW2.

Supplementary Fig. 2. Design layout of *Chlorophytum comosum* and *Spathiphyllum wallisii* modules used during Experiment 2.2 (Plant response to light angle/intensity) and 2.3 (Phototropism and plant response).



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400 **Supplementary Fig. 3.** Experimental setup adopted for the "CO_2 removal efficiency and phototropic
401 adaptation study", composed by: A) a luminary disposed to recreate the three artificial lighting
402 treatments; B) the Nikon D3200 camera adjusted to take photographs from the left and the right
403 side of the sealed chamber; C) the sealed glass chamber; D) the single-species plant module; E) the
404 IAQ-CALC 7525 infrared gas analyzer; F) a black screen used to increase the image's contrast in
405 photographs. Each photograph was post-processed and analysed as shown.

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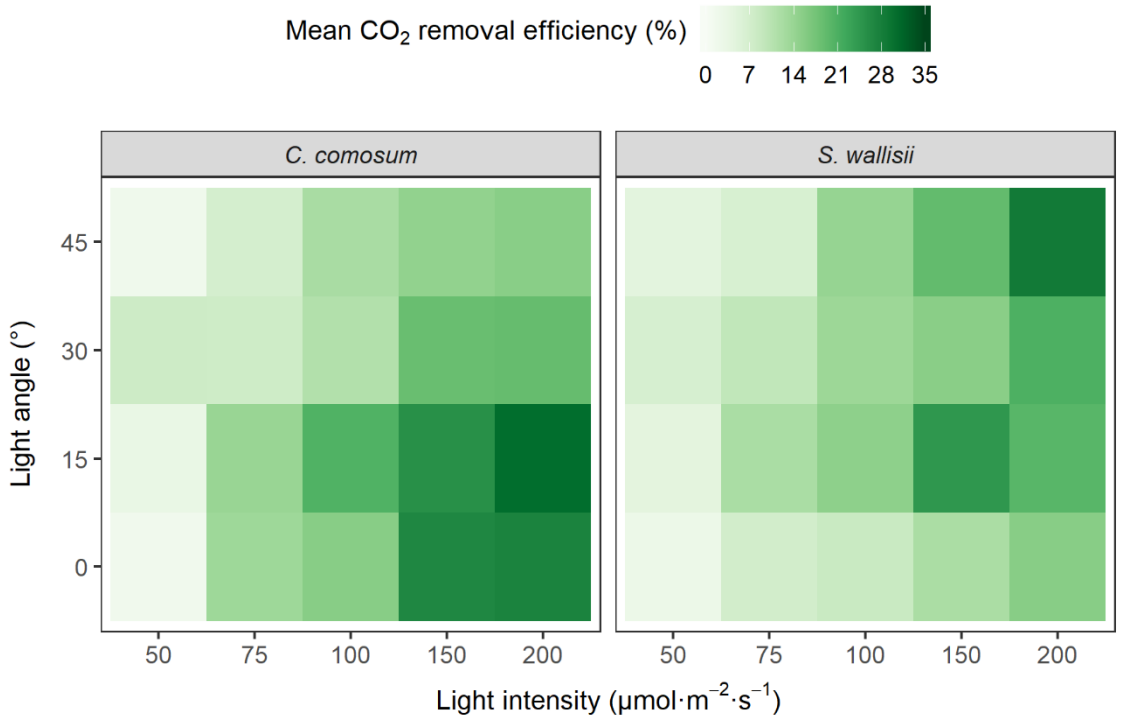

408

409 **Supplementary Fig. 4.** Mean CO_2 removal efficiency (%) from input concentration (~1000 ppm) over
410 40-minute period for *C. comosum* and *S. wallisii* species under various intensities and angles of light
411 (n = 3).

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413

Supplementary Table 1. Summary of methodology adopted in the study with details about experiments' motivation, measurements assessed, methods and instruments used.

	Experiment	Measurements	Method & Instruments
in situ	*In situ* living wall lighting assessment *Description of artificial lighting features observed in the* in situ *applications*	Light intensity along living wall surface	Data collection using the Li-250A light meter
		Luminary angles	Images post processing and analysis using a Nikon D3200 camera, Adobe Photoshop CC and AutoCAD 2019 software
Manipulative laboratory experiments	Preliminary study: non-photoadapted CO_2 removal of *Chlorophytum comosum* and *Spathiphyllum wallisii* *Description of plants response to varied lighting conditions*	CO_2 drawdown assessment	Data collection using IAQ-CALC 7525 infrared gas analyzer *Additional instrument: Li-250A light meter*
	CO_2 removal efficiency and phototropic adaptation study on *Chlorophytum comosum* and *Spathiphyllum wallisii* *Description of plants response to the 10-days exposure to varied lighting conditions determined from results obtained in the* in situ *assessment and in the preliminary study*	CO_2 drawdown assessment	Data collection using IAQ-CALC 7525 infrared gas analyzer *Additional instrument: Li-250A light meter*
		Leaf and stem angles	Images post processing and analysis using a Nikon D3200 camera, Adobe Photoshop CC and AutoCAD 2019 software

Supplementary Table 2. Average light availability at the proportion of the total plant foliage area at the four *in situ* living walls.

Light intensity ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	LW 1	LW 2	LW 3	LW 4	Average
≤ 10	6.7 %	62.5 %	26 %	44.6 %	35 %
11–49	65 %	32.5 %	66.6 %	43.1 %	51.8 %
50–74	11.6 %	2.5 %	7.4 %	1.5 %	5.8 %
75–99	6.7 %	0 %	0 %	4.6 %	2.8 %
100–149	8.3 %	2.5 %	0 %	3.1 %	3.4 %
150–199	1.7 %	0 %	0 %	3.1 %	1.2 %

Supplementary Table 3. Statistical output of multiple linear regression models for net non-photoadapted CO_2 removal over 40-minutes across levels of light intensity and light angle, for both *Chlorophytum comosum* ("*C.*com") and *Spathiphyllum wallisii* ("*S.wal*") models. Variable levels listed are in reference to 50 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for light intensity effects, and 0° for light angle effects.

Variable	Coefficient	SE	*t*-value	*p*-value
***C.com*:**		$F(7,52) = 46.390$, $p < 0.001$, $R^2 = 0.86$, Adj $R^2 = 0.84$		
Intercept	7.189	1.237	5.812	< 0.001
Intensity				
75 $\mu mol \cdot m^{-2} \cdot s^{-1}$	6.816	1.383	4.929	< 0.001
100 $\mu mol \cdot m^{-2} \cdot s^{-1}$	11.228	1.383	8.119	< 0.001
150 $\mu mol \cdot m^{-2} \cdot s^{-1}$	17.702	1.383	12.801	< 0.001
200 $\mu mol \cdot m^{-2} \cdot s^{-1}$	19.375	1.383	14.010	< 0.001
Angle				
15°	1.836	1.237	1.484	0.144
30°	-4.115	1.237	-3.327	0.002
45°	-6.755	1.237	-5.461	< 0.001
S.wal:		$F(7,52) = 37.420$, $p < 0.001$, $R^2 = 0.83$, Adj $R^2 = 0.81$		
Intercept	1.993	1.127	1.769	0.083
Intensity				
75 $\mu mol \cdot m^{-2} \cdot s^{-1}$	4.137	1.260	3.284	0.002
100 $\mu mol \cdot m^{-2} \cdot s^{-1}$	8.153	1.260	6.472	< 0.001
150 $\mu mol \cdot m^{-2} \cdot s^{-1}$	13.119	1.260	10.413	< 0.001
200 $\mu mol \cdot m^{-2} \cdot s^{-1}$	16.712	1.260	13.265	< 0.001
Angle				
15°	6.068	1.127	5.385	< 0.001
30°	4.013	1.127	3.561	0.001
45°	5.408	1.127	4.799	< 0.001

Supplementary Table 4. Statistical output of linear regression models for photoadapted CO_2 removal efficiency time series in *Chlorophytum comosum* ("*C.com*") and *Spathiphyllum wallisii* ("*S.wal*").

Variable	Coefficient	SE	*t*-value	*p*-value
***C.com*: 100 µmol·m^{-2}·s^{-1} at 15°**		$F(1,31) = 0.779$, $p = 0.384$, $R^2 = 0.03$, Adj $R^2 = 0.01$		
Intercept	19.455	0.549	35.468	< 0.001
Days	-0.082	0.093	-0.882	0.384
***C.com*: 200 µmol·m^{-2}·s^{-1} at 15°**		$F(1,31) = 15.890$, $p < 0.001$, $R^2 = 0.34$, Adj $R^2 = 0.32$		
Intercept	35.980	1.368	26.303	< 0.001
Days	-0.922	0.231	-3.987	< 0.001
***C.com*: 200 µmol·m^{-2}·s^{-1} at 45°**		$F(1,31) = 1.143$, $p = 0.293$, $R^2 = 0.04$, Adj $R^2 \sim 0.00$		
Intercept	13.699	0.632	21.680	< 0.001
Days	0.114	0.107	1.069	0.293
***S.wal*: 100 µmol·m^{-2}·s^{-1} at 15°**		$F(1,31) = 0.195$, $p = 0.662$, $R^2 = 0.01$, Adj $R^2 = 0.03$		
Intercept	15.173	0.704	21.547	< 0.001
Days	0.053	0.119	0.442	0.662
***S.wal*: 200 µmol·m^{-2}·s^{-1} at 15°**		$F(1,31) = 13.500$, $p = 0.001$, $R^2 = 0.30$, Adj $R^2 = 0.28$		
Intercept	16.967	0.537	31.622	< 0.001
Days	0.333	0.091	3.674	0.001
***S.wal*: 200 µmol·m^{-2}·s^{-1} at 45°**		$F(1,31) = 0.264$, $p = 0.611$, $R^2 = 0.01$, Adj $R^2 = 0.02$		
Intercept	18.739	0.979	19.133	0.024
Days	0.085	0.166	0.514	0.611

Supplementary Table 5. Statistical output of linear regression models for photoadapted leaf and stem position time series in *Chlorophytum comosum* ("*C.com*") and *Spathiphyllum wallisii* ("*S.wal*").

Variable	Coefficient	SE	*t*-value	*p*-value
Leaf angle in *C.com*: 100 µmol·m^{-2}·s^{-1} at 15°				
$F(1,130) = 8.083$, $p = 0.005$, $R^2 = 0.06$, Adj $R^2 = 0.05$				
Intercept	-20.682	1.892	-10.933	< 0.001
Days	-0.909	0.320	-2.842	0.005
Leaf angle in *C.com*: 200 µmol·m^{-2}·s^{-1} at 15°				
$F(1,130) = 21.200$, $p < 0.001$, $R^2 = 0.14$, Adj $R^2 = 0.13$				
Intercept	-6.068	1.443	-4.207	< 0.001
Days	-1.123	0.244	-4.604	< 0.001
Leaf angle in *C.com*: 200 µmol·m^{-2}·s^{-1} at 45°				
$F(1,130) = 4.623$, $p = 0.033$, $R^2 = 0.03$, Adj $R^2 = 0.03$				
Intercept	-12.080	2.408	-5.018	< 0.001
Days	-0.875	0.407	-2.150	0.033
Leaf angle in *S.wal*: 100 µmol·m^{-2}·s^{-1} at 15°				
$F(1,130) = 36.770$, $p < 0.001$, $R^2 = 0.22$, Adj $R^2 = 0.22$				
Intercept	-6.136	4.125	-1.488	0.139
Days	4.227	0.697	6.064	< 0.001
Leaf angle in *S.wal*: 200 µmol·m^{-2}·s^{-1} at 15°				
$F(1,130) = 42.860$, $p < 0.001$, $R^2 = 0.25$, Adj $R^2 = 0.24$				
Intercept	25.239	4.656	5.421	< 0.001
Days	5.152	0.787	6.547	< 0.001
Leaf angle in *S.wal*: 200 µmol·m^{-2}·s^{-1} at 45°				
$F(1,130) = 24.420$, $p < 0.001$, $R^2 = 0.16$, Adj $R^2 = 0.15$				
Intercept	-6.034	6.054	-0.997	0.321
Days	5.057	1.023	4.942	< 0.001
Stem angle in *S.wal*: 100 µmol·m^{-2}·s^{-1} at 15°				
$F(1,130) = 56.770$, $p < 0.001$, $R^2 = 0.30$, Adj $R^2 = 0.30$				
Intercept	-2.023	1.520	-1.330	0.186
Days	1.936	0.257	7.534	< 0.001
Stem angle in *S.wal*: 200 µmol·m^{-2}·s^{-1} at 15°				
$F(1,130) = 144.900$, $p < 0.001$, $R^2 = 0.53$, Adj $R^2 = 0.52$				
Intercept	-5.455	0.735	-7.421	< 0.001
Days	1.496	0.124	12.036	< 0.001
Stem angle in *S.wal*: 200 µmol·m^{-2}·s^{-1} at 45°				
$F(1,130) = 124.000$, $p < 0.001$, $R^2 = 0.49$, Adj $R^2 = 0.48$				
Intercept	1.841	1.271	1.449	0.150
Days	2.391	0.215	11.133	< 0.001