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Accepted Version

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Declaration of interest: none.

Acknowledgments

This work was supported by the Royal Horticultural Society and the Engineering and Physics Research Council (EPSRC). The authors would also like to thank Dr Dalila Touhami, Dr Fiona Lahive and Dr Sarah Kemp, Rob Stirling, Val Jasper, Matthew Richardson and Will Johnson for their practical guidance and support.

Abbreviations:

RH:	Relative humidity (%)
DLI:	Daily light integral (mol m^{-2} d^{-1})
SMC:	Substrate moisture content (m^3 m^{-3})
LCP:	Light compensation point (µmol $m^{-2}s^{-1}$)
ET:	Evapo-transpiration (g)
PPM:	Uptake or emission of CO_2 by potted plant microcosm
LA:	Leaf area (m^2)
ETLA:	Evapo-transpiration per unit leaf area (g cm^{-2})

Abstract

High indoor CO_2 concentrations and low relative humidity (RH) create an array of well-documented human health issues. Therefore, assessing houseplants' potential as a low-cost approach to CO_2 removal and increasing RH is important.

We investigated how environmental factors such as 'dry' (< 0.20 $m^3 m^{-3}$) or 'wet' (> 0.30 $m^3 m^{-3}$) growing substrates, and indoor light levels ('low' 10 µmol $m^{-2} s^{-1}$, 'high' 50 µmol $m^{-2} s^{-1}$ and 'very high' 300 µmol $m^{-2} s^{-1}$), influence the plants' net CO_2 assimilation ('A') and water-vapour loss. Seven common houseplant taxa – representing a variety of leaf types, metabolisms and sizes – were studied for their ability to assimilate CO_2 across a range of indoor light levels. Additionally, to assess the plants' potential contribution to RH increase, the plants' evapo-transpiration (ET) was measured.

At typical 'low' indoor light levels 'A' rates were generally low (< 3.9 mg hr^{-1}). Differences between 'dry' and 'wet' plants at typical indoor light levels were negligible in terms of room-level impact. Light compensation points (i.e. light levels at which plants have positive 'A') were in the typical indoor light range (1-50 µmol $m^{-2} s^{-1}$) only for two studied *Spathiphyllum wallisii* cultivars and *Hedera helix;* these plants would thus provide the best CO_2 removal indoors. Additionally, increasing indoor light levels to 300 µmol $m^{-2} s^{-1}$ would, in most species, significantly increase their potential to assimilate CO_2. Species which assimilated the most CO_2 also contributed most to increasing RH.

Key words: *Dracaena;* drought; *Hedera;* indoor light; indoor air quality; *Spathiphyllum*

Introduction

Indoor CO_2 concentrations are primarily dependent on the occupancy level and outdoor air supply rate (Zhang *et al.*, 2017). Humans produce and exhale CO_2; therefore, a greater occupancy coupled with lower ventilation rates – intended to reduce energy consumption – gives rise to higher and often harmful CO_2 concentrations indoors (Satish *et al.*, 2012). Additionally, even when ventilation by ambient air is employed, the problems may be exacerbated in the future: ambient CO_2 concentrations increased by 40% over the last century, to 400 ppm – with a rise to 670 ppm expected by 2100 (Hersoug *et al.*, 2012).

The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) recommends a maximum indoor CO_2 concentration of 1000 ppm (Torpy *et al.*, 2017). Concentrations indoors (e.g. in fully occupied offices or meeting rooms) often reach 2000 to 2500 ppm but can rise as high as 5000 ppm (Zhang *et al.*, 2017). Although discrepancies in the maximum safe exposure concentration are commonplace in literature, prior research suggests typical indoor CO_2 concentrations will continue to present unwanted health issues (Zhang *et al.*, 2017). These include mucus membrane symptoms (i.e. sore/dry throat, dry eyes and sneezing) and respiratory problems (i.e. tight chest, wheezing/coughing and shortness of breath) (Seppanen *et al.*, 1999; Erdmann and Apte, 2004). Elevated CO_2 can also reduce the cognitive performance of students in schools, while long-term, regular exposure has been linked to increased absenteeism, weight gain and obesity (Hersoug *et al.*, 2012; Satish *et al.*, 2012; Gaihre *et al.*, 2014; Nieuwenhuis *et al.*, 2014; Vehvilainen *et al.*, 2016; Zhang *et al.*, 2017).

An additional challenge in indoor environments is low relative humidity (RH). An RH below 30% has been shown to cause eye irritation and skin dryness, with an RH below 10% causing dryness of the nasal mucus membrane. Low RH can also increase the likelihood of influenza transmission, enhance indoor ozone concentration and produce static electricity (Arundel *et al.*, 1986; Berglund, 1998; Sunwoo *et al.*, 2006; Lowen *et al.*, 2007; Abusharha and Pearce, 2013; Zhang and Yoshino, 2010). However, high RH (> 60%) too can cause issues by encouraging fungal/mould growth and contributing to the deterioration of building materials (Berglund, 1998; Bin, 2002; Zhang and Yoshino, 2010; Frankel *et al.*, 2012). The majority of adverse health effects concerning RH can be avoided by maintaining indoor levels between 40 and 60% (Arundel *et al.*, 1986).

Various techniques are used in the built environment to control and regulate CO_2 levels. They include highly engineered approaches to ventilation (Hesaraki *et al.*, 2015; Mateus and da Graca, 2017) as well as low-tech approaches which can include the use of plants (Raji *et al.*, 2015; Charoenkit and Yiemwattana, 2016). A number of studies investigate a houseplants' potential to sequester CO_2 from indoor environments (Oh *et al.*, 2011; Pennisi and van Iersel, 2012; Torpy *et al.*, 2014). Studies vary in scale and focus – from those focusing on individual plants in experimental chambers, to room scale studies *in situ*.

A range of studies investigated houseplants' ability to sequester CO_2 in home, school, and office environments. Various combinations of houseplants were found to generally reduce room CO_2 concentrations and increase RH; however, studies rarely specify exact plant numbers and plant types. Plant species commonly used include *Dracaena*

deremensis, Dracaena marginata, Ficus benjamina, *Hedera helix*, and *Spathiphyllum clevelandii* (Raza et al., 1991; Lohr and PearsonMims, 1996; Jeong et al., 2008; Lim et al., 2009; Oh et al., 2011; Pegas et al., 2012).

Light levels and substrate moisture are the key factors influencing gas exchange between the plant and the environment, with 'low' light and 'dry' substrate both reducing houseplants' ability to sequester CO_2 and contribute to RH increases indoors *via* transpiration (Lawlor and Cornic, 2002; Flexas et al., 2006; Torpy et al., 2017). In indoor environments light levels are typically at least 100-fold lower compared to outdoors (on a clear summer day for example) and are maintained in the range of approximately 1 – 50 µmol m^{-2} s^{-1} (Thimijan and Heins, 1983; Boyce and Raynham, 2009; Lai *et al.*, 2009; Hawkins, 2011). Research suggests however, that having higher indoor light levels (approximately 30 – 50 µmol m^{-2} s^{-1}) would greatly increase occupant comfort (Lai *et al.*, 2009; Huang *et al.*, 2012). As previously proposed, indoor light is the most limiting factor for CO_2 assimilation (Pennisi and van Iersel, 2012).

The positive contribution of plants to the reduction of CO_2 levels and RH increases indoors are based on the premise that plants function optimally and are sequestering CO_2/releasing water vapour at their maximum capacity. However, the main challenges for maintaining plant function in the indoor environment are 'low' indoor light levels and issues arising from plants' (miss) management, most frequently plants' being under or over watered without the correct nutrients (RHS, 2017). A few studies addressed these questions in part by investigating a wide range of light levels and their effect on CO_2 assimilation (Pennisi and van Iersel, 2012; Torpy *et al.*, 2014). However, no study to our knowledge investigated the effect of differing substrate moisture content (SMC) – namely investigating the effect of 'wet' (> 0.30 m^3 m^{-3}) and 'dry' (< 0.20 m^3 m^{-3}) SMC conditions. Additionally, previous studies have not specifically focused on plants' cultivar-level differences; this may be of interest as for many houseplant species there are a range of cultivars available, which may potentially offer augmented service compared to straight species if they are larger in size or more physiologically active.

Pennisi and van Iersel (2012) investigated the CO_2 assimilation of 17 houseplant species in both a simulated controlled environment utilising light levels of 10, 20 and 30 µmol $m^{-2}s^{-1}$ and a public office building in Atlanta (USA). In the public office, the amount of CO_2 assimilated by plants varied depending on plant size. In the controlled environment, most species exhibited positive carbon assimilation over a 10-week period. The study found that in both environments larger, woody plants (such as *Ficus benjamina*) assimilated more CO_2 than herbaceous species.

Torpy *et al.* (2014) investigated the CO_2 assimilation of eight common indoor plant species by producing light response curves and light compensation points (LCPs) using an infra-red gas analyser. The results indicated that at least some CO_2 sequestration could be expected from the studied species under current indoor lighting systems and plants could be effectively utilised in the built environment to sequester CO_2 given a moderate increase in the targeted lighting levels.

Our research aims to improve the understanding of which taxa (i.e. plant species and cultivars) as well as which light and substrate moisture conditions are best placed to regulate indoor CO_2 and RH. Specifically, the aims of the study were to determine:

1. The impact of drying substrate on CO_2 removal capacity by different taxa
2. The impact of light levels on net CO_2 assimilation of taxa (i.e. to test the potential to improve the performance by supplementing indoor light levels)
3. The evapo-transpiration (ET) rates of each taxon and their potential contribution to increasing indoor RH.

2 Material and Methods

2.1 Plant material

Five common houseplant species, including two cultivars, were selected for the study to represent a range of leaf types (succulent and herbaceous), metabolisms and plant sizes (Table 1). Selected plants were 2-years old at the time of purchase in July 2016 from the RHS plant centre (Wisley, Surrey, UK), ranging between 10cm - 60cm in height, depending on the taxon. Within the species, plant height and stature were uniform (data not shown). Plants were maintained in Sylvamix growing medium (6:2:2 sylvafibre: growbark pine: coir; Melcourt, Tetbury, Gloucestershire, UK) in 3 L containers, with a slow release fertiliser feed (Osmocote, Marysville, OH, USA) at ambient temperatures and 'low' light levels in an indoor office environment within the Crops Laboratory in the Glasshouse Complex of the School of Agriculture, Policy and Development, at the University of Reading (UK).

Table 1: Characteristics of the houseplant taxa (i.e. plant species and cultivars) chosen for experiments. Leaf area (n = 2) and plant height (n = 5) are means ± SEM. Species' Latin name is given in italic and cultivar, where applicable, follows.

Species/cultivars	Family	Metabolism	Leaf area (cm^2)	Plant height (cm)
Dracaena fragrans 'Lemon Lime'	*Asparagaceae*	C3	1742 ± 91	51 ± 1
Dracaena fragrans 'Golden Coast'	*Asparagaceae*	C3	1438 ± 10	60 ± 1
Guzmania ' Indian Night'	*Bromeliaceae*	C3/CAM	1230 ± 6	32 ± 1
Hedera helix	*Araliaceae*	C3	1509 ± 243	9 ± 0
Spathiphyllum wallisii 'Bellini'	*Araceae*	C3	1766 ± 189	35 ± 1
Spathiphyllum wallisii 'Verdi'	*Araceae*	C3	5451 ± 1104	36 ± 1
Zamioculcas zamiifolia	*Araceae*	CAM	1388 ± 88	57 ± 1

2.2 Net leaf-level CO_2 assimilation at 'low' and 'high' indoor light levels under 'dry' and 'wet' conditions

Experiments were conducted on five plants per taxon. Measurements of the net CO_2 assimilation rate (µmol m^{-2} s^{-1}) were made using a LCPro infrared gas analyser (ADC Bioscientific, Hoddesdon, Hertfordshire, UK) on three young, fully expanded leaves per plant (with consistent leaf selection i.e. third fully expanded leaf from the plant tip) under office conditions (16.6 – 21.8 °C, RH > 35%) at 'low' and 'high' indoor light levels (Hawkins, 2011; Huang *et al.*, 2012). 'Low' 10 µmol m^{-2} s^{-1} lighting was achieved in the usual lighting conditions of the room (eight fluorescent lights, Osram, Munich, Germany lighting a floor area of 20 m^2). To achieve 'high' 50 µmol m^{-2} s^{-1} during measurements, the photosynthetic photon flux density (i.e. light level, µmol m^{-2} s^{-1}) was supplemented at the leaf by an external halogen

source (50 W, 12 V). Each light increment was administered for seven minutes and the net CO_2 assimilation rate recorded at the end of the seven-minute period.

Substrate moisture content (SMC) based on volume of water per volume of substrate was measured daily for each plant, in two locations per container using a SM300 capacitance-type probe connected to a HH2 Moisture Meter (Delta-T Devices, Cambridge, Cambridgeshire, UK; 0–100% range and an accuracy of ± 2.5%). At the start of the experiment, substrate moisture was at the container capacity (SMC > 30%, 0.3 m^3 m^{-3}) and plants were thus considered optimally watered (Vaz Monteiro *et al.*, 2016). Measurements were also made on 'dry' plants (SMC < 20%, 0.2 m^3 m^{-3}). Measurements were made over approximately one month.

2.2.1 Calculation of the respiration of the potted-plant microcosm

To ensure that CO_2 removal by the aboveground parts of the plant (i.e. leaves and stem) was not cancelled out by respiration of the potted-plant microcosm (PPM) (i.e. substrate and non-photosynthetic plant parts) the PPM was investigated for CO_2 contributions at both 'high' and 'low' light and under 'wet' and 'dry' SMC conditions (n = 3). The PPM respiration values were then subtracted from all the leaf CO_2 assimilation values made, to obtain the overall contribution of the plant and substrate.

Measurements of the PPM respiration were made utilising a 150 L (45 x 45 x 75 cm, 0.15 m^3) Perspex chamber (The plastic people, Leeds, West Yorkshire, UK) sealed with Swagelok's (Swagelok, Bristol, South Gloucestershire, UK). Enclosed inside the Perspex chamber was a HOBO MX1102 CO_2 logger (Onset Computer Corporation, Bourne, MA, U.S.A), a 12 V DC brushless fan (RS Components, Corby, Northants, UK), and a calibrated (20 – 90 % RH, 0 – 40 °C) Tinytag RH/temperature logger (Gemini data loggers, Chichester, West Sussex, UK). The external RH/temperature surrounding the chamber was also monitored with another, identical Tinytag logger. Inside the chamber 'low' light levels were achieved as described in Section 2.2; 'high' levels were generated by two LED lights (V-TAC Europe Ltd, Sofia, Bulgaria) and measured with a calibrated light sensor (Skye instruments, Llandrindod Wells, Wales, UK). Bare substrate was prepared for the experiment as explained in Section 2.2. Experiments were undertaken for 2 hr, with the chamber analysed for leakage prior, during and after experimentation; leakage was found to be < 2% of the starting concentration over a 2-hr test period. Measurements were made over approximately one week.

Data obtained in Section 2.2 was normalised by leaf area by multiplying CO_2 assimilation (mg m^{-2} hr^{-1}) with leaf area (m^2), providing CO_2 assimilation in mg hr^{-1} for each taxon. Data were also corrected for PPM respiration and leakage by calculation of an average conversion value (mg hr^{-1}) for both 'wet' and 'dry' SMC conditions.

2.3 Generating light response curves

To generate light response curves, measurements of the net photosynthetic rate (µmol m^{-2} s^{-1}) were made as explained in Section 2.2 on four plants per taxon. Environmental conditions within the leaf cuvette were: temperature controlled at 25 °C, ambient CO_2 concentration (~400-450 ppm) and an ambient RH of 35-45%. Plants were prepared for the experiment as explained in Section 2.2, achieving a SMC > 0.30 m^3 m^{-3} and were considered

optimally watered on the commencement of each experiment (Vaz Monteiro *et al.*, 2016). SMC was maintained at this level for the duration of the experiment.

To generate the light response curve the light was supplemented in the following set increments: 0, 50, 300, 1200 µmol m^{-2} s^{-1} as described in Section 2.2. An increment of 0 µmol m^{-2} s^{-1} was chosen to investigate each species CO_2 assimilation in the dark; 50 µmol m^{-2} s^{-1} the highest indoor light level; 300 µmol m^{-2} s^{-1} was chosen to represent the highest feasible light level which could be engineered (with supplementary artificial lighting) in an indoor environment; 1200 µmol m^{-2} s^{-1} (a sunny day in a UK climate) was chosen to present information on a plant's maximal capacity for net CO_2 assimilation. Measurements were made over approximately one week.

The light response curves were based on an equation proposed by Prioul and Chartier (1977) and were produced using the model by Lobo *et al.* (2013). LCPs (which represent the minimum light level required for CO_2 assimilation to occur) (Torpy *et al.*, 2014) were calculated with the same model (Lobo *et al.*, 2013) for all taxa apart from *Guzmania* 'Indian night', which was omitted due to very low assimilation rates and therefore, unreproducible results.

Figure 1: Images of the experimental setup for leaf CO_2 assimilation measurements, equipment pictured includes infra-red gas analyser, leaf cuvette and external halogen source.

2.4 Plants' water use/evapo-transpiration (ET) experiments

Water use/ET of the plant taxa were inferred by consecutive plant/pot weight measurements using a precision balance (CBK 32, Adam Equipment, Milton Keynes, Buckinghamshire, UK) under indoor office conditions (RH > 35%). Plants were prepared for the experiment as explained in Section 2.2, starting the experiment with SMC at full water-holding capacity and were not watered for the duration of the experiment. Measurements were made at 0 h and then every 24 hr over a three-week period on a whole 'plant – substrate system' (i.e. potted plant, with uncovered substrate) enabling the calculation of the water loss at each time-point. We were interested in total potential RH contribution of the plant along with substrate, mimicking a real-life scenario of an indoor plant. Each plant was removed from the experiment when its SMC dropped < 20% (0.2 m^3 m^{-3}). Destructive measurements of LA were

made using a LA meter (Delta-T Devices, Cambridge, Cambridgeshire, UK) on two plants per taxon, at the end of the experiment. While we appreciate that measuring the leaf area at the end of the experiment may lead to under/over-estimating assimilation measured earlier in the experiment, we were limited by the number of experimental plants we could destructively harvest. Given that this approach was applied to all taxa, that the leaf areas were assessed within two months of the assimilation experiments, and that plants did not increase in size significantly over this period (as evidenced by height measurements which we made at the start and the end of the experiment), we believe that the risk of the error is small and evenly spread. SMC was measured daily as explained in Section 2.2. Water use/ET per unit leaf area (ETLA, expressed in g cm^{-2}) was calculated by dividing the ET (i.e. water loss) from a plant in a 24-hr period by the mean leaf area.

2.5 Statistical analysis

Experimental data (gas exchange parameters and water loss/ET) were analysed using GENSTAT (16th Edition, VSN International, Hemel Hempstead, Hertfordshire, UK). An analysis of variance (ANOVA) was performed to compare means for each measured parameter between different taxa and/or over time. Values were presented as means with associated Tukey's 95% confidence intervals for multiple comparisons. Data on plants' water loss were log-transformed and Tukey's 95% confidence intervals were used to compare between taxa in the text (Section 3.3).

3 Results

3.1 Net leaf-level CO_2 assimilation at 'low' and 'high' indoor light levels under 'dry' and 'wet' conditions

At 'low' indoor light 'dry' *Spathiphyllum wallisii* 'Verdi' was statistically significantly respiring the most (-87.6 mg hr^{-1}, $p < 0.001$), and was therefore the only taxon to measure significant differences between 'dry' and 'wet' substrate. In 'dry' substrate statistically significant differences in CO_2 assimilation were measured between the cultivars of *Spathiphyllum wallisii* 'Bellini' and 'Verdi' (-19.6 and -60.7 mg h^{-1}, respectively; $p < 0.001$). In 'wet' substrate, there were no significant differences in CO_2 between any studied taxa (Table 2).

At 'high' indoor light only *Spathiphyllum wallisii* 'Verdi' measured statistically significant differences between 'dry' and 'wet' substrate (-60.7 and 60.0 mg hr^{-1}, respectively; $p < 0.001$; Table 2). No statistically significant differences in CO_2 assimilation were measured between cultivars under the same SMC conditions; significant differences were measured with *Spathiphyllum wallisii cvs '*Bellini' and 'Verdi' between 'dry' (-19.6 and -60.7 mg h^{-1}, respectively) and 'wet' (11.7 and 60.0 mg h^{-1}, respectively) SMC conditions ($p < 0.001$, Table 2).

Table 2: Net leaf-level CO_2 assimilation of each species at 'low' and 'high' indoor light (< 10 and 50 µmol m^{-2} s^{-1}) in 'wet' (> 0.30 m^3 m^{-3}) and 'dry' (< 0.20 m^3 m^{-3}) conditions. Data are a mean of five plants of each species, three young, fully expanded leaves per plant (n=15). Data are adjusted to account for PPM respiration and chamber leakage and is normalised by leaf area (Table 1). Different letters next to means correspond to statistically significant differences between means based on Tukey's 95% confidence intervals. (–) values signify respiration (i.e. the release of CO_2).

'Low' Light (< 10 µmol m^{-2} s^{-1})	Net CO_2 assimilation (mg hr^{-1})	
Taxa	'Wet' (> 0.30 m^3 m^{-3})	'Dry' (< 0.20 m^3 m^{-3})
Dracaena fragrans 'Lemon Lime'	-17.4^{b}	-35.7^{b}
Dracaena fragrans 'Golden Coast'	-28.4^{b}	-25.3^{b}
Guzmania ' Indian Night'	-14.3^{b}	-23.8^{b}
Hedera helix	-9.5^{b}	-27.3^{b}
Spathiphyllum wallisii 'Bellini'	-14.8^{b}	-22.7^{b}
Spathiphyllum wallisii 'Verdi'	3.9^{b}	-87.6^{a}
Zamioculcas zamiifolia	-17.5^{b}	-23.9^{b}
'High' Light (50 µmol m^{-2} s^{-1})	Net CO_2 assimilation (mg hr^{-1})	
Taxa	'Wet' (> 0.30 m^3 m^{-3})	'Dry' (< 0.20 m^3 m^{-3})
Dracaena fragrans 'Lemon Lime'	-5.5^{abc}	-41.97^{ab}
Dracaena fragrans 'Golden Coast'	-21.8^{ab}	-24.0^{ab}
Guzmania ' Indian Night'	-11.5^{ab}	-19.6^{ab}
Hedera helix	-6.6^{abc}	9.4^{bc}
Spathiphyllum wallisii 'Bellini'	11.7^{bc}	-19.6^{ab}
Spathiphyllum wallisii 'Verdi'	60.0^{c}	-60.7^{a}
Zamioculcas zamiifolia	-12.2^{ab}	-20.9^{ab}

3.2 Generating light response curves and light compensation points

Light compensation points (LCPs), which represent the minimum light level required for a positive net CO_2 assimilation to occur, were calculated for each species (Table 3). Of the studied species, *Spathiphyllum wallisii* 'Verdi' and *Hedera helix* had the lowest LCPs of 20 and 31 µmol m^{-2} s^{-1} respectively. The highest LCP was recorded for *Dracaena fragrans* 'Golden Coast' (96 µmol m^{-2} s^{-1}), with both *Dracaena fragrans* 'Lemon Lime' and *Zamioculcas zamiifolia* also having LCP values outside of the light level typically experienced in indoor environments (93 and 65 µmol m^{-2} s^{-1} respectively, Table 3).

Table 3: Light compensation points (LCPs) for each of the studied species.

Taxa	LCP (µmol m^{-2} s^{-1})
Dracaena fragrans 'Lemon Lime'	92.9
Dracaena fragrans 'Golden Coast'	95.6
Guzmania 'Indian Night'	N. A
Hedera helix	30.9
Spathiphyllum wallisii 'Bellini'	31.9
Spathiphyllum wallisii 'Verdi'	20.1
Zamioculcas zamiifolia	64.7

At 0 µmol m^{-2} s^{-1}, *Hedera helix* was statistically significantly respiring the most (- 1.2 µmol m^{-2} s^{-1}, $p < 0.001$; Figure 2), no significant differences were measured in net assimilation between other studied taxa.

At 300 µmol m^{-2} s^{-1}, all taxa were assimilating CO_2. Net assimilation was highest in *Hedera helix* (7.7 µmol m^{-2} s^{-1}) and was statistically significantly different to all other taxa ($p < 0.001$). *Spathiphyllum wallisii '*Bellini' and *S. wallisii* 'Verdi' (2.4 and 2.4 µmol m^{-2} s^{-1} respectively) measured a net assimilation that was statistically significantly higher than three other studied taxa (*Dracaena fragrans* 'Lemon Lime', *Dracaena fragrans* 'Golden Coast' and *Guzmania* 'Indian Night', $p < 0.001$; Figure 2). At this highest indoor photosynthetic photon flux density, there were no cultivar level differences within the same species in net assimilation.

At 1200 µmol m^{-2} s^{-1}, all taxa were assimilating CO_2. Net assimilation was highest in *Hedera helix* (10.7 µmol m^{-2} s^{-1}) and was statistically significantly higher than all other taxa ($p < 0.001$). *Spathiphyllum wallisii '*Bellini' (2.7 µmol m^{-2} s^{-1}) measured a net assimilation that was statistically significantly higher than three other studied taxa (*Dracaena fragrans* 'Lemon Lime', *Dracaena fragrans* 'Golden Coast' and *Guzmania* 'Indian Night', $p < 0.001$; Figure 2). Again, no net assimilation was statistically significantly different between cultivars of the same species.

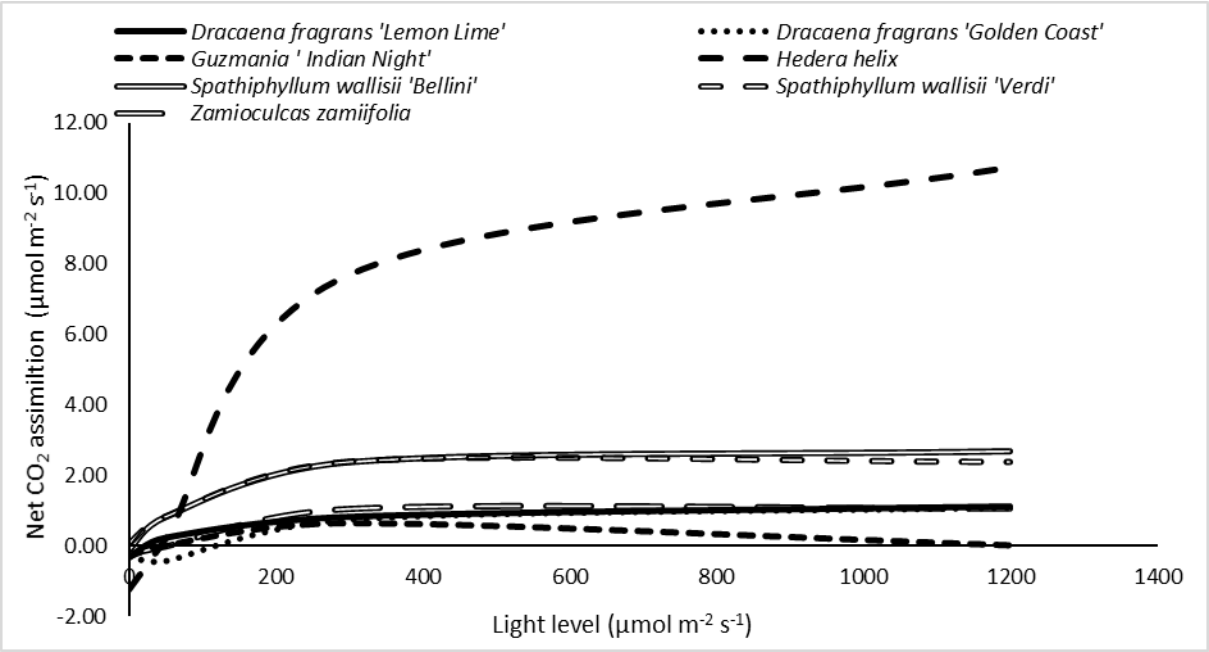


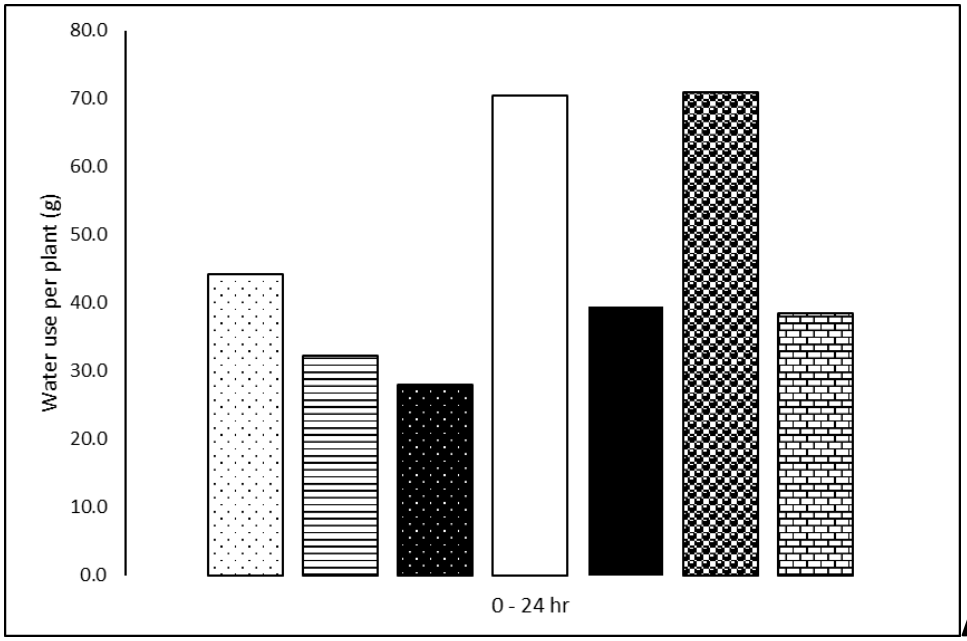
Figure 2: Net CO_2 assimilation across three light levels (0, 300, 1200 µmol m^{-2} s^{-1}); data are a mean of four containers of each species and two young fully expended leaves per plant (n=8). Tukey's 95% confidence intervals are used for species comparison in text.

3.3 Plants' water use/evapo-transpiration experiments

In terms of ET per plant per day, when well-watered, the ET was statistically significantly higher for *Hedera helix* (70.5 g) and *Spathiphyllum wallisii* 'Verdi' (71.0 g) compared to all the other taxa ($p < 0.001$). ET per plant was also statistically significantly different between the taxa *Guzmania* 'Indian Night' (28.0 g) and *Dracaena fragrans* 'Lemon Lime' (44.3 g, $p < 0.001$); ET per plant at 24 hr was statistically significantly different between *Spathiphyllum wallisii* cultivars ($p < 0.001$; Figure 3A).

In terms of ET per leaf area per day, when well-watered the ET was statistically significantly higher for *Hedera helix* (0.047 gcm^{-2}) in comparison to other taxa ($p < 0.001$). ET per leaf area was statistically significantly lower for *Spathiphyllum wallisii* 'Verdi' (0.013 g cm^{-2}), in comparison to the other taxa tested ($p < 0.001$) - no ET per leaf area was statistically significantly different between any other taxa. The ET per leaf area was statistically significantly different between one pair of cultivars: *Spathiphyllum wallisii* 'Bellini' and *Spathiphyllum wallisii* 'Verdi' (0.02 g cm^{-2} and 0.013 g cm^{-2}, respectively; $p < 0.001$; Figure 3B).

At the time when SMC decreased to 20%, ET reduction ranged between 7% (*Spathiphyllum wallisii* 'Verdi') and 63% (*Guzmania* 'Indian Night') (data not shown). The time taken for the SMC to decrease to < 20% ranged between 10 days (*Dracaena fragrans* 'Golden Coast' and *Spathiphyllum*) and 23 days (*Zamioculcas zamiifolia*) across studied taxa.



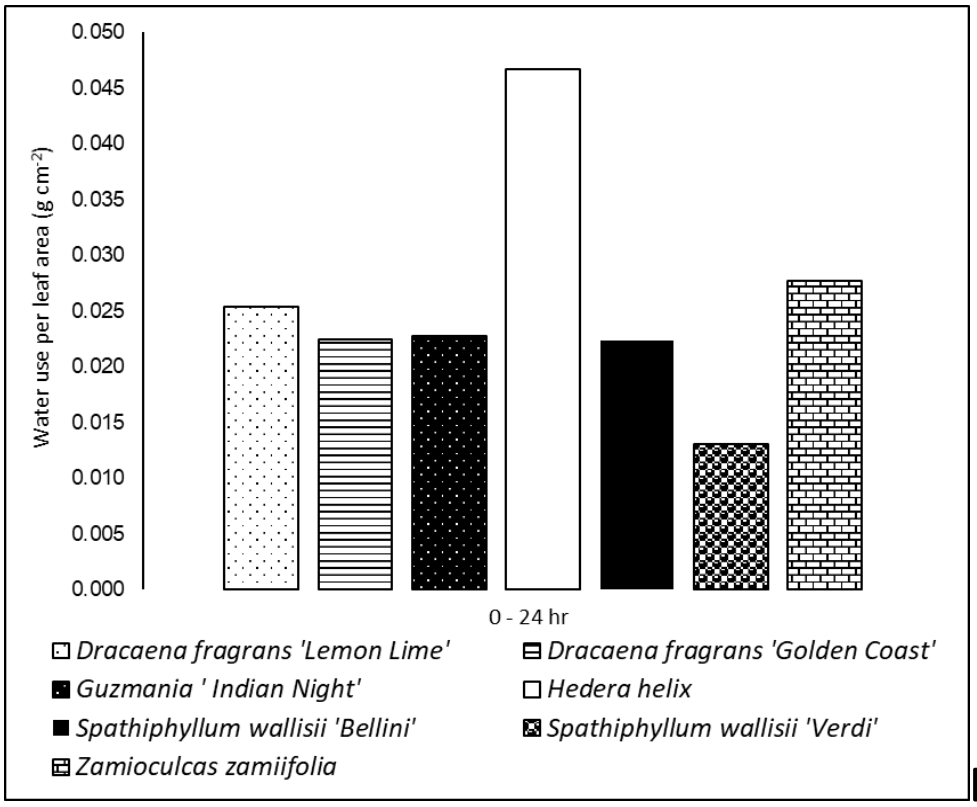


Figure 3: Water use per plant (A) and per leaf area (B) per day; data are a mean of four containers of each species (n=4). ANOVA was performed on the log transformed data only (data not shown) – Tukey's 95% confidence intervals were generated in the analysis of the transformed data are used for species comparison in text.

4 Discussion

The current work presents the first insight into leaf-level CO_2 assimilation - from plants in both 'dry' and 'wet' substrate – and potential RH increases for a range of common houseplant taxa (i.e. species and cultivars), differing in structure and physiology.

In this study we demonstrate that little potential is offered by the studied houseplants alone to reduce CO_2 concentrations in 'low' light indoor environments – with only three taxa's light compensation points falling within the typical indoor light level range (0 – 50 µmol m^{-2} s^{-1}; Table 3). However, our findings demonstrate that although respiration was generally occurring in houseplants grown in 'dry' substrate, the net CO_2 exchange recorded was extremely low and thus likely to have little or no negative impact on the CO_2 levels at a room scale. Our results suggest that increasing light levels to a technically feasible 300 µmol m^{-2} s^{-1} (e.g. through use of supplementary lighting) would provide a significant increase in CO_2 assimilation in most of the studied taxa. The study also indicates that the best performing taxa for CO_2 assimilation will also contribute the most to raising RH indoors.

From the results of this study we estimated the mass (in grams) of CO_2 removed per hour, per plant and per m^2 of each taxon. In home and office environments, each person contributes 30g (CO_2)/hour and 36g (CO_2)/hour, respectively (Persily and de Jonge, 2017) and these different values are consequences of the level of individual's activity in various environments. Using both these values, we calculated the number of plants required to remove 10% of a single person's CO_2 contribution at the 'very high' (300 µmol m^{-2} s^{-1}) indoor light level (Supplementary Table 1). The plant numbers range from 15 (for more active plants like *Hedera* and *Spathiphyllum*) to >100 for physiologically less active plants. Estimates of the number of plants required to remove the CO_2 generated by human contributions were also made by Pennisi and van Iersel (2012) and Torpy *et al.* (2014). However, widely different estimates of the CO_2 generated per person were used by each study – making direct comparisons difficult.

In typical indoor environments with 'low' light levels, only one taxon, in 'wet' substrate conditions was assimilating CO_2 (*Spathiphyllum wallisii* 'Verdi') and would contribute to CO_2 concentration reduction (3.9 mg hr^{-1}, respectively; Table 2). Additionally, only three taxa were found to possess light compensation points that fall within the range of typical indoor light levels (i.e. *Hedera helix and Spathiphyllum wallisii* 'Verdi' and 'Bellini'). Both *Hedera helix and Spathiphyllum wallisii* would require an unrealistic number of plants to see any significant CO_2 concentration reduction (data not shown); at typical 'low' indoor light levels, the study indicates that a plants' potential benefits psychologically or in productivity terms (Thomsen *et al.*, 2011; Raanaas *et al.*, 2011; Nieuwenhuis *et al.*, 2014) would be more important than their contribution to indoor CO_2 removal. Furthermore, as suggested in Torpy *et al.* (2014) plants should not be expected to completely replace ventilation systems, but to act as a supplement in reducing the energy load required.

In typical 'low' light indoor environments, when grown in 'dry' substrate, all studied taxa were respiring. The results also indicated that in the range of typically observed indoor light levels, six of the studied species (*Dracaena fragrans* cvs 'Lemon Lime' and 'Golden Coast', *Guzmania* 'Indian Night', *Hedera helix, Spathiphyllum wallisii* 'Bellini' and *Zamioculcas zamiifolia*) were respiring in both 'dry' and 'wet' SMC conditions (Table 2).The (miss) management and

297 under watering of houseplants is anecdotally a common problem; therefore, determining if a 'dry' houseplant is
298 releasing significant amounts of CO_2 into an indoor environment and detrimentally impacting health is important;
299 our results however, suggest this is not the case. In 'dry' SMC conditions, in typical office light, *Spathiphyllum wallisii*
300 'Verdi' was releasing the most CO_2 into the indoor environment out of all studied taxa at 0.0876 g hr^{-1}. In
301 comparison, a single person, in an office environment would release 36 g/hour into the indoor environment (Persily
302 and de Jonge, 2017). This confirms that in typical office light conditions – even for plants growing in drying substrate
303 – the contribution of plants to room-level CO_2 is negligible.

304 At a 'high' indoor light level (50 µmol m^{-2} s^{-1}), a greater net CO_2 assimilation was generally measured for all taxa, but
305 no statistically significant differences were found between cultivars of the same species in 'dry' or 'wet' conditions.
306 Although measurements were only made under 'wet' SMC conditions, this trend for the lack of cultivar differences
307 continued at higher light levels of 300 and 1200 µmol m^{-2} s^{-1} suggesting that cultivar level differences were not
308 pronounced in this study.

309 Our study suggests that for most studied taxa, light saturation occurs at around 300 µmol m^{-2} s^{-1} and further
310 increases beyond this show little difference in assimilation terms (Figure 2). As discussed in Torpy *et al.* (2014)
311 targeted indoor lighting could be used to maximise a houseplants CO_2 assimilation potential. Extensive research has
312 been undertaken into various light systems for plant cultivation and development on indoor living walls but not
313 specifically with potted houseplants or concerning CO_2 assimilation (Yeh and Chung, 2009; Egea *et al.*, 2014). Our
314 findings support the notion that increased light levels maximise plant gas exchange and we suggest future research
315 should investigate the suitability of testing targeted lighting installations in indoor environments. Light compensation
316 points calculated in our study are generally higher, but comparable with other indoor species previously tested
317 (Burton *et al.*, 2007; Pennisi and van Iersel, 2012; Torpy *et al.*, 2014; Torpy *et al.*, 2017; Tan *et al.*, 2017).

318 Earlier attempts at estimating the CO_2 removal of houseplants (Pennisi and van Iersel, 2012) did not take into
319 account ambient CO_2 concentrations or consider the effects of substrate moisture on CO_2 assimilation. A more
320 robust study by Torpy *et al.* (2014) investigated several factors which could influence assimilation including different
321 acclimatisation treatments, the respiration of the 'potted-plant microcosm', but again did not consider impact of
322 substrate moisture conditions. Other studies did not specify the exact number or type of houseplant (Lim *et al.*,
323 2009; Pegas *et al.*, 2012) which contributed to any CO_2 concentration reduction or, only considered a single light
324 level (Oh *et al.*, 2011).

325 The results from the ET experiment indicate that the best performing species in CO_2 assimilation terms (*Hedera helix*
326 and *Spathiphyllum wallisii* 'Verdi') both have the highest ET rates per plant. However, the comparative water use per
327 area results show *Spathiphyllum wallisii* 'Verdi' having the lowest ET *per leaf area*; this species is therefore,
328 inherently more water use efficient and only uses more water *per plant* due to its large size. We found a difference
329 between the *Spathiphyllum wallisii* cultivar pair in terms of water use per plant and per area – with no difference per
330 plant or per area measured for the *Dracaena fragrans* pair. This confirms that our hypothesis that inherent
331 physiological differences can be measured in water use terms down to a cultivar level. The results also suggest that

certain species (i.e. *Spathiphyllum wallisii* 'Verdi') do not restrict their water loss under water stress conditions (SMC < 20%). *Spathiphyllum wallisii* 'Verdi' would therefore, in a drying substrate, continue to contribute the most to RH increases. We suggest that future studies should evaluate the CO_2 assimilation ability of other more physiologically active, vigorous species (i.e. *Osmunda japonica*, *Selaginella tamariscina* and *Hemigraphis alternata*), which also performed well in pollutant sequestration experiments (Yang *et al.*, 2009; Kim *et al.*, 2010) under 'high' indoor light levels (300 µmol m^{-2} s^{-1}).

From the results of the ET experiment we estimated the contribution of studied taxa to raising RH indoors. Calculations of the amount of water vapour in the air were made through the equation: RH (%) = 100 * actual vapour density (g m^{-3}) / saturation vapour density (g m^{-3}) (using a saturation vapour density of 19.1 g m^{-3} at 22 °C) (Galindo *et al.*, 2005). A RH of 40 – 60% is considered optimal in terms of human health (Arundel *et al.*, 1986), we therefore calculated the number of plants – per taxon - required to raise RH from 40 to 60 % in a static 100 m^3 office (Supplementary Table 2). Calculations assume that 100% of the water vapour 'lost' by taxa (Figure 3A) was released into the surrounding environment. The results do not take into account the impact of ventilation, occupancy or the feedback effect of taxa (i.e. as RH increases plants release less water vapour into the indoor environment). These calculations are intended to act as a guide on how the studied taxa could influence RH indoors. Our results indicate that five *Spathiphyllum wallisii* 'Verdi' or *Hedera helix* plants growing in an unmulched (i.e. uncovered) growing medium - over a 24-hr hour period - could raise the RH from 40 to 60% (Supplementary Table 2).

5 Conclusions

The results indicate that net CO_2 assimilation of all studied plants was generally 'low', with *Spathiphyllum* cultivars and *Hedera helix* removing most CO_2.

While CO_2 assimilation of plants in 'wet' substrate was higher than in 'dry' conditions, in practical terms however (*i.e.* when considering the plant's potential to influence indoor CO_2 levels), net CO_2 assimilation differences between 'dry' and 'wet' plants at 'high' and 'low' indoor light levels were negligible for the taxa studied. Light compensation points were in the typical indoor light range for both *Spathiphyllum wallsii* 'Verdi' and *Hedera helix,* suggesting that these plants would be best suited to provide most CO_2 removal in a typical indoor setting. Additionally, both these taxa, per plant, had the highest transpiration rates, suggesting the highest potential for influencing the RH. Finally, our study indicates that increasing indoor light levels to 300 µmol m^{-2} s^{-1} would, in most taxa, have a significant impact on the potential for houseplants to assimilate CO_2 and increase RH in indoor environments.

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Supplementary Information

Supplementary table 1: Net CO_2 assimilation (mg hr^{-1}) of each species and number of taxa required to remove 10 % of the CO_2 generated per person at 'very high' indoor light (300 µmol m^{-2} s^{-1}) in 'wet' (> 0.30 m^3 m^{-3}) conditions. Data is taken from Figure 2 and adjusted to account for PPM respiration and chamber leakage and is normalised by leaf area (Table 1). Plant numbers for each taxon were calculated by dividing the 30 g (CO_2)/hour or 36 g (CO_2)/hour exhaled per person in home and office environments respectively (Persily and de Jonge, 2017) by the net CO_2 assimilation of each taxon (mg hr^{-1}).

'Very high' Light (300 µmol m^{-2} s^{-1})	mg hr^{-1}	Number of plants	
Taxa	'Wet' (> 0.30 m^3 m^{-3})	Home	Office
Dracaena fragrans 'Lemon Lime'	10.9	275	330
Dracaena fragrans 'Golden Coast'	5.7	526	632
Guzmania ' Indian Night'	0.9	3333	4000
Hedera helix	172.3	17	21
Spathiphyllum wallisii 'Bellini'	55.0	55	65
Spathiphyllum wallisii 'Verdi'	194.9	15	18
Zamioculcas zamiifolia	11.5	261	313

Supplementary table 2: Number of plants required to raise the RH from 40 to 60% in a static 100 m^3 office. Numbers of plants were generated from our data in Figure 3A at a temperature of 22 °C, where ventilation, occupancy and the feedback effect were not considered. Calculations of the amount of water vapour in the air were made through the equation: RH (%) = 100 * actual vapour density (g m^{-3}) / saturation vapour density (g m^{-3}) (using a saturation vapour density of 19.1 g m^{-3} at 22 °C) (Galindo *et al.*, 2005).

Species/cultivar	Number of Plants
Dracaena fragrans 'Lemon Lime'	9
Dracaena fragrans 'Golden Coast'	12
Guzmania ' Indian Night'	14
Hedera helix	5
Spathiphyllum wallisii 'Bellini'	10
Spathiphyllum wallisii 'Verdi'	5
Zamioculcas zamiifolia	10