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Accepted Version

Gubb, C., Blanusa, T., Griffiths, A. and Pfrang, C. (2019) Interaction between plant species and substrate type in the removal of CO2 indoors. Air Quality, Atmosphere & Health, 12 (10). pp. 1197-1206. ISSN 1873-9326 doi: 10.1007/s11869-019-00736-2 Available at https://centaur.reading.ac.uk/85876/

To link to this article DOI: http://dx.doi.org/10.1007/s11869-019-00736-2

Publisher: Springer

Interaction between plant species and substrate type in the removal of CO_2 indoors

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Acknowledgments

This work was supported by the Royal Horticultural Society (RHS) and the Engineering and Physical Sciences Research Council (EPSRC). The authors would also like to thank Dr Dalila Touhami, Rob Stirling, Kaan Alkan, David Tubbs, Nicholas Davidson, Val Jasper, Matthew Richardson, Liam Doherty, Will Johnson and Michael Dawes for their practical guidance and support.

Highlights

Substrate type has a significant impact on the ability of indoor plants to remove CO_2

Plants were unable to reduce the 1000 ppm CO_2 at typical indoor light levels

Plants were able to remove 1000 ppm CO_2 at a light level of 22200 lux

Respiration was deemed negligible in comparison to human contributions

Abstract

Elevated indoor concentrations of carbon dioxide [CO_2] cause health issues, increase workplace absenteeism and reduce cognitive performance. Plants can be part of the solution, reducing indoor [CO_2] and acting as a low-cost supplement to building ventilation systems.

Our earlier work on a selection of structurally and functionally different indoor plants identified a range of leaf-level CO_2 removal rates, when plants were grown in one type of substrate. The work presented here brings the research much closer to real indoor environments by investigating CO_2 removal at a whole-plant level and in different substrates. Specifically, we measured how the change of growing substrate affects plants' capacity to reduce CO_2 concentrations. *Spathiphyllum wallisii* 'Verdi', *Dracaen*a *fragrans* 'Golden Coast' and *Hedera helix*, representing a range of leaf types and sizes and potted in two different substrates, were tested. Potted plants were studied in a 0.15 m^3 chamber under 'very high' (22000 lux), 'low' (~ 500 lux) and 'no' light (0 lux) in 'wet' (> 30 %) and 'dry' (< 20 %) substrate.

At 'no' and 'low' indoor light, houseplants increased the CO_2 concentration in both substrates; respiration rates, however, were deemed negligible in terms of the contribution to a room-level concentration, as they added ~ 0.6% of a human's contribution. In 'very high' light *D. fragrans,* in substrate 2, showed potential to reduce [CO_2] to a near-ambient (600 ppm) concentration in a shorter timeframe (12 hrs, e.g. overnight) and *S. wallisii* over a longer period (36 hrs, e.g. weekend).

Keywords

Indoor air quality, houseplants, indoor light, *Dracaena*, *Spathiphyllum, Hedera*

Abbreviations:

ASHRAE:	The American society of heating, refrigeration and air-conditioning engineers
SMC:	Substrate moisture content (m^3 m^{-3})
VOCs:	Volatile organic compounds
ANOVA:	Analysis of variance
SEM:	Standard error of the mean

1 Introduction

Elevated indoor concentrations of CO_2 (> 600 ppm) are harmful to human health, increase absenteeism and reduce cognitive performance (Seppanen *et al.*, 1999; Erdmann and Apte, 2004; Shendell *et al.*, 2004; Shaughnessy *et al.*, 2006; Gaihre *et al.*, 2014; Zhang *et al.*, 2017). Traditional building ventilation systems are designed to keep CO_2 concentrations near-ambient with outdoor air infiltration, albeit increasing building energy consumption (Perez-Lombard *et al.*, 2008). Indoor plants can act as a simple low-cost form of ventilation, reducing indoor ventilation requirements (by ~ 6%) with CO_2 removal and consequently providing a reduction in building energy consumption, but only under certain environmental conditions i.e. a very high light level (~ 22000 lux) – as confirmed by several previous studies (Torpy *et al.*, 2014; Torpy *et al.*, 2017; Gubb *et al.*, 2018).

Numerous health guidelines exist for maximum safe CO_2 concentrations, the lowest of these being 1000 ppm produced by the American society of heating, refrigeration and air-conditioning engineers (ASHRAE) – a concentration often exceeded indoors (Shendell *et al.*, 2004; Gaihre *et al.*, 2014; Torpy *et al.*, 2014; Torpy *et al.*, 2017). Concentrations indoors are typically less than 2000 – 2500 pm, but can rise as high as 5000 ppm, with the main source of CO_2 indoors being humans themselves (Zhang *et al.*, 2017).

Elevated CO_2 concentrations (> 600 ppm) can cause an array of health issues including eye irritation, 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; Tsai *et al.*, 2012). Additionally, elevated concentrations have been associated with declines in cognitive function (at ~ 950 ppm); absenteeism, with increases of 100 ppm associated with a reduced annual attendance of half a day per annum and reductions in cognitive performance, with concentrations of 600 – 1000 ppm found to significantly reduce decision making ability (Shaughnessy *et al.*, 2006; Satish *et al.*, 2012; Gaihre *et al.*, 2014; Vehvilainen *et al.*, 2016; Allen *et al.*, 2016).

Several studies have shown that light levels significantly influence a plants ability to remove CO_2 via their impact on stomata as a main pathway for CO_2 uptake (Pennisi and van Iersel, 2012; Torpy *et al.*, 2014; Torpy *et al.*, 2017; Gubb *et al.*, 2018). Indoors, the light level is typically between 0 – 500 lux, but can be as high as 3000 lux in certain workplace environments (Boyce and Raynham, 2009; Lai *et al.*, 2009; Hawkins, 2011; Huang *et al.*, 2012). Often, supplementary lighting is required to support specific plant installations such as a green wall, where higher light levels are utilised above the installation and not throughout the entire room – this supplementary light can be engineered at least as high as 22200 lux (Gubb *et al.*, 2018). Plants' under- or over-watering also affects a plant's ability to remove CO_2 (Sailsbury and Ross, 1991) but our previous work showed that indoor light level was the primary driver of CO_2 uptake and the soil drying had smaller impact (Gubb *et al.*, 2018).

Plants remove airborne pollutants via four different pathways: the aboveground plant part (by photosynthesis, deposition and/or diffusion through the waxy layer), the roots (by deposition and/or direct uptake), and two of which directly involve the substrate - namely, sorption by the substrate itself, along with breakdown by the microbial activity within the substrate (Cruz *et al.*, 2014). It can therefore be expected that both the type and condition (wet/dry) of the substrate will affect plants CO_2 removal ability. Experiments investigating the ability of plants to remove volatile organic compounds (VOCs) have found that the removal of VOCs is predominately associated with the microflora in the substrate, plants themselves are only utilised indirectly to maintain and support substrate microorganisms (Wood *et al.*, 2002; Orwell *et al.*, 2004; Kim *et al.*, 2008; Cruz *et al.*, 2014; Irga *et al.*, 2018; Kim *et al.*, 2018); these microorganisms – especially those associated with the root system – have been shown to metabolise an array of different pollutants (Weyens *et al.*, 2015).

Various substrates are available in the UK for growing indoor plants, including various types of peat and peat-free (Barrett *et al.*, 2016). Peat – an organic material – is a limited resource, hence attempts by the UK government for voluntary phasing out of peat by 2030 (Defra, 2018). Despite this peat-based substrates are still commonly used across the UK because of their uniformity, providing easier water management (Schmilewski, 2008; Alexander *et al.*, 2013). Peat has been shown to have higher water-holding capacity compared to some alternatives such as coir, sand and wood fibres (Schmilewski, 2008). As several studies have linked soil moisture to microbial respiration, an investigation into substrates moisture content is of significance to CO_2 removal (Cook *et al.*, 1985; Manzoni, 2012). Furthermore, with different substrate types able to support different microorganisms (Zhang *et al.*, 2013) it was hypothesised that differences in removal would be measured between our chosen substrates. Therefore, two different substrates (peat free and peat) –referred to as Substrate 1 and Substrate 2, respectively, within this paper – were chosen for this experiment to determine to what extent they affected plants' ability to remove CO_2 within test chambers. We hypothesised that growing the same taxa in differing substrates might provide differing CO_2 removal abilities.

If houseplants are to reduce elevated CO_2 concentrations, they must be functioning optimally i.e. experience appropriate light levels, feeding and watering (i.e. substrate moisture content - SMC). A few studies have investigated these issues in part, testing various plants potted in different peat-free substrates (Irga *et al.,* 2013; Torpy *et al.*, 2014; Torpy *et al.*, 2017; Gubb *et al.*, 2018)

Torpy *et al.*, 2014 determined the light response curves of eight common plants potted a peat-free substrate consisting of composted hardwood, sawdust, composted bark fines, and coarse river sand (2:2:1). These authors suggested that in typical 'low' indoor light some CO_2 removal could be expected but, moderately increasing light levels would mean the studied plants could be effectively utilised in a built environment setting. (Torpy *et al.*, 2017) also investigated the ability of two taxa (*Chlorophytum comosum* and *Epipremnum aureum*) potted in a peat-free substrate comprising of coconut fibre – as part of an active green-wall – to remove 1000 ppmv of CO_2 at light levels of 50 and 250 µmol m^{-2} s^{-1}. The study found removal was much more effective at 250 µmol m^{-2} s^{-1} and found that removal from a 5 m^2 wall of *C. comosum* could balance the respiratory emissions of a full-time occupant.

Our research aims to test which houseplants together with the substrate they are grown in (from now on referred to as houseplants or taxa) can best reduce a CO_2 concentration of 1000 ppm under differing environmental and growing conditions. Specifically we tested the selected taxa:

- Under three light levels: 'very high' (~ 22000 lux), typical 'low' light (~ 500 lux) and 'no' indoor light (0 lux);
- In 'wet' (SMC > 30 %, 0.3 m^3 m^{-3}) and 'dry' (SMC < 20 %, 0.2 m^3 m^{-3}) substrate moisture conditions;

- With two different substrate types.

Zero lux (0 µmol m^{-2} s^{-1}) was chosen to investigate CO_2 assimilation/respiration in the dark; ~ 500 lux (~ 7 µmol m^{-2} s^{-1}) was chosen to represent typical office conditions; 22000 lux (~ 300 µmol m^{-2} s^{-1}) was chosen to represent the highest technically feasible light level which could be engineered indoors (with supplementary artificial lighting) (Torpy *et al.*, 2017).

This experiment was undertaken on a whole plant/substrate scale as opposed to leaf-level experiments investigated in prior work (Gubb *et al.*, 2018). It was hypothesised that experiments on this larger scale would provide more accurate estimations for how plants can influence 'room-scale' concentrations of CO_2. Additionally, this study looks to highlight if substrate type can make a difference to the CO_2 removal ability of taxa and justify the need for further research with a more extensive range of appropriate substrates in subsequent studies.

2 Material and Methods

2.1 Plant material

Three common houseplant taxa (*Dracaena fragrans* 'Golden Coast', *Hedera helix* and *Spathiphyllum wallisii* 'Verdi') which were shown in our previous study to have a range of CO_2 removal capacities were selected for this study. They represented a range of leaf types (succulent and herbaceous) and plant sizes (Table 1). Plants were maintained in either 'Substrate 1- peat-free substrate i.e. Sylvamix growing medium (Melcourt, Tetbury, Gloucestershire, UK; 6:2:2 sylvafibre: growbark pine: coir; air-filled porosity, 21%; moisture content by weight, 60%) or in 'Substrate 2' - peat substrate i.e. Clover professional pot bedding substrate (100% Irish Moss Peat; Clover, Dungannon, Co. Tyrone, UK). Plants were maintained in 3 L containers, with a slow release fertiliser feed (6-9 months, Osmocote, Marysville, OH, USA). Plants were purchased in Summer 2016 (apart from *Dracaena fragrans* 'Golden Coast' in Substrate 2, which was purchased in Spring 2018). Prior to experimentation (for > 90 days) plants were kept at room temperatures (17 – 22 °c) and 'low' light levels (~ 500 lux) 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). *Hedera helix* could not be successfully grown in the Substrate 2 and was omitted from the study in this substrate after several failed attempts.

Table 1: Characteristics of the houseplant taxa chosen for experiments in both substrates. Leaf area (n = 3) and plant height (n = 5) are means ± SEM. Species' botanical Latin name is given in italic and cultivar, where applicable, follows.

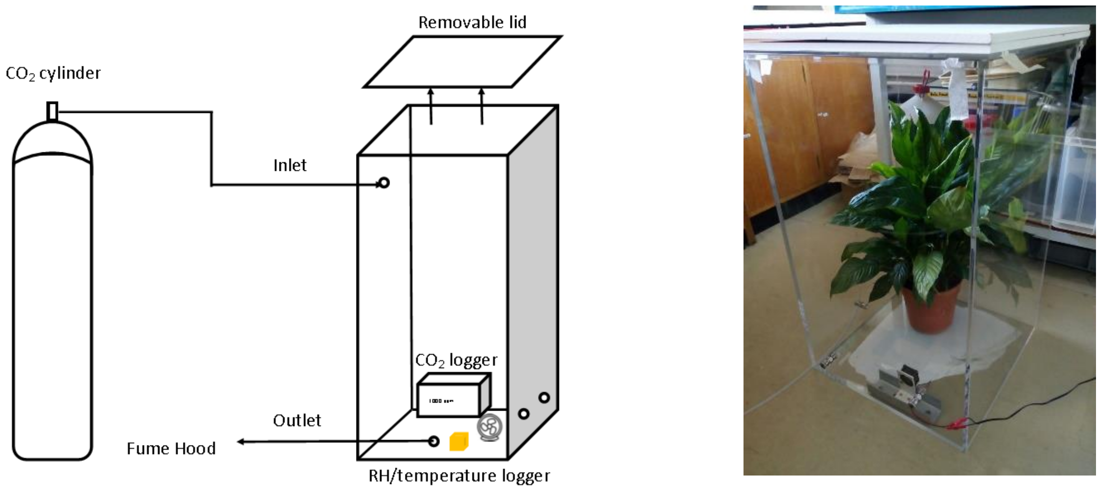
Taxa – Substrate 1	Family	Metabolism	Leaf area (cm^2)	Plant height (cm)
Dracaena fragrans 'Golden Coast'	*Asparagaceae*	C3	4057 ± 337	83 ± 1
Hedera helix	*Araliaceae*	C3	1542 ± 122	8 ± 1
Spathiphyllum wallisii 'Verdi'	*Araceae*	C3	6033 ± 128	38 ± 1

Taxa – Substrate 2	Family	Metabolism	Leaf area (cm^2)	Plant height (cm)
Dracaena fragrans 'Golden Coast'	*Asparagaceae*	C3	1417 ± 112	48 ± 1

Spathiphyllum wallisii 'Verdi'	*Araceae*	C3	2591 ± 442	42 ± 2

2.2 CO_2 Chamber experiments

Experiments were carried out in an experimental laboratory with a non-bypass fume hood at the University of Reading (UK). The experimental setup (Figure 1) consisted of a ~150 L (45 x 45 x 75 cm, 0.15 m^3) Perspex chamber (The plastic people, Leeds, West Yorkshire, UK) connected to a CO_2 cylinder (CO_2 > 99% purity, Air Liquide, Coleshill, West Midlands, U.K) with a combination of Teflon tubing (¼ inch diameter) and 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), 500 g of silica gel (Sigma – Aldrich Company Ltd, Gillingham, Dorset, U.K) 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 'no' (0 lux, 0 $\mu mol\ m^{-2}\ s^{-1}$) light was achieved by undertaking at experiments at night; 'low' (~ 500 lux, ~ 7 $\mu mol\ m^{-2}\ s^{-1}$) light levels were achieved in the usual lighting conditions of the room (four fluorescent ceiling lights, Osram, Munich, Germany lighting a floor area of 11 m^2); 'very high' levels were achieved with two LED lights (V-TAC Europe Ltd, Sofia, Bulgaria) which were positioned on stands externally, one at an ~ 30 cm height above the chamber and another ~ 30 cm from the side of the chamber. Colour temperature of those lights was 6000k and both lights combined produced a 'very high' (~ 22000 lux, ~ 300 $\mu mol\ m^{-2}\ s^{-1}$) light level inside the chamber — all three levels were measured with a calibrated light sensor (SKP 200, Skye instruments, Llandrindod Wells, Wales, UK). This 'very high' light level approximately corresponds to the light saturation for the studied species on a light response curve (Gubb *et al.*, 2018) and was chosen to represent the highest feasible light level which could be engineered (with supplementary artificial lighting) in an indoor environment.



A

B

Figure 1: Schematic diagram (A) and image (B) of the CO_2 chamber experimental setup

Measurements of the ability of studied taxa to reduce CO_2 concentrations of 1000 ppm (ASHRAE recommended maximum 8 hr exposure guideline taken from Torpy *et al.*, 2014; Torpy *et al.*, 2017) were undertaken on either three ('no' and 'low' light) or five ('very high' light) plants per taxon. Taxa were prepared for experiments with substrate moisture at the container capacity (SMC > 30%) and plants were thus considered optimally watered on the commencement of each experiment (Vaz Monteiro *et al.*, 2016). Measurements were also made on each houseplants 'dry' substrate (SMC < 20%) after a period of drying – the length of which was dependent on the type of plant and its inherent evapo-transpiration rate (Gubb *et al.*, 2018). To ascertain when each taxon was 'dry' SMC was measured prior to experimentation 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%). Experiments were made on one whole 'plant – substrate system' (i.e. potted plant, with uncovered substrate) enclosed inside the Perspex chamber at a CO_2 concentration of 1000 ppm (± 10%). Experiments were for a duration of 1 hr with the CO_2 concentration logged every second. Appropriate 'control' measurements were run at all three light levels on both the empty chamber and pot with substrate, but no plant (in both 'wet' and 'dry' SMC). The number of runs with only substrate and pot were either three for 'no' and 'low' light or five for 'very high' light.

Experimental parameters for each lighting treatment were as follows: 'no' light, ambient (CO_2 < 500 ppm; Temperature 17 – 26 °C; RH 23 – 64 %) and inside chamber (Temperature 17 – 26 °C; RH 31 – 90 %, average 61%); 'low' light, ambient (CO_2 < 500 ppm; Temperature 13 – 23 °C; RH 24 – 61 %) and inside chamber (Temperature 13 – 24 °C; RH 36 – 90 %, average 68%); and high light, ambient (CO_2 < 500 ppm; Temperature 15 – 22 °C; RH 21 – 60 %) and inside chamber (Temperature 15 – 24 °C; RH 32 – 90 %, average 64%). The chamber was also analysed for leakage prior, during and after experimentation; leakage was found to be < 5% of the starting concentration over the test period. All results were corrected for leakage. This was achieved – for 'no' and 'low' light - by adding the average CO_2 concentration lost through leakage (ppm) to the amount of CO_2 respired by each taxon (ppm) – correcting for the fact that each taxon would have measured a greater concentration of CO_2 if the chamber was airtight. The opposite was done for 'very high' light, correcting for the fact that each taxon would have removed more CO_2 if the chamber was airtight.

Based on the findings of our previous leaf-level work with the same taxa (Gubb *et al.*, 2018) we hypothesised that at 'no' and 'low' indoor light levels taxa would increase CO_2 concentrations within the enclosure. The CO_2 concentration (ppm hr^{-1}) removed by each taxon were calculated with the data measured directly every second by the appropriate logger and divided by the leaf area in m^2 presented in Table 1 to give a unit of ppm m^{-2} h^{-1}.

2.3 Statistical analysis

Experimental data (CO_2 concentrations) were analysed using GENSTAT (17th 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. Variance levels were checked for homogeneity and values were presented as means with either associated least significant differences (lsd) at a 5% significance level, standard error of the mean (SEM) or as Tukey's 95% confidence intervals for multiple comparisons. Where a lsd or Tukey's confidence interval has been used for data comparison, the associated p-value is presented. Where this is not displayed SEM has been used.

3 Results

3.1 CO_2 chamber experiments – 'no' light

At 'no' indoor light no taxa reduced CO_2 from the initial 1000 ppm concentration, and the CO_2 concentration inside the chamber increased with all treatments; no statistically significant differences in concentration were measured within taxon between 'dry' or 'wet' conditions (Table 2). Additionally, statistical differences were measured between the Substrates 1 and 2 for *Dracaena fragrans* 'Golden Coast' in both 'dry' (331 and 138 ppm m^{-2} hr^{-1}, respectively; Table 2) and 'wet' conditions (332 and 151 ppm m^{-2} hr^{-1}, respectively; Table 2).

Table 2: Mean CO_2 increase in the chamber per m^2 of leaf area for each taxon potted in the two substrates at 'no' (0 lux, 0 µmol $m^{-2} s^{-1}$) indoor light in 'wet' (SMC > 30 %, 0.3 $m^3 m^{-3}$) and 'dry' (SMC < 20 %, 0.20 $m^3 m^{-3}$) conditions. Data are a mean of three plants per taxon ± SEM.

Taxa – Substrate 1	Mean CO_2 increase at 'no' light ppm $m^{-2} hr^{-1}$	
	'Wet' (> 30 % SMC)	'Dry' (< 20 % SMC)
Dracaena fragrans 'Golden Coast'	332 ± 24	331 ± 18
Hedera helix	745 ± 189	408 ± 148
Spathiphyllum wallisii 'Verdi'	177 ± 30	155 ± 15

Taxa – Substrate 2	Mean CO_2 increase at 'no' light ppm $m^{-2} hr^{-1}$	
	'Wet' (> 30 % SMC)	'Dry' (< 20 % SMC)
Dracaena fragrans 'Golden Coast'	151 ± 78	138 ± 67
Spathiphyllum wallisii 'Verdi'	228 ± 42	185 ± 18

3.2 CO_2 chamber experiments – 'low' light

At 'low' indoor light *Spathiphyllum wallisii* 'Verdi' potted in the Substrate 2 reduced the concentration of CO_2 from the initial 1000 ppm concentration ('dry' and 'wet', 43 and 1 ppm $m^{-2} hr^{-1}$, respectively; Table 3). All other plant/substrate combinations increased the CO_2 concentration. Statistically significant differences were measured within taxon between 'dry' and 'wet' conditions for *Hedera helix* in the Substrate 1 (379 and 518 ppm $m^{-2} hr^{-1}$, respectively; Table 3). Additionally, statistical differences in removal were measured between the two substrates for *Spathiphyllum wallisii* 'Verdi' in 'wet' conditions (227 and -1 ppm $m^{-2} hr^{-1}$, respectively; $p = 0.03$; Table 3) but not 'dry' (192 and -43 ppm $m^{-2} hr^{-1}$, respectively, $p = 0.126$; Table 3) and for *Dracaena fragrans* 'Golden Coast' in 'dry' conditions (147 and 7 ppm $m^{-2} hr^{-1}$, respectively, Table 3).

Table 3: Mean CO_2 increase in the chamber per m^2 of leaf area for each taxon potted in the two substrates at 'low' (~ 500 lux, ~ 7 µmol m^{-2} s^{-1}) indoor light in 'wet' (SMC > 30 %, 0.3 m^3 m^{-3}) and 'dry' (SMC < 20 %, 0.20 m^3 m^{-3}) conditions. Data are a mean of three plants per taxon ± SEM, (-) values signify CO_2 assimilation (i.e. CO_2 uptake by the plant thus its removal from the chamber).

Taxa – Substrate 1	Mean CO_2 increase at 'low' light ppm m^{-2} hr^{-1}	
	'Wet' (> 30 % SMC)	'Dry' (< 20 % SMC)
Dracaena fragrans 'Golden Coast'	142 ± 8	147 ± 13
Hedera helix	518 ± 42	379 ± 54
Spathiphyllum wallisii 'Verdi'	227 ± 57	192 ± 104

Taxa – Substrate 2	Mean CO_2 increase at 'low' light ppm m^{-2} hr^{-1}	
	'Wet' (> 30 % SMC)	'Dry' (< 20 % SMC)
Dracaena fragrans 'Golden Coast'	66 ± 68	7 ± 52
Spathiphyllum wallisii 'Verdi'	-1 ± 38	-43 ± 64

3.3 CO_2 chamber experiments – 'very high' light

At 'very high' indoor light all treatments reduced the concentration of CO_2 from the initial 1000 ppm. Significant differences were measured in CO_2 reduction between all taxa, under both 'dry' and 'wet' conditions and between the two substrates (Figure 2). The range of removal rates was the smallest at 15 mins and the largest at 60 mins in both 'wet' and 'dry' conditions. After 15 minutes, no statistically significant differences in CO_2 reduction were measured within the same taxon in either substrate between 'dry' and 'wet' conditions. After 60 minutes, statistically significant differences were measured in both *Spathiphyllum* and *Dracaena* potted in the Substrate 2 between 'dry' and 'wet' conditions, but not in the Substrate 1 (Figure 2).

In 'wet' conditions after 15 minutes, no statistically significant differences were measured between any studied taxa in either substrate (Figure 2, $p = 0.550$). After 60 minutes, *Dracaena fragrans* 'Golden Coast' in the Substrate 2 reduced statistically the largest amount of CO_2 from the initial 1000 ppm concentration (1420 ppm m^{-2} hr^{-1}; $p < 0.001$). No statistically significant differences in CO_2 removal were measured between *Spathiphyllum wallisii* 'Verdi' (623 ppm m^{-2} hr^{-1}) in Substrate 2 or any of the taxa potted in Substrate 1 - *Hedera helix*, *Spathiphyllum wallisii* 'Verdi' and *Dracaena fragrans* 'Golden Coast' (541, 436 and 463 ppm m^{-2} hr^{-1}, respectively; $p < 0.001$; Figure 2).

In 'dry' conditions after 15 minutes, no statistically significant differences were measured between any studied taxa in either substrate (Figure 2, $p = 0.221$). After 60 minutes, *Dracaena fragrans* 'Golden Coast' in Substrate 2 reduced statistically the largest amount of CO_2 from the initial 1000 ppm concentration (1703 ppm m^{-2} hr^{-1} $p < 0.001$). A statistically significant difference was measured between *Spathiphyllum wallisii* 'Verdi' (820 ppm m^{-2} hr^{-1}) in Substrate 2 and *Hedera helix* in the Substrate 1 (401 ppm m^{-2} hr^{-1}; $p < 0.001$). No statistically significant differences were measured between other studied taxa i.e. *Spathiphyllum wallisii* 'Verdi' and *Dracaena fragrans* 'Golden Coast' (524 and 470 ppm m^{-2} hr^{-1}, respectively; $p < 0.001$; Figure 2).

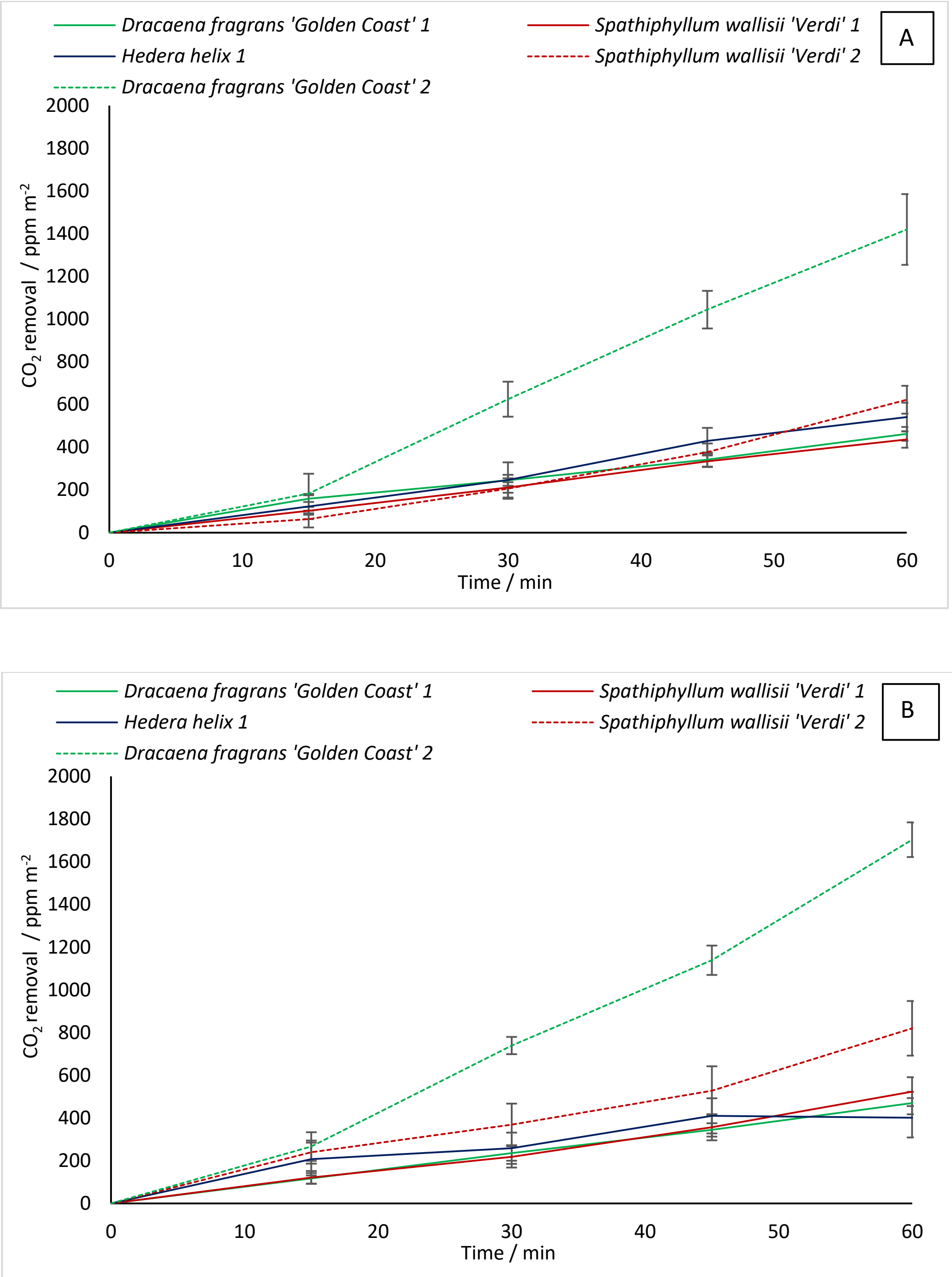


Figure 2: Mean CO_2 removal by each taxon in substrates 1 and 2 at 'very high' indoor light (~ 22000 lux, ~ 300 µmol m^{-2} s^{-1}) per m^2 of leaf area in **'**wet' (SMC > 30 %, 0.3 m^3 m^{-3}) (A), and 'dry' (SMC < 20 %, 0.20 m^3 m^{-3}) (B) conditions over a 60 min period. Data are a mean of five plants per taxa – error bars represent SEM.

4 Discussion

This work investigates how potting common houseplants in two differing substrates influenced their ability to reduce a harmful CO_2 concentration of 1000 ppm at a whole plant/substrate scale.

In this study we demonstrated that at 'low' light in 'dry' substrate conditions assimilation occurred with *Spathiphyllum wallisii* 'Verdi' potted in Substrate 2 (- 43 ppm m^{-2} hr^{-1}) but not in Substrate 1 (192 ppm m^{-2} hr^{-1}), contrary to the initial hypothesis where an increase in CO_2 concentration was expected from all studied taxa (Gubb *et al.*, 2018). Similarly, the study found that *Dracaena fragrans* 'Golden Coast' was the most effective taxon at reducing high concentrations of CO_2 at 'very high' indoor light levels when potted in the Substrate 2 (1703 ppm m^{-2} hr^{-1}). When the same taxon was maintained in the Substrate 1, CO_2 removal was statistically significantly lower (470 ppm m^{-2} hr^{-1}). Although less strongly, there was a suggestion in our measurements that *S. wallisii* 'Verdi' in high light removed more CO_2 by the end of a 60 minute period, when potted in Substrate 2 compared to Substrate 1.

These measurements suggest that differing substrate types may be able to influence CO_2 assimilation. A taxon may grow more effectively and be more physiologically active in a particular substrate, facilitating a stronger CO_2 removal ability. Peat has long been cited as a substrate which supports good plant growth, having good air-filled porosity, high water-holding capacity and a relatively pest- and pathogen-free environment (Schmilewski, 2008). Moreover, peat contains a carbon concentration in the range of 30 -70 kg/m^3 (18 -60%) whereas, for other mineral soils this concentration is typically < 20% (Agus *et al.*, 2011), this additional carbon might be a possible reason for greater CO_2 sequestration in our Substrate 2. Alternatively, the substrate and plant combined may support differing microorganisms, which in turn could provide a superior removal ability (Zhang *et al.*, 2013). This however, would need to be explored further by evaluation of the differing microorganisms in both substrates and additional inoculation experiments with the microorganism species in question (De Kempeneer *et al.*, 2004). Moreover, studies have also found differences in CO_2 removal between species grown in traditional potting mix and hydroculture (Irga *et al.,* 2013). Clearly, the substrate type is of importance in terms of CO_2 removal, and this should be further investigated in subsequent studies. Additionally, this needs to be kept in context of the fact that overall capacity of individual plants to remove CO_2 indoors is small (Pennisi and van Iersel, 2012; Irga *et al.,* 2013; Torpy *et al.*, 2014; Torpy *et al.*, 2017; Gubb *et al.*, 2018). Furthermore, while we have expressed our CO_2 removal data per unit leaf area (thus taking differences in plant size into the account), we cannot exclude possible impact of age differences between the plants. We made every effort to source the plants simultaneously, but their lifecycle and management prior to reaching us were beyond our control. Moreover, the authors acknowledge that photosynthetic activity can be reduced at high RH (Sailsbury and Ross, 1991) , and therefore the results may have underestimated the CO_2 removal in some treatments.

At 'no' and 'low' light levels typically experienced in indoor environments (Hawkins, 2011), most of the studied taxa would increase the concentration of CO_2 in indoor environments as measured in our earlier leaf-level work (Gubb *et al.*, 2018). However, *Hedera*, the taxon which potted in a Substrate 1 respired most, increased the CO_2 concentration by 115 ppm hr^{-1} (i.e. 0.2 g m^{-3} hr^{-1}); comparatively, each person contributes 36 g hr^{-1} of CO_2 in an office environment (Persily and de Jonge, 2017). The contribution of plants to CO_2 concentration increases can therefore be considered negligible in comparison to human contributions indoors at ~ 0.6 % of a humans contribution, in agreement with prior experiments (Gubb *et al.*, 2018).

Our study clearly suggests that increasing the lighting levels indoors – made possible with targeted lighting installations – would allow taxa to significantly reduce CO_2 concentration. This agrees with other similar studies, which show that light is the limiting factor for CO_2 reduction indoors (Pennisi and van Iersel, 2012; Gubb *et al.*, 2018) and that houseplants can be expected to aid ventilation systems – by providing additional CO_2 removal - but not replace them completely (Torpy *et al.*, 2014).

The results of the current study allow us to estimate the number of houseplants required to reduce CO_2 concentrations to a safe acceptable indoor level – literature suggests that concentrations of 600 ppm and below cause fewer health issues then elevated CO_2 concentrations (Seppanen *et al.*, 1999; Erdmann and Apte, 2004; Allen *et al.*, 2016) Therefore, for a small office of 15 m^3 (11 m^3 is the minimum space required per person; HSE, 1992), we calculated the time required for a 'dry' *Dracaena fragrans* 'Golden Coast' potted in the Substrate 2 (as this plant/substrate combination led to most CO_2 removal under our experimental conditions) to remove 400ppm of CO_2 (i.e. reduce CO_2 concentration from 1000 to 600 ppm), at a 'very high' light level assuming a sealed environment with no other sources of CO_2 (Equation 1).

$$\text{Time per } m^2 \text{ of LA (hr)} = \text{Concentration of } CO_2 \text{ to remove (ppm)} / \text{Rate of } CO_2 \text{ removal (ppm } m^{-2} \text{ hr}^{-1}) \times 1/100 \qquad (1)$$

Taking into account volumetric loading differences (Girman, 1992) between the test chamber (0.15 m^3) and the small office (15 m^3), the rate of CO_2 removal is reduced by a factor of 100. Consequently, from the results in Figure 2 we estimate 2 m^2 of *Dracaena fragrans* 'Golden Coast' (equating to 14 plants) in 'dry' conditions would require 12 hr to remove 400 ppm of CO_2 in the office as per the above stipulated conditions.

Differences in removal between 'dry' and 'wet' conditions across taxa at all light levels and substrates was deemed negligible in agreement with (Gubb *et al.*, 2018). This indicates that if plants are left to dry out – anecdotally a common occurrence – the impact on a room scale CO_2 flux is small, although on a leaf level there are differences in CO_2 assimilation. Additionally, at 'no' and 'low' light levels most taxa (i.e. the overall system) were respiring. Our study suggests that although at typical 'no' indoor light all studied taxa added CO_2 to the indoor environment, the highest increase was approximately half the CO_2 concentration removed at 'very high' light levels. This current work therefore confirms that placing a number of the studied houseplants in a typical home/office environment would not significantly damage health by increasing CO_2 concentrations indoors under either 'wet' or 'dry' substrate conditions.

Even at 'very high' light levels, both *Spathiphyllum wallisii* 'Verdi' and *Hedera helix* would require an unrealistic number of plants in both substrates to reduce CO_2 concentrations from 1000 ppm to a near-ambient level. This is in contrast with plants' pronounced benefits in health and productivity terms (Park and Mattson, 2008; Park and Mattson, 2009; Shibata and Suzuki, 2002; Shibata and Suzuki, 2004).

Our findings support the notion that the light level significantly impacts CO_2 removal, as suggested in previous studies (Pennisi and van Iersel, 2012; Torpy *et al.*, 2014; Torpy *et al.*, 2017; Gubb *et al.*, 2018). Other previous work had also determined that unrealistic numbers of plants (> 200) are required to remove a significant amount of CO_2 in indoor environments (Pennisi and van Iersel, 2012; Torpy *et al.*, 2014). These studies, however, did not take into account substrate moisture differences, or ambient CO_2 concentrations (Pennisi and van Iersel, 2012). Other studies did not specify which, or how many taxa provided any CO_2 removal (Lim *et al.*, 2009; Pegas *et al.*, 2012), or only considered one light level (Oh *et al.*, 2011).

Torpy *et al.*, 2017 estimated that a 2 m^2 active green wall of *Chlorophytum comosum* (where substrate is actively ventilated by pushing air through it) in peat-free substrate would be capable of removing 11 g of CO_2 per hour in a 16 m^3 room. Our previous work estimated that 2 m^2 (of leaf area) of *Spathiphyllum wallisii* 'Verdi' in unventilated peat-free substrate removed 0.75 g of CO_2 per hour at a comparable light level (Gubb *et al.*, 2018). This current work estimated that 2 m^2 (of leaf area) of *Dracaena fragrans* 'Golden Coast' at a light level comparable to both of the previous removes 3 g per m^3 of CO_2 per hour in a 15 m^3 room, clearly highlighting the benefits of 'active' walls (i.e. substrate ventilation) opposed to traditional 'passive' houseplants.

We support the notion that any future work should focus on green walls (Pettit *et al.*, 2017; Torpy *et al.*, 2017) (especially 'active' walls) which yield more effective removal due to an increased LA of taxa and increased substrate airflow. Additionally, taxa which have performed well in removing other indoor pollutants at high indoor light levels i.e. *Osmunda japonica* (Kim *et al.*, 2010) should be further examined. Furthermore, more substrate types should also be investigated. This study has shown that the ability of plants to remove CO_2 at typical indoor light levels may be maximised with certain substrate types and moisture conditions, therefore lower – more realistic – numbers of plants may be required to reduce harmful concentrations of CO_2. Additionally, as 'active' walls – which are clearly superior removers – place extra emphasis on the substrate, removal differences between substrate types will likely be further highlighted.

5 Conclusion

The study confirmed that growing the same taxa in differing substrates significantly influenced removal ability in most of the studied species – highlighting the key role substrate types play**.** The results from the current work indicates that 2 m^2 of *Dracaena fragrans* 'Golden Coast' would require 12 hr at a 'very high' light level (~ 22000 lux) in 'dry' conditions to reduce 1000 ppm of CO_2 – the ASHRAE recommended maximum 8 hr exposure guideline – to a 600 ppm concentration in a 15m^3 closed environment (i.e. small office) with no other sources of CO_2. Other studied taxa (*Spathiphyllum wallisii* 'Verdi' and *Hedera helix*) were found to require an unrealistic number of plants at the same 'very high' light level.

At typical 'no' and 'low' indoor light levels most studied houseplants increased CO_2 concentrations albeit, for the highest respiring taxa at approximately half the concentration removed at 'very high' light. Therefore, none of the studied houseplants would significantly elevate CO_2 concentrations indoors and thus, cause detrimental health effects. Differences between 'dry' and 'wet' substrates in their capacity for CO_2 removal at either 'no', 'low' or 'very high' light can be considered negligible. Our findings support the notion that raising the light level indoors is paramount for studied taxa to remove CO_2.

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