**Profiling indoor plants for the amelioration of high CO2 concentrations**

**Abstract**

Research over the last three decades has shown that indoor plants can reduce most types of urban air pollutants, however there has been limited investigation of their capacity to mitigate elevated levels of CO2. This study profiled the CO2 removal potential of eight common indoor plant species, acclimatised to both indoor and glasshouse lighting levels, to develop baseline data to facilitate the development of indoor plant installations to improve indoor air quality by reducing excess CO2 concentrations. The results indicate that, with the appropriate choice of indoor plant species and a targeted increase in plant specific lighting, plantscape installations could be developed to remove a proportion of indoor CO2. Further horticultural research and development will be required to develop optimum systems for such installations, which could potentially reduce the load on ventilation systems.

**Keywords:**

Indoor air quality, Light compensation points, Light response curves, Phytomitigation, Potted plants

**Introduction**

Indoor air pollution levels are commonly two to five times higher and sometimes as much as 100 times more concentrated than outside air (Environment Australia 2003). This is the result of contaminated outdoor air entering buildings, where it is further mixed with indoor-sourced pollutants, comprised mainly of CO2 from occupant respiration, along with a range of volatile organic compounds. Although not normally regarded as toxic, at elevated concentrations CO2 can act as a simple narcotic (Milton et al. 2000), and has been associated with sick building syndrome (Milton et al. 2000; Erdmann and Apte 2004; Seppänen and Fisk 2004). With levels higher than the outdoor ambient concentration (approximately 390 ppmv in 2012; Conway et al. 2012), CO2 has been associated with adverse symptoms relating to the mucous membranes (dry eyes, sore throat, nose congestion, sneezing) and to the lower respiratory tract (tight chest, short breath, cough and wheezing) (Erdmann and Apte 2004). Student academic performance and workplace productivity have both been shown to decline with increased CO2 levels (Bakó-Biró et al. 2004; Seppänen et al. 2006; Shaughnessy et al. 2006). The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) recommends a maximum CO2 concentration of 1,000 ppm for comfort acceptability, and as a surrogate estimate of the total indoor air pollution load (ASHRAE 2011), and this maximum is also generally recognised in Australia (Environment Australia 2001).

In office buildings, CO2 levels are normally modulated by ducted ventilation systems ([Redlich et al. 1997](#_ENREF_13)). Inefficiencies arise when there is a substantial temperature difference between outdoor ambient and indoor set-points, as considerable energy is required to heat or cool the ventilation airstream. It has been recognised that the benefits of increased building ventilation must be balanced against the costs of its energy use (Schell and Inthout, 2001), and the resultant contribution of greenhouse gas emissions if fossil fuel derived energy is in use. Research is needed to identify passive methods of decreasing ventilation requirements, by reducing airborne pollutant concentrations within buildings (Fisk et al., 2009).

Research over the last three decades has demonstrated that indoor potted-plants can significantly reduce concentrations of most types of urban air pollutants (Wolverton et al., 1989; Coward et al., 1996; Lee & Sim, 1999; Yoneyama et al., 2002; [Orwell et al. 2004](#_ENREF_12); [Wood et al. 2006](#_ENREF_20); Yoo et al., 2006; Kim et al., 2008, Irga et al., 2013).

Several studies have also been conducted to test the potential of indoor plants for mitigating excess CO2. In a laboratory test-chamber study by Oh et al. (2011), the CO2 reduction capacity of three indoor plant species was measured, in the presence of increasing CO2 concentrations generated by the respiration of experimental animals. They found that CO2 removal rates were concentration-dependent, and that the plants assisted in mitigating increasing CO2 concentrations. However, the tests were conducted at a single light level (16±5 μmol photosynthetically active radiation [PAR] m-2 sec-1), and thus the influence of variations in light levels on photosynthetic responses was not addressed. In another study, Pennisi and van Iersel (2012) profiled the carbon sequestration of common indoor plants acclimatised to simulated indoor environmental conditions and *in situ*, concluding that an unfeasible number of indoor plants would be required to make a substantial difference to indoor CO2 levels. A field study using 55 city offices ([Tarran et al. 2007](#_ENREF_19)) found that rooms with three or more potted-plants were associated with a 10% reduction in CO2 concentrations in an air-conditioned building, and a 25% reduction in a non-air-conditioned building. However, a follow-up study, using the same two plant species, in two more modern air-conditioned buildings, found only insignificant CO2 removal (Brennan, 2011). It was concluded that the lower removal rates recorded in the second study were due to the more efficient heating, ventilation and air conditioning (HVAC) systems in the newer buildings, which masked the potential contribution of plants to improve indoor air quality by virtue of their higher ventilation rates. The combined findings of the two field studies suggest that indoor plants could be used to lower the HVAC ventilation requirements, reducing not only energy costs but also the building’s contribution to greenhouse gas emission and carbon footprint. It has been estimated that the use of appropriate green plant design could reduce HVAC energy loads by 10–20% ([Afrin 2009](#_ENREF_1)).

Any healthy green plant, given adequate light, will photosynthesise, absorbing CO2 and releasing equimolecular amounts of O2. However, species vary in their light requirements and intrinsic photosynthetic rates per unit of leaf area; thus photosynthetic rates at any given light level are species-specific. In addition, although leaf photosynthetic rates have been widely used to estimate the CO2 removal capacity of outdoor plants (Asensio et al., 2007), this data does not reflect the true performance of any plant system, since plants also possess both non-green tissues and have associations with root zone microorganisms in their substrates, all of which have their own carbon use and release profiles (Somova and Pechurkin, 2001). Thus at the low light levels usually encountered in office buildings (4–10 μmol PAR m-2 sec-1; Safe Work Australia, 2011), indoor plant netphotosynthetic CO2 removal may be reduced to zero. In order to be effective for indoor CO2 mitigation, the combined respiration of the system must be exceeded by photosynthetic CO2 uptake, which is typically rate limited by the low light levels indoors.

No previous investigation appears to have been published on the photosynthetic performance of indoor plants which also directly takes account of the respiration of the ‘potted-plant microcosm’ (PPM), which includes the substrate and non-photosynthetic plants parts. In this investigation, foliar light response curves were determined for eight common indoor plant species, to compare intrinsic photosynthetic capacities when subjected to increasing light levels. Secondly, whole potted-plant CO2 exchanges were measured, using sealed test chambers, to determine the gross CO2 removal of the PPM that can be expected under both normal indoor and elevated lighting conditions, thus providing baseline data to enable the development of indoor plant installations to improve indoor air quality.

**Methods**

*Plant materials*

Eight test species were selected for this study, which are are all commonly-used indoor plants (Table 1). The ‘industry category’ data in Table 1 are the general light level ranges for each species recommendedby the indoor plant-hire industry for the health of the plant (eg. Ambius, 2011). Plant material was supplied by Ambius Australia (Alstonville, NSW, Australia). Plants were 12 months of age, grown in standard potting mixes consisting of composted hardwood, sawdust, composted bark fines, and coarse river sand (2:2:1) (bulk density ~0.6 gL-1; air-filled porosity ~30%), in 200 mm diameter plastic pots, a size commonly used in the indoor horticulture industry. Plants were fertilised before acclimatisation with 5 g per pot of a 9-month slow-release pellet fertiliser (Macrocote, Sydney, NSW). At the conclusion of the experiments, the substrate was gently washed from the roots, and the plants were divided into shoots (stems, leaves) and roots, and fresh weights were determined. Leaf areas were measured using a leaf area meter (Licor LI-3000-A, Nebraska, USA). The tissues were then oven dried at 70°C until they reached constant mass to estimate dry weights (Table 2).

*Light acclimatisation treatments*

Plants (n = 8) were acclimatised under two light treatments for 93 d prior to testing. Average photoperiod for both acclimatisation treatments was 9 h. Plants were watered with deionised water as required. The acclimatisation conditions selected were based on normal plant hire situations. The ‘low light’ (LL) acclimatisation treatment represented ‘well-lit’ indoor light levels, determined by a survey of workspaces around the University (Brennan, 2011), and was achieved by maintaining the plants in an air-conditioned laboratory. The mean light intensity at canopy height available to these plants was 10±2 μmol PAR m-2 sec-1; average temperature 23.0 ± 0.1°C, and relative humidity 45 ±10% (means ± SD). The ‘high light’ (HL) treatment simulated conditions that indoor plants experience during growth or maintenance in a glasshouse prior to distribution to customers. The HL plants were acclimatised in a glasshouse lined with shade cloth, with maximum mid-day light level of 90±10 μmol PAR m-2 sec-1; average temperature 23.7 ± 3.6°C and relative humidity 68.1 ± 16.0%. Both peak and daytime average light levels in the HL treatment were thus substantially higher than those from the LL group, and the humidity and temperature ranges were also different. Since such differences would be expected to influence the substrate microflora and their respiration rates, the differences between treatment groups in gross CO2 fluxes cannot be attributed solely to differences in light levels. Rather, the treatment groups were designed to realistically represent the relative performances of freshly-delivered, and well used, indoor plants.

*Leaf-based light response curves and compensation points*

The photosynthetic performance of plants from both acclimatisation groups were tested using a leaf-chamber infra-red gas analyser (IRGA: LI-COR 6400 portable photosynthesis system; LI-COR Inc., NB, USA) with an enclosed leaf area of 6.0 cm2. Light of variable intensity was provided by built-in red/blue light emitting diodes. Chamber relative humidity was continuously monitored, and ranged from 40 to 60%. Tests were carried out between 9.00 am and 5.00 pm, when natural photosynthesis could be expected to occur. For each acclimatisation treatment, four young, fully opened mature leaves per plant, from 4 plants per species, were tested. Initial chamber CO2 concentration was set at 400 ppmv (775 mg/m3) as this is at the lower end of average ambient indoor CO2 concentrations ([Hess-Kosa 2002](#_ENREF_9)). The illumination provided to the leaves were gradually increased step-wise at intervals of 0, 2, 5, 10, 20, 50, 100, 200, 350, 500, 1000, 2000 μmol PAR m-2 s-1. Each intensity level was maintained for 3–5 minutes to allow photosynthetic response to stabilise before increasing to the next intensity. The final chamber CO2 concentration at each intensity was the resultant of photosynthesis and/or leaf respiration. Light response curves were derived, and leaf-based light compensation points (LCPs) were estimated by interpolation on the curves produced. The LCP is the light intensity at which CO2 flux equals zero, i.e. when photosynthetic CO2 removal by the leaf tissue is exactly balanced by its own respiratory CO2 emissions.

*Whole-potted-plant CO2 fluxes*

To estimate the true influence of the potted-plant specimens on the CO2 concentrations of their surrounding environment, their carbon flux performance was then measured on the total PPM basis. Eight perspex test chambers (216 L)were used, fitted with a portable IRGA CO2 monitor (TSI IAQ-CALC, TSI Inc., MN, USA) to record chamber CO2 concentrations. Fans (100 mm diameter) were installed to circulate chamber air. Temperature was regulated at 23±0.1°C with circulating water from a water bath and a cooling coil in the chambers. Plants were watered to field capacity and drained for 1 h before being sealed in the chambers. All trials used a starting CO2 concentration of 1000 ± 50 ppmv, this being the ASHRAE (2011) recommended maximum for air-conditioned buildings. Chamber CO­2 concentrations were recorded at 1 min intervals for 40 min. Sampling was curtailed at 40 min because it was found that after this time chamber CO2 levels became low enough to affect the linearity of the draw-down rate, and thus were not representative of an open system; and at the same time chamber humidity rose to levels that could affect stomate function and hence leaf gas exchange and photosynthesis. Data were adjusted for variations in initial CO2 concentrations by expressing changes in chamber air as percentages of the initial concentrations. The plants were tested at two or three light levels, as follows:

1. An intensity of 10 μmol PAR m-2 s-1, produced with Wotan ‘daylight’ incandescent tubes (Wotan GMBH, Munich). This intensity had been the most commonly encountered ‘well-lit’ office light level during our previous studies ([Brennan 2011](#_ENREF_5)), and has also been used in other investigations (Pennisi and Iersel 2012, Irga et al., 2013).
2. An intensity of 350 μmol PAR m-2 s-1, using a 400 W metal arc discharge lamp (Sylvania M59R, Sylvania Lighting Australasia Pty Ltd ). This was the maximum intensity found within 0.5 m of any high-intensity lighting source found in the three buildings investigated in our previous office studies ([Burchett et al. 2010](#_ENREF_6); [Wood et al. 2006](#_ENREF_20)). The intensity represents the maximum practical intensity to which plants indoors are likely to be subjected.
3. Where an increase in chamber CO2 concentration of more than 5% was recorded over the 40 min. period for either of the two treatments above, i.e. when rates of respiratory emissions exceeded rates of leaf CO2 removal, a trial-and-error process was used to determine the light intensity at which zero CO2 flux in the chamber was achieved. This final value indicates the minimum indoor light intensity above which the potted-plant unit would achieve gross CO2 removal, giving the ‘pot-and-plant microcosm light compensation point’ (PPM-LCP).

**Results**

Plant characteristics are shown in Table 2. There were no significant differences (ANOVA; p>0.05) between the two acclimatisation treatments for leaf areas, or fresh or dry weights, thus only single values are given for each species. Whilst it is not know why no physiological differences were observed between plants from the different acclimatisation treatments, it is possible that the acclimatisation period used was insufficient for substantial growth to have occurred, or that light adaptation in these species is not demonstrated by changes in physical dimensions of the photosynthetic apparatus.

*Leaf light response curves*

The leaf LRCs for the 8 species are shown in Figure 1. CO2 removal efficiency was high for two species, *F. benjamina* and *D. lutescens*, with maximum reductions ranging from 2 to 8 µmol CO2 m-2 leaf area s-1 for both acclimatisation treatments. In 7 of the 8 species from the HL treatment, and in 4 species from the LL treatment, CO2 removal rates continued to rise with increasing light intensities up to 2000 μmol PAR m-2 s-1, indicating at least a short-term ability to respond to light intensities approximating full sunlight. The majority of plants from the HL acclimation treatment yielded higher photosynthetic rates than the same species acclimatised to lower light. This is to be expected, since plants can down-regulate their photosynthetic activity when transferred to lower light conditions (Havaux 1990). However, three species, *C. elegans*, *A. commutatum* and *H. forsteriana* recorded greater CO2 reductions in the LL treatment than the HL treatment, indicating that for these species, chronic photoinhibition of photosynthesis may have resulted from their being acclimatised at light levels higher than optimal.

*Leaf light compensation points (LCPs)*

The leaf LCPs (Table 3) represent the minimum light intensity that must be exceeded for net leaf photosynthetic CO2 removal to occur. Of the HL acclimatised plants, 7 species recorded LCP values below 4.1 μmol PAR m-2 s1. The exception was *D. deremensis*, with an LCP of 14.5 μmol PAR m-2 s-1. Most plants showed low light induced photosynthetic down-regulation under the LL treatment, with all species except *C. australe* recording LCP values lower than those recorded for their HL treatment. The mean LCP across species for low light-acclimatised plants was 2.86 μmol PAR m-2 s-1, and for high light-acclimatised plants, 4.90 μmol PAR m-2 s-1.

*Potted-Plant Microcosm CO2 removal*

The potted-plant specimen is the most practically relevant measure of comparison between species with respect to CO2 removal for real world scenarios. Tables 3 and 4 show that, as anticipated, the potted-plants tested at 10 μmol PAR m-2 s-1 tended to produce little effect on chamber CO2 concentrations over the 40 min test period. At this light level gross CO2 removal occurred in only three species, irrespective of acclimation treatment, namely for LL-adapted *C. elegans* and *H. forsteriana,* and HL-adapted *C. australe*. In contrast, all other treatments showed a trend towards increasing CO2 levels when tested at this low intensity, denoting respiration of the microbial communities in the potting mix, plus respiratory emissions from roots or other underground plant organs. Conversely, at 350 µmol.m-2.s-1, all species and treatments showed net CO2 draw down. The highest rates of removal on a PPM basis were recorded by the three palm (Arecaceae) species, with either acclimatisation treatment, with *H. forsteriana* demonstrating the fastest rate, at 167 mg CO2/plant/h. The high rates of CO2 removal by the palms are at least partly the result of these plants possessing larger leaf areas compared with the other species tested (Tables 2), as discussed further below.

*Potted-Plant Microcosm Light Compensation Points*

Two Arecaceae, *H. forsteriana* and *D. lutescens,* showed the lowest PPM-LCPs regardless of light acclimation treatment (Table 3), indicating that they were capable of net removal of CO2 at very low light levels. The LL-acclimatised *C.* *elegans* and *A. commutatum* also performed well, with a PPM-LCP of ~10 μmol PAR m-2 sec-1. Although *C. australe* is generally recommended for medium–high-light conditions (Table 1), this species on the whole showed effective CO2 draw down under low light conditions. On the other hand, *A. elatior* and *A. commutatum*, regarded as very low-light tolerant, did not show positive CO2 removal responses when LL-acclimatised and tested at 10 μmol PAR m-2 s-1. *Dracaena* ‘Compacta’ is also regarded as a suitable plant for low-light situations, but recorded the highest PPM-LCP, of 50 μmol PAR m-2 sec-1, for both acclimatisation treatments. For most other species and treatments, however, net microcosm CO2 removal was obtained at light intensities of between 10 and 30 μmol PAR m-2 sec-1. These findings suggest that the light levels recommended by the indoor horticulture industry, whilst they may be suitable for the long term health of the plants, may not be ideal if indoor plants are to have a functional role in mitigating high indoor CO2 concentrations.

The estimated PPM-LCPs provide useful guidelines for minimum light intensities which must be exceeded for functional CO2 removal.In contrast to the leaf chamber LCPs, no PPM-LCP was lower than 10 μmol PAR m-2 sec-1, which indicates that, for these species, useful net CO2 removal is unlikely to occur at normally recommended office lighting levels. The results also clearly indicate that respiratory CO2 emissions from non-photosynthetic plant parts and substrate microorganisms play a substantial role in counterbalancing the photosynthetic CO2 draw down by the green shoots. Of the 16 species/acclimatisation treatments, half had PPM-LCPs at or above 10 µmol PAR m-2 sec-1 (Table 3). The average PPM-LCP across LL acclimatised plants was 21.1 µmol PAR m-2 sec-1, and for the HL treatment, 20.6 µmol PAR m-2 sec-1. The difference between PPM-LCPs was not significantly different across species (ANOVA, *P* = 0.808). The results indicate that a moderate increase in plant lighting would be required for these species to contribute effectively in mitigating indoor CO2.

*CO2 removal per unit leaf area*

The leaf areas of the potted plants, and the number of individual potted plants required for 1 m2 of leaf area are shown in Table 2. CO2 removal performance calculated on the basis of leaf area has practical implications for the design of interior plantscape installations, either for vertical gardens and plant walls, or for standard arrangements using discrete pots. When calculated on the basis of CO2 removal per m2 leaf area (Table 4), the comparative performances of the 8 species appear quite different from those calculated on a per potted-plant basis. The most efficient species per unit leaf area was HL-acclimatised *D. lutescens*, which removed ~655 mg CO2 per m2 leaf area at 350 μmol PAR m-2 s-1. This was a considerably higher value than for any other species / treatment. This species also removed comparatively large amounts of CO2 per unit leaf area when acclimatised at low light levels. The other treatments that removed substantial amounts of CO2 were HL-acclimatised *D*. *deremensis* and *F. benjamini*, and LL-acclimatised *H. fosteriana*. The finding for *D. deremensis* contrasts with Pennisi and van Iersel’s (2012) finding that a similar *Dracaena* sp. was one of the least effective carbon sequestering species tested, although this may have been due to the methods used by the latter authors (discussed later).

As a final step, a correlation analysis was performed for a range of variables associated with CO2 removal per plant, including leaf area, and fresh and dry weights. No statistically significant, taxonomically independent relationships were detected between leaf area, fresh weight or dry weight and CO2 removal, indicating that species-specific behaviour is the primary determinant of photosynthetic capacity for these species. These results support the finding that the CO2 removal responses of any species cannot be wholly predicted; they must to be empirically tested.

**Discussion**

Our findings clearly indicate that large variations exist among indoor plants in their response to long and short-term changes in light intensity. The findings coincide with what is known of the habits of shade plants in their natural habitats; that they have the capacity to efficiently utilise intermittent high intensity light, such as sun flecks hitting the forest floor intermittently during the day, but will become photoinhibited, and possibly bleached of chlorophyll, if held under supra-optimal light intensities (Naumberg et al., 2001).

The leaf LCP findings indicate that, in these species, light-acclimatisation conditions have a considerable effect on the LCP of the indoor plants, although all the LCP values detected are below the light levels generally encountered indoors. The results lead to the inference that at least some leaf photosynthetic activity could be expected from these plants under current building lighting system designs. The LCP values recorded are comparable with those previously reported for other indoor species (Pennisi and van Iersel 2012; Burton et al. 2007; Hull 2002).

Measurements of leaf CO2 fluxes are useful for comparing the photosynthetic performance among plant species under a range of different environmental conditions. Overall, from either light acclimatisation treatment, the test species recorded LCPs at extremely low light levels, and reached 50–65% of their maximum short-term CO2 removal rates at an intensity at or below 350 μmol PAR m-2 s-1 (Fig. 1).

Whilst the accuracy of extrapolating from chamber experiments to real-world conditions is questionable due to a range of factors (Llewellyn and Dixon 2011), it is nonetheless worthwhile to estimate the potential ventilation equivalence of the plants tested here, as has been done for other indoor plant species (Irga et al., 2013). The highest CO2 draw down rate recorded in the current study was ~657 mg CO2 / m2 leaf area / h by HL acclimatised *D. lutescens* at 350 µmol PAR m-2.s-1. Using the estimate calculated by Irga et al. (2013), an average human exhales 34.5 mg CO2/h. At this level, 249 potted *D. lutescens* would be required to completely remove all of the exhaled CO2 from a single occupant, in a completely unventilated room. This number is slightly reduced if HL adapted *H. forsteriana* under 350 µmol PAR m-2.s-1 is considered; due to its greater leaf area, 206 individual plants would be required. These estimates are obviously impractical, although they are lower than Pennisi and van Iersel’s (2012) estimate of ~400 plants per person. However rather than completely replacing the ventilations systems of buildings, we see plants as a means to reduce, rather than eliminate ventilation energy use. A reasonable 15 potted *D. lutescens* could potentially reduce ventilation requirements by ~6%. Horticultural biotechnology could make significant improvements on these estimates: 5 m2 of green wall contains ~57 m2 of leaf area (Irga et al., 2013), and thus has strong potential for overcoming the space inefficiency problems of our estimates.

The current work thus represents the most extensive investigation to date to assess the potential of indoor plants to ameliorate CO2 concentrations. It also provides the first robust quantitative basis for indoor plant species comparison. Pennisi & van Iersel (2012) attempted such estimates previously, but did not record ambient CO2 concentrations, and estimated carbon assimilation *in situ* as the mass of senesced foliage produced over an extended experimental period, a process that was recognised by the authors to underestimate carbon sequestration. Another previous study (Oh et al. 2011) tested a number of indoor plant species in 500 L chambers, finding a greatest carbon removal rate of ~68 mg CO2 / m2 leaf area / h for ‘areca palm’, but only tested at a very low light level (16 µmol PAR m-2 sec-1). Interestingly, Oh et al. (2011) found chamber CO2 removal rates to be virtually independent of leaf area for a given species for leaf areas ranging from 3–15 m2 per chamber, suggesting the possibility of a saturation effect, an aspect worthy of further investigation as it may set an upper limit to the CO2 removal rates that can be achieved by a particular species. Irga et al. (2013) tested *Syngonium* *podophyllum* indoor plants under similar conditions to those used in the current investigation, although in this case the plants were grown in hydroculture, which resulted in an evident reduction of reduced microbial respiration. The best CO2 removal rate detected in Irga et al.’s (2013) study was 214 mg CO2 / m2 leaf area / h, which was lower, although comparable with, the results observed in the current work. Fujii et al. (2005) examined CO2 removal by *Juniperus* *conferta*, detecting a best CO2 removal rate of 99 mg/m2/h under natural daylight, with a maximum light level of 1025 µmol PAR m-2 sec-1.

The contrast in CO2 removal rates between the current work and these previous studies clearly demonstrates that substantial interspecies variations in photosynthetic rate occur, and as a result it is recommended that future studies carefully determine the most appropriate light level for the species tested.

The system we have tested here has significant scope for performance enhancement. Glasshouse and tissue culture laboratory lighting are advanced technologies, and could readily be applied to indoor plantings in urban buildings. Targeted plant-specific (PAR) LED lighting for indoor plants may be an option for low energy use assisted increases in CO2 removal in a similar way to their increasing use with commercial crop yields (Yeh and Chung 2009). Alterations in the irradiation wavelengths may have the potential to improve photosynthetic capacity (eg. Buckhov et al., 1995), and alternating high and low light intensities has also been shown to have the capacity to increase CO2 reductions (Giorgioni 2012). Horticultural technologies that reduce the density of substrate bacteria relative to potting mix, such as hydroculture, have been shown to reduce the relative respiratory CO2 concentration of the substrate, whist maintaining the capacity to reduce volatile organic compounds (Irga et al., 2013), and thus could make a major contribution to the development of functional systems. None of the indoor plants selected for this study are fast-growing species: research is also thus worthwhile into whether highly productive plant types such as grasses and various herbaceous species have the potential for increasing carbon removal capacity.

The primary direction for future developments in this field, however, is clearly to trial CO2-removal specific plant installations in real buildings. The installation of vertical gardens, living walls etc. is increasing in the developed world (Almusaed, 2011). The major emphasis for these living structures to date has been on their beneficial aesthetic and psychological purposes, although there is now a growing understanding and appreciation that they can additionally have significant effects on indoor air quality as well.

The results of this study show that the intrinsic CO2 mitigating properties of plants could be optimised and routinely applied for the purpose of reducing the load on the ventilation component of HVAC systems, given a moderate increase in targeted lighting levels. Indoor plants represent a potential low-cost, easily maintained, air-cleansing component in the built environment.

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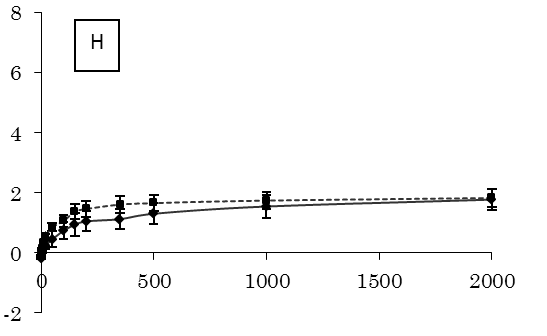
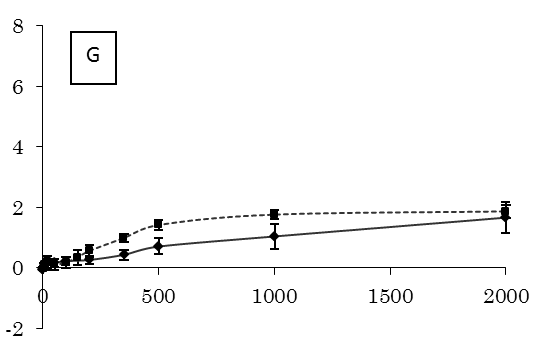
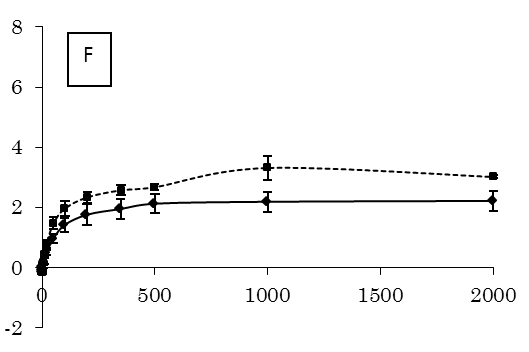
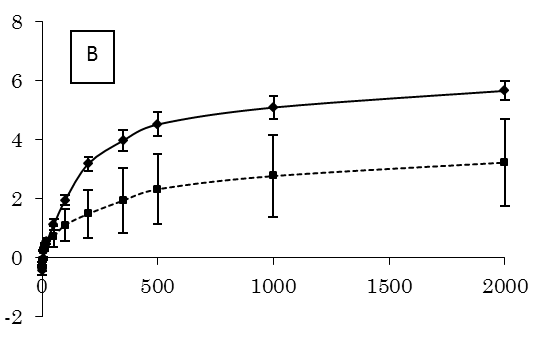
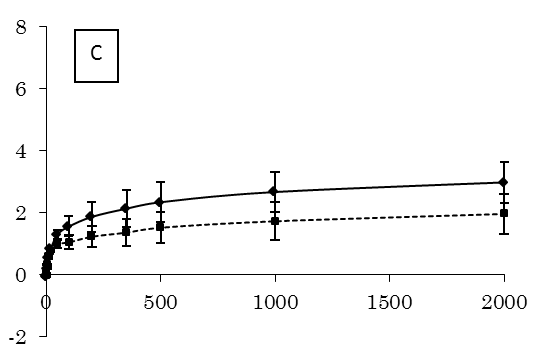
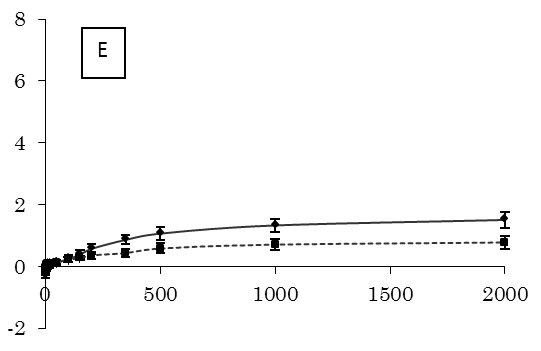
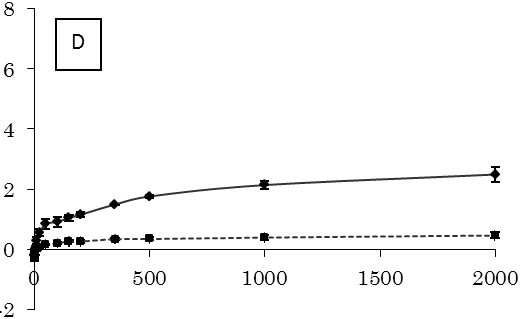
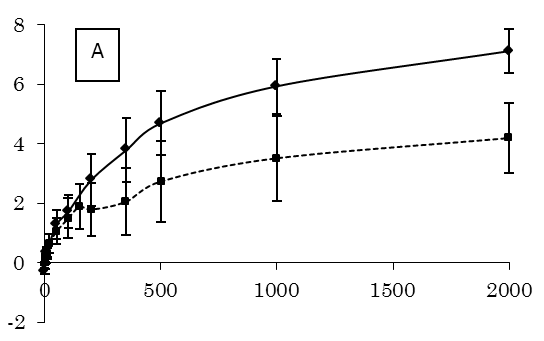
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**Figure 1.** Light response curves of *Dypsis lutescens* (A), *Ficus benjamina* (B), *Aspidistra eliatior* (C), *Castanospermum australe* (D), *Dracaena deremensis* (E), *Chamaedorea elegans (F), Aglaonema commutatum* (G), *Howea forsteriana* (H) acclimatised to two light regimes: high light (unbroken line) and low light (broken line) . Means ± SEM; n=16.



CO2 removal (µmol.m-2.s-1)

PAR (µmol.m-2.s-1)

**Figure 1**: Torpy, F.R., Irga, P.J., Burchett, M.D.

**Table 1:** Indoor plant species tested in the current experiment. Industry category is as per the classification used by Ambius (2011) for the recommended indoor light level for the different plants: L = low light; M = medium light; H = high light.

|  |  |  |  |
| --- | --- | --- | --- |
| Test species | Family | Industry category | Light range  (μmol PAR m-2 sec-1) |
| *Aglaonema commutatum* Schott | Araceae | L | 5–10 |
| *Aspidistra elatior* Blume | Ruscaceae | L | 5–10 |
| *Castanospermum australe* A. Cunn ex Hook. | Fabaceae | M–H | 10–45 |
| *Chamaedorea elegans* Willd. | Arecaceae | M | 10–30 |
| *Dracaena deremensis* ‘compacta’ Engl. | Ruscaceae | M | 10–30 |
| *Dypsis lutescens* (H. Wendl.) Beentje & J. Dransf. | Arecaceae | H | 30–45 |
| *Ficus benjamina* L. | Moraceae | H | 30–45 |
| *Howea forsteriana* Becc. | Arecaceae | L–H | 5–45 |

**Table 2:** Characteristics of the indoor plant species tested in the current experiment. Eight plants were samples for each species. All plants were grown in 200 mm diameter pots. Fwt = fresh weight; Dwt = dry weight.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| |  |  |  |  |  | | --- | --- | --- | --- | --- | | Test species | Leaf area (m2) | Plants per m2 leaf area | Fwt  (g/plant) | Dwt (g/plant) | | *C. elegans* | 1.24±0.05 | 0.81 | 154±18.0 | 41.7±4.9 | | *H. forsteriana* | 0.75±0.10 | 1.34 | 68.7±9.7 | 39.6±5.6 | | *C. australe* | 0.52±0.06 | 1.91 | 373±43.3 | 132±15.3 | | *D. lutescens* | 0.21±0.02 | 4.73 | 32.1±3.6 | 11.2±0.7 | | *F. benjamina* | 0.21±0.02 | 4.81 | 35.5±3.5 | 6.88±0.7 | | *D. deremensis* | 0.22±0.02 | 4.63 | 76.9±5.7 | 11.4±0.9 | | *A. elatior* | 0.23±0.06 | 4.29 | 58.1±17.4 | 14.9±4.5 | | *A. commutatum* | 0.45±0.02 | 2.20 | 133±5.7 | 14. 8±0.1 | |
|

**Table 3:** Comparison of light compensation points (LCPs). The leaf LCPs indicate the lowest light level at which net CO2 removal occurs in the leaves of the test plants. Potted-Plant Microcosm (PPM) LCPs represent the lowest light level at which gross CO2 removal can be expected for the potted plant, including the potting mix.

|  |  |  |  |
| --- | --- | --- | --- |
| Species | Acclimatisation treatment\* | Leaf LCP | PPM LCP |
|  |  | (μmol PAR m-2 sec-1) | |
| *A. commutatum* | Low light | 1.6 | 10 |
|  | High light | 1.8 | 25 |
| *A. elatior* | Low light | 0.5 | 20 |
|  | High light | 2.2 | 10 |
| *C. australe* | Low light | 9.1 | 20 |
|  | High light | 4.1 | 10 |
| *C. elegans* | Low light | 2.4 | 10 |
|  | High light | 2.7 | 20 |
| *D. lutescens* | Low light | 1.8 | 10 |
|  | High light | 3.2 | 10 |
| *D. deremensis* | Low light | 2.2 | 50 |
|  | High light | 14.5 | 50 |
| *F. benjamina* | Low light | 1.8 | 30 |
|  | High light | 3.2 | 30 |
| *H. forsteriana* | Low light | 3.5 | 10 |
|  | High light | 4.3 | 10 |

\*Low light = plants acclimatised for 93 d at 10±2 μmol PAR m-2 sec-1; High light = plants acclimatised for 93 d at 90±10 μmol PAR m-2 sec-1.

**Table 4:** CO2 removal performance of the test species at two test light levels. ‘Plant’ represents the net CO2 flux per individual potted plant, including substrate. Data are arranged in order of decreasing CO2 removal / plant / h at 10 µmol PAR m-2.s-1. Negative values indicate the net production of CO2. Values are means ± SEM (n = 8).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Test species | Acclimatisation | mg CO2 removed /  plant / h | mg CO2 removed / m2 leaf area/ h | mg CO2 removed / plant / h | mg CO2 removed / m2 leaf area / h |
|  |  | 10 µmol PAR m-2.s-1 | | 350 µmol PAR m-2.s-1 | |
| *C. elegans* | Low light | 5.21±0.00 | 4.20±0.03 | 110±0.00 | 88.7±0.03 |
|  | High light | -402±0.04 | -13.5±0.03 | 118±0.00 | 95.4±0.03 |
| *H. forsteriana* | Low light | 3.88±0.00 | 5.21±0.02 | 168±0.00 | 225±0.02 |
|  | High light | -9.51±0.00 | -12.8±0.02 | 154±0.00 | 206±0.02 |
| *C. australe* | Low light | -21.3±0.00 | -40.5±0.02 | 59.4±0.00 | 113±0.02 |
|  | High light | 1.87±0.00 | 3.57±0.03 | 36.1±0.00 | 68.9±0.02 |
| *D. lutescens* | Low light | -4.66±0.00 | -22.0±0.08 | 76.1±0.00 | 360±0.08 |
|  | High light | -7.23±0.00 | -34.2±0.08 | 139±0.00 | 6570.07 |
| *F. benjamina* | Low light | -8.08±0.00 | -491±0.09 | 18.5±0.00 | 89.12±0.09 |
|  | High light | -6.41±0.00 | -30.8±0.09 | 46.9±0.00 | 225±0.09 |
| *D. deremensis* | Low light | -11.0±0.00 | -51.0±0.10 | 33.1±0.00 | 153±0.10 |
|  | High light | -13.6±0.00 | -63.0±0.10 | 85.8±0.00 | 397±0.09 |
| *A. elatior* | Low light | -356±0.04 | -63.6±0.03 | 90.0±0.00 | 386±0.03 |
|  | High light | -12.6±0.00 | -54.1±0.03 | 59.2±0.00 | 254±0.03 |
| *A. commutatum* | Low light | -62.4±0.04 | -5.72±0.08 | 73.5±0.00 | 162±0.08 |
|  | High light | -76.5±0.04 | -7.02±0.08 | 47.9±0.00 | 106±0.08 |