Indoor-plant technology for health and environmental sustainability

Margaret Burchett
University of Technology Sydney

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Indoor Plant Technology for
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MD Burchett et al.,
University of Technology, Sydney (UTS)

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Project NY10024

MD Burchett, FR Torpy, J Brennan, L. De Filippis, & P. Irga

Plants and Indoor Environmental Quality Group
Centre for Environmental Sustainability
Faculty of Science, UTS

Address correspondence to:

Prof Margaret Burchett
Faculty of Science, UTS
PO Box 123, Broadway, NSW 2007, Australia
Margaret.Burchett@uts.edu.au

Industry collaborators: Ambius

The purpose of this Report is to present the findings of a project undertaken to provide baseline information to further the horticultural development of indoor plant species, for deployment as routine installations to reduce the energy load on building air-conditioning, and hence the carbon-footprint of the city. The results indicate directions for advancing the horticultural technology needed to fulfil this goal, which will also include collaborations with horticultural lighting engineers and interior designers.

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14 October, 2011

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## Abbreviations

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ASHRAE</td>
<td>American Society of Heating, Refrigeration and Air Conditioning Engineers</td>
</tr>
<tr>
<td>CAM</td>
<td>Crassulacean acid metabolism; a modification of a normal (C-3) photosynthetic pathway, in which leaf stomates are closed during the day and open at night, when CO$_2$ diffuses in and is held on a carrier molecule until next day, when it is transferred over into the C-3 pathway</td>
</tr>
<tr>
<td>C-3 photosynthesis</td>
<td>An enzymic pathway in leaf chloroplasts for the synthesis of glucose (a sugar containing 6 carbon atoms) via a 3-carbon intermediate sugar compound</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, Ventilation and Air-Conditioning (HVAC) systems (for large buildings)</td>
</tr>
<tr>
<td>IRGA</td>
<td>Infra red gas analyser, commonly used as instrument to measure CO$_2$ fluxes</td>
</tr>
<tr>
<td>LCP</td>
<td>Light compensation point; the light intensity (PAR) at which CO$_2$ removal by the green leaf, or the whole plant, tissues is exactly matched by respiratory emissions of the leaf, or of the whole plant</td>
</tr>
<tr>
<td>LRC</td>
<td>Light response curves, often measured in leaves with a leaf-chamber IRGA</td>
</tr>
<tr>
<td>PAR</td>
<td>Photosynthetically active radiation (wavelengths 400 to 700 nm)</td>
</tr>
<tr>
<td>PPM</td>
<td>‘Potted-plant microcosm’, referring to plant plus potting-mix with microorganisms as an integrated unit</td>
</tr>
<tr>
<td>PPM-CLP</td>
<td>‘Potted-plant microcosm’s net light compensation point’; the intensity which must be exceeded for net CO$_2$ removal to be achieved</td>
</tr>
<tr>
<td>ppm</td>
<td>Parts per million; 1/10$^6$ of medium; e.g., µL/L air; mg/kg soil</td>
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Media summary

International research has demonstrated that indoor plants can substantially improve indoor environmental quality, reducing all major types of urban air pollution and directly improving health and wellbeing of occupants. Our UTS studies have shown that indoor plants can significantly reduce volatile organic compounds (VOCs) and CO₂, two classes of air pollutant always higher indoors than outside, even in the centre of the city. Indoor plants have potential for further development so that they can be installed to bring about significant reductions in loads on the air-conditioning (A-C) of city buildings, by reducing the frequency with which the A-Cs must cut in to refresh air when CO₂ levels get too high. A recent UTS office study showed us that any plant CO₂ reductions may be masked by modern A-C systems, indicating potentially unnecessary energy use. The building sector accounts for one third of global energy use, so reductions here would contribute to sustainability goals.

The aim of this laboratory study was to examine, under a range of test light intensities, both the photosynthetic light responses of individual leaves and of whole-potted-plant net CO₂ reductions, in nine commonly used indoor species. Whole-plant responses need to be considered, since photosynthetic CO₂ uptake occurs only in the green shoots, and only under adequate light, while respiratory emissions of CO₂ are being produced continually in the non-green plant parts, and by the potting mix microorganisms. This project is the first systematic comparative research to have been made on the photosynthetic characteristics of indoor plants.

Results for net CO₂ removal were calculated on the basis of CO₂ removal per potted-plant, per unit leaf area, the number of 200 mm pots need to provide 1 m² leaf area, and per unit weight of green shoot tissue. The results found that, in the lower range of ‘normal’ office lighting intensities, the potted-plant microcosm of most of the test species would not be able to achieve the net CO₂ reductions required to reduce significantly the load on the A-C systems. However, the results also indicate that with horticultural lighting technology applied to indoor plant installations such as plant walls, vertical gardens, ‘break-out’ zones and the like, the plants do indeed have the potential to reduce A-C loads significantly, and suggestions for future horticultural technology R&D are offered. The findings thus provide a basis for developing horticultural technology for the deployment of indoor plants to maintain lower indoor CO₂ levels, reducing the A-C energy requirements of city buildings, contributing to remediation of the built environment and assisting the goal urban sustainability.
Technical summary

International research has demonstrated that indoor plants can substantially improve indoor environmental quality, reducing all major types of urban air pollution and directly improving health and wellbeing of occupants. Our UTS studies have shown that indoor plants can significantly reduce volatile organic compounds (VOCs) and CO₂, two classes of air pollutant always higher indoors than outside, even in the centre of the city. Indoor plants have potential for further development so that they could be installed to bring about significant reductions in loads on the air-conditioning (A-C) of city buildings, by reducing the frequency with which the A-Cs must cut in to refresh air when CO₂ levels get too high. A recent UTS office study showed us that any plant CO₂ reductions may be masked by modern A-C systems, indicating potentially unnecessary energy use. The building sector accounts for one third of global energy use, so reductions here would contribute to sustainability goals.

The aim of this laboratory study was to profile the photosynthetic responses of nine commonly grown test species, under a range of test light intensities, both the light responses of individual leaves and of whole-potted-plant net CO₂ reductions. Whole-plant responses need to be considered, since photosynthetic CO₂ uptake occurs only in the green shoots, and only under adequate light, while respiratory emissions of CO₂ are being produced continually in the non-green plant parts, and by the potting mix microorganisms. This project is the first systematic comparative research to have been made on the photosynthetic characteristics of indoor plants. Before testing, batches of plants the nine species were light-acclimatised for at least six weeks under one of two light regimes – the shaded glasshouse, or in the laboratory. Light response curves for leaves from plants from both light regimes were tested with a leaf-chamber infra red gas analyser (IRGA), across the range of photosynthetically active radiation (PAR) from 0 to 2000 µmol m⁻² s⁻¹. Whole potted-plants from the two light regimes were then tested for ‘potted-plant microcosm’ (PPM) net CO₂ removal under the very high indoor level of 350 µmol m⁻² s⁻¹, under the ‘normal’ low intensity of 10 µmol m⁻² s⁻¹ and, if necessary, at a slightly light intensity. The purpose of these tests was to ascertain the critical light level that had to be exceed to achieve net CO₂ reduction by the PPM. Results for net CO₂ removal were calculated on the basis of CO₂ removal per potted-plant, per unit leaf area, and per unit weight of green shoot tissue.

The results showed that at the lower range of ‘normal’ office lighting intensities, the potted-plant microcosm of most of the test species would not be able to achieve the net CO₂ reductions required to reduce significantly the load on the A-C systems. However, the results also indicate that with horticultural lighting technology applied to indoor plant installations such as plant walls, vertical gardens, ‘break-out’ zones and the like, the plants do indeed have the potential to reduce A-C loads significantly, and suggestions for future horticultural technology R&D are offered. The findings thus provide a basis for developing horticultural technology for the deployment of indoor plants to maintain lower indoor CO₂ levels, reducing the A-C energy requirements of city buildings, contributing to remediation of the built environment and assisting the goal urban sustainability.

Technology transfer

The UTS team have made presentations for the Brisbane meeting of Green Infrastructure Australia (Oct. 2010) and the Gold Coast Conference of the National Interior Plantscape Association (Oct. 2010). We gave approximately 40 radio/magazine interviews associated with the NGIA campaign, launched ‘To improve your plant/life balance’ and the advice to ‘Put a plant on your desk’. F. Torpy and M. Burchett together gave a talk on the topic in June 2011, in the UTS Public Lecture series. We have made contributions to newsletters of the National Interior Plantscape Association. We are now preparing this material for submission to peer-reviewed scientific journals.
1. Introduction

1.1 Project aim

The aim of this project was to profile the photosynthetic carbon dioxide (CO₂) removal capacities of nine selected indoor plant species under a range of lighting conditions; to obtain baseline information to forward the development of potted-plants to improve indoor air quality. Indoor plants have the potential for development as routine installations to lower the energy load on sealed building air-conditioning units, and thus to reduce the C-footprint of the city.

International research has demonstrated that potted-plants can substantially improve indoor environmental quality, reducing all types of urban air pollution (UAP) and yielding directly measurable benefits to health and wellbeing of building occupants. Indoor plants have the potential to be developed for use in lowering loads on building Heating, Ventilation and Air-Conditioning (HVAC) systems. Green-plant installations could be developed for routine use in lowering the frequency with which the HVAC system must accelerate ventilation in order to refresh air, when CO₂ levels reach the allowable occupational maximum. Plant installations could in this way reduce energy loads, fuel costs and the carbon-footprint of city buildings, contributing to the goal of sustainable urban settlements (Commonwealth of Australia, 2005; Summerville et al., 2008; Bibby, 2009).

1.2 Background– energy needs of city air-conditioning systems

The United Nations Environment Program (UNEP 2008) estimates that the building sector accounts for 30–40% of global energy use, so that substantial reductions in carbon pollution can be brought about by increasing the energy efficiency of the CBD. As in Britain, Europe and North America, 80% of Australians live in urban areas and spend 90% of their time indoors (Cavallo et al., 1997; Environment Australia, 2003). A large percentage of the urban workforce is employed inside sealed buildings which are ventilated and temperature-controlled by HVAC systems. Indoor CO₂ levels inside any building are higher than outdoor levels, because of occupants’ breathing (and any unflued gas-fuelled appliances) (Erdmann et al., 2003). Excess CO₂ acts as a narcotic, i.e. increasing levels cause increasing drowsiness and loss of concentration. Measurements of indoor CO₂ levels are also used as a surrogate for total indoor air pollutant loads, including, e.g., organic air toxics (i.e volatile organic compounds, VOCs), which constitute the other class of UAP that is always found in higher concentrations indoors than outside, often up to 10 times higher (Apte et al., 2000; US EPA, 2011). Staff performance and productivity have been found to decline, and coughing & wheezing symptoms increase, with every 100 ppm increment in CO₂ concentrations (Erdmann et al., 2003; Seppänen et al., 2006).

The main purpose of the ventilation function of HVAC systems is not so much to replenish oxygen, but to remove excess CO₂ and accompanying indoor pollutants (US EPA 2004). The World Health Organisation (WHO, 2000) guideline for maximum allowable indoor CO₂ concentrations, and the Standard specified by American Society of Heating, Refrigeration and
Air Conditioning Engineers (ASHRAE, 2000, 2011) for sealed, air-conditioned buildings, is 1,000 parts per million (ppm), while the USA Occupational Safety and Health Administration (OSHA, 2011) recommends a maximum of 600 ppm.

Workplace indoor air quality in Australia is the responsibility of State governments, which generally adhere to the maximum limit of 1,000 ppm CO₂ (Standard AS1668.2-1991; ASHRAE, 2011). However, some organisations (e.g. UTS) use a lower level of 800 ppm CO₂ as the maximum before extra ventilation is required. The ventilation requirements of sealed buildings mean continuous or pulsed outdoor-air (‘refresh’) input. The process generally involves the entry of air which is at a temperature unsuitable for building occupants, so the energy draw of the HVACs for temperature-regulation is substantially increased because of the primary ventilation needs. The HVACs of many buildings are pre-set so as to maintain CO₂ levels below the US OSHA recommended maximum of 600 ppm, at a large energy and financial cost.

1.3 Indoor plants can be developed and deployed to reduce building ventilation needs

In an initial office study of 60 offices in two UTS buildings we found that potted-plants reduced CO₂ levels by 10 to 25% (Tarran et al., 2007), and it was considered that such removal could be enhanced with further research and development. But in a second office study, in two newer UTS buildings (Burchett et al., 2010) it was found that the plant-based CO₂ reductions were largely masked by the more modern HVAC systems; i.e. the free air quality improvement capacity of the plants was supplanted by the energy-intensive activities of the air-conditioning systems. In unplanted offices, average CO₂ concentrations in the four buildings investigated ranged from 380 to 600 ppm, although some spaces recorded transient levels of up to 1,600 ppm. Ambient global CO₂ concentrations have risen to approximately 385 ppm, and predicted further rises would narrow the gap between outdoor concentrations and indoor maximum tolerable levels, putting greater pressures on HVAC systems as a consequence. Our office findings are in line with the conclusion of Afrin (2009), that an indoor ‘living wall’ (or equivalent green-plant design) could reduce HVAC energy loads by 10-20%.

1.4 Indoor plants can improve many aspects of indoor environmental quality

1.4.1 Effects on indoor air quality (IAQ)

HVAC systems filter out some particulates from incoming air, but have no effect on concentrations of incoming gaseous pollutants. Potted-plants have been found to bring about significant reductions in indoor concentrations of: nitrogen oxides (NOₓ) (Wolverton et al., 1985; Coward et al., 1996; Yoneyama, 2002); sulfur oxides (SOₓ) (Lee and Sim 1999); ozone (O₃) (Papinchak, 2009); carbon monoxide (CO) (Tarran et al., 2007); and particulates (Lohr and Pearson-Mims, 1996). The plants and their root-zone microorganism communities are involved in the removal of these airborne pollutants. Following the pioneering USA studies on indoor plant VOC removal by Wolverton and colleagues (1989, 1991, 1993), our UTS laboratory has conducted detailed test-chamber studies with 15 internationally used plant species and four test VOCs: benzene, toluene, xylene and n-hexane. All of the species trialled show an almost equally robust capacity for VOC removal (Wood et al., 2006; Orwell et al., 2006; Tarran et al., 2007; Burchett et al., 2009, 2010). All species could repeatedly eliminate high doses of VOCs within about 24 hours, once the system has been stimulated (‘induced’) by
initial exposure to the contaminant. We have also shown that the uniformity of VOC removal capacity is because it is normal bacteria of the potting mixes which are the primary removal agents, although there is also clear evidence of interactions between the microbes and the plants. Other laboratory studies have also shown substantial VOC removal by indoor plants (e.g. Yang et al., 2009; Aydogan and Montoya, 2011). In addition, our office studies, referred to earlier, showed that indoor potted-plants can maintain reductions in total VOC (TVOC) loads of up to 75% (Wood et al., 2006). However, this air pollutant removal by the potted-plant microcosm can also be masked by the activity of HVAC systems (Apte and Apte, 2010; Burchett et al., 2010). These findings demonstrate that the routine installation of plants for CO₂ reduction in city buildings would also have significant general air-cleansing benefits for building occupants.

1.4.2 Other health and wellbeing benefits
Indoor plants also provide a number of other benefits to the health and wellbeing of occupants that appear to be independent of normal air quality considerations. Plant presence has resulted in substantially reduced illness and discomfort symptoms (Fjeld et al., 1998; Lohr and Pearson-Mims, 2000; Fjeld, 2002; Park et al., 2002), improvements in work performance and productivity (Lohr et al., 1996; Lohr and Pearson-Mims, 1996, 2000; Bergs, 2002), and enhanced job satisfaction (Dravigne et al., 2008). Environmental psychologists postulate that the beneficial psychological effects of indoor plants are because living greenery in our immediate environment relieves attention fatigue and tension and restores a feeling of calm, even when the plants are not consciously noticed (Kaplan, 1995; Shibata and Suzuki, 2002; Bringlismark et al., 2009).

1.5 Office building CO₂ levels could rise faster than as predicted for outdoors
In Australia, city governance policies are likely to increase significantly the HVAC ventilation requirements, and similar trends are no doubt being considered elsewhere around the globe. The City of Sydney Floor Space and Employment Survey (2009) found that, in cost-cutting measures by employers, the average office-room size per worker had declined by 10% over the last decade to 18.57 m², and in open-plan offices floor-space had declined by 25% to 11.49 m². ‘Hot-desk’ (shift-share) offices, e.g. call centres, now had an average of only 7.6 m² per employee. As well, from another perspective, the Conference of Lord Mayors of Capital Cities (Australia) in 2009 agreed that workspaces in CBDs should be reduced further over the next decade. Their aim was to increase building use efficiency and slow the spread of the C footprint of our cities, in a bid towards sustainable urban settlements (Bibby, 2009). Such a strategy could result in a more than doubling of office CO₂ levels (and associated other air pollutants), and therefore loads on the HVAC systems, unless complementary measures such as effective indoor plantings can be brought into routine use in city buildings.

1.6 Plant lighting arrangements require R&D
For plant installations to be of maximum benefit in reducing HVAC energy consumption, optimal plant lighting requirements also need to be met, e.g. by means of lighting fixtures over ‘vertical gardens’, ‘green walls’, filing-cabinet ‘hedges’, or break-out ‘green zones’, near lifts, etc. Lighting also uses energy, but the financial and energy costs of maintaining lighting are far less than for many other building fittings, including air-conditioning, especially if modern LED technology is used. In a residential analogy, lighting for an eight-room house might involve, using 7-15 watts of energy per modern compact-fluorescent type lamp, a total of no more than
400–500 watts. Room air-conditioners (which heat and/or cool but do not generally ventilate) use from 5,000–7,000 watts, and whole-house-ducted systems require anything from 15,000 to 25,000 watts. LED lighting with extremely low energy draws is now available in wavelengths specifically suited to promote plant growth. Determination of the light intensity requirements of potted-plants for effective CO₂ removal, and how much CO₂ removal can be expected given specific light conditions, were primary aims of this study.

1.7 Factors affecting indoor plant CO₂ uptake

Green plants are the primary global carbon sink. Given adequate light intensities, green shoots refresh air in two complementary ways in the process of photosynthesis, taking up CO₂ (to manufacture carbohydrates) and emitting equimolecular quantities of oxygen as a by-product. Rates of photosynthesis are affected by a number of factors, some of which are intrinsic to individual species, such as light and shade tolerance, foliage area and leaf age. Environmental factors are also crucial to photosynthetic performance and for indoor plants, environmental variables include nutrient and moisture contents of the potting mix, humidity, surrounding CO₂ levels (Valladares and Niinemets, 2008), and light intensity and wavelengths.

‘Indoor’ plant species are perforce shade tolerant, but adequate lighting for them can be problematic in many indoor spaces. Net CO₂ reduction by a plant occurs only when its leaf photosynthetic CO₂ uptake exceeds the CO₂ emissions produced by the respiration of the plant as a whole (from roots, tubers, non-green stems etc., as well as from the leaves when in the dark or in lighting too dim for normal functioning). A plant’s photosynthetic ‘light compensation point’ (LCP) is defined as the intensity at which net CO₂ reduction is zero because the two processes of leaf photosynthesis and whole-plant respiration are in balance. At this light intensity over an extended period the plant is starving, since it will have no means to produce any carbohydrate for use in tissue maintenance, let alone growth.

One of the nine genera investigated in this study, Dracaena (like Sansevieria, also in Fam. Asparagaceae) has the ability to activate either a normal photosynthetic CO₂ removal pathway (‘C-3’), or that of Crassulacean acid metabolism (CAM). It is hence referred to as a “facultative CAM plant” (Holtum et al., 2007). When the CAM pathway is activated, the plant closes its leaf pores (stomates) during the day and opens them at night, when it absorbs CO₂ that is held on a carrier molecule until the next day. It is then transferred in a series of steps into the C-3 biochemical pathway (Griffiths et al., 2008). About 6% of vascular plants show this ‘night-shift’ capacity, which is understood to have evolved as an adaptation to arid environments (Silvera et al., 2005; Osmond, 2007). It was therefore of interest in this project to note responses in this species to differing light intensities, in a situation where the potting mix moisture content was always adequate, and hence not acting as an environmental stressor that might trigger a switching to the CAM pathway. In an earlier study in this laboratory (Brennan, 2011) it was found that the facultative CAM species Zamioculcas zamiifolia (ZZ plant; Fam. Araceae) could shut down immediately in response to sudden changes in test light intensity, under circumstances where there was no change or shortage of potting mix water content. Indoor plants, being usually derived from forest understoreys, can maintain growth at very low light levels compared with ‘high light’ (full sun) species. However there has been no previous systematic research conducted which quantifies the range of shade tolerances among indoor species.
1.8 Photosynthetically active radiation

Plants absorb light of different colours with different efficiency. Chlorophylls absorb most strongly in the red and blue wavelengths of the spectrum, with ancillary leaf pigments (carotenes and xanthophylls) that can absorb some of the light at intermediate wavelengths and transfer the energy to chlorophylls. The term ‘photosynthetically active radiation’ (PAR) denotes the range of light wavelengths that can be used by green plants to power photosynthesis, i.e. from 400 to 700 nanometres (nm), which is almost the same range as of visible light. PAR is generally measured as irradiance or photon flux density [PFD], i.e. the number of photons (or quanta or Einsteins), hitting 1 square metre of surface per second (as micro-moles [µmol] PAR m⁻² s⁻¹). Full sunlight has an intensity of approximately 2,000 µmol m⁻² s⁻¹. In a recent office study (Burchett et al., 2010) we found that average light intensities in the two university office buildings sampled ranged from only 5-30 µmol m⁻² s⁻¹. Nevertheless, even at these low intensities, as mentioned above (Tarran et al., 2007), we recorded indoor plant-associated reductions in office CO₂ levels of 10% in an air-conditioned building and 25% in a naturally ventilated building. ‘Shade plants’ are able to down-regulate their photosynthetic apparatus when they are acclimatised to yet lower light conditions, reducing both light compensation points and light saturation levels for photosynthesis (Poole and Conover, 1988; Akoumianaki-Ionnidou et al., 2004; Liu and Huang, 2008).

An aim of the current study was to assess the degree to which this down-regulation was achieved in the test species.

Tazawa (1999) published a review of light compensation points (LCPs) for 29 indoor plant species, reporting that all the values were at or below 5 µmol m⁻² s⁻¹. We have previously conducted a preliminary investigation of photosynthetic light responses in leaves of two species, Spathiphyllum wallisii ‘Petite’ and Epipremnum aureum (Pothos), monitoring responses from dark conditions through to photosynthetic light saturation intensities (Burchett et al., 2009). We used a leaf-chamber infra red gas Analyser (IRGA) method (description below) for measuring the CO₂ fluxes (i.e. net removal or emission). We found that S. ‘Petite’ reached 80% of its maximum CO₂ uptake rate at about 12 µmol m⁻² s⁻¹, but the equivalent value for E. aureum was at about 150 µmol m⁻² s⁻¹. In the same study we also tested CO₂ fluxes for whole potted-plants of the two species, in sealed bench-top chambers, at indoor light levels ranging from 10 to 20 µmol m⁻² s⁻¹. We found almost zero net change in CO₂ concentrations in the chamber air at these light intensities, i.e zero net CO₂ removal, although we had just shown CO₂ uptake in the leaves. The zero change in the whole-potted-plant chamber was because CO₂ emissions from respiration in the roots and potting mix microorganisms were balancing the photosynthetic removal in the shoots (Burchett et al., 2009).

The present study examined the light levels needed to exceed what can be considered as the ‘the potted-plant microcosm’s net light compensation point’ (PPM-LCP) for the nine species, after acclimatisation under two lighting regimes - a shaded glasshouse or indoors. This is the first such study to be undertaken on this matter, and the information obtained provides a baseline for further horticultural development of indoor plant technology.
2. Materials and Methods

2.1 Species selection

The nine test species were selected in consultation with the nursery industry and with Ambius, industry funding sponsor for the project, who also supplied the plant materials from their nursery at Alstonville, NSW. The species are all commonly used in the indoor plant industry, and three species were chosen from each of the three shade-tolerant categories empirically recognised in the industry (Table 1).

Table 1: Selected test species in industry-assigned categories of indoor light tolerances.

<table>
<thead>
<tr>
<th>Very Low (VL)*</th>
<th>Medium (M)*</th>
<th>Medium High (MH)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aglaonema commutatum Chinese evergreen (Fam: Araceae)</td>
<td>Chamaedorea elegans Parlour palm (Fam: Arecaeeae)</td>
<td>Agathis robusta Qld. Kauri (Fam: Araucariaceae)</td>
</tr>
<tr>
<td>Aspidistra elator Cast Iron Plant (Fam: Aparagaceae/ Ruscaceae)</td>
<td>Castenospermum australe Black Bean (or MH) (Fam: Fabaceae)</td>
<td>Ficus benjamina Benjamin/Small-leaved rubber plant (Fam: Moraceae)</td>
</tr>
<tr>
<td>Dracaena deremensis 'Compacta' (Fam: Aparagaceae/ Ruscaceae)</td>
<td>Howea forsteriana Kentia palm (Fam: Arecaeeae)</td>
<td>Dypsis lutescens Golden Cane Palm (MH or M) (Fam: Arecaeeae)</td>
</tr>
</tbody>
</table>

* Very low light levels indoors are in the range of 4–10 µmol m⁻² s⁻¹, equivalent to most artificially lit indoor spaces; medium light levels are what would be expected if a plant was located directly near a light source or window (15–30 µmol m⁻² s⁻¹); and high light levels are equivalent to location near a sunny window or very bright light source (50–350 µmol m⁻² s⁻¹)

2.2 Light acclimatisation regimes

Fourteen healthy, mature specimens of the 9 test species were supplied by Ambius (Alstonville nursery) in 200 mm pots (soil volume 3.85 L). The potting mixes for the different plant species were the standard potting mixes for each species provided by the industry (Ambius nursery). This is a more appropriate alternative than using an arbitrary standard potting mix for all species, and more accurately reflects their real world performance. Seven pots of every species were acclimatised for a minimum of six weeks under one of two light-acclimatisation regimes, which were considered likely to represent the maximum and minimum lighting levels to which indoor species are likely to be subjected in the absence of plant-specific lighting installations. The locations were the UTS shaded roof-top glasshouse (maximum mid-day light intensities 50–100 µmol m⁻² s⁻¹) and on the laboratory bench (6–12 µmol m⁻² s⁻¹). Trials were then conducted on each species to examine:

(a) leaf CO₂ fluxes, under wide range of PAR intensities
In order to characterise the photosynthetic responses of each test species to different light intensities, and to provide a comparison of CO₂ uptake capacity among the species, individual leaves in situ were tested for photosynthetic rate, measured as CO₂ removal, across a range of light levels from dark to 2000 µmol m⁻² s⁻¹; and

(b) whole-potted-plant CO₂ fluxes, under selected PAR intensities
To establish the light intensity that represented the whole ‘potted-plant microcosm light compensation point’ (PPM), trials were conducted to discover the intensity that would have to
be exceeded for the microcosm to show net CO\textsubscript{2} reduction. Plants were well watered and allowed to drain for 1 hour prior to any testing.

2.3. Leaf-chamber measurements of CO\textsubscript{2} fluxes

Leaves were tested using a leaf-chamber infra red gas analyser (IRGA) with an enclosed chamber area of 6 cm\textsuperscript{2} (LI-COR 6400 portable photosynthesis system; LI-COR Inc.) (Figure 1). Light was provided via the chamber’s inbuilt red/blue LED light source. Chamber relative humidity (RH) was also monitored, and ranged from 40 and 60%. Tests were carried out between 9.00 am and 4.00 pm, i.e. under indoor conditions when natural photosynthesis could be expected to be in progress. All experiments were performed at 23°C.

Young, fully-opened mature leaves were used for sampling, and four leaves per plant on each of four replicates per acclimatisation regime, were sampled for each species. A concentration of 400 ppm CO\textsubscript{2} was passed through the chamber, this being a low average indoor CO\textsubscript{2} level. Light intensity in the chamber was sequentially increased from 0 to 2000 µmol m\textsuperscript{-2} s\textsuperscript{-1} (intervals: 0, 2, 5, 10, 20, 50, 100, 150, 200, 350, 500, 1000 and 2000 µmol m\textsuperscript{-2} s\textsuperscript{-1}). Each light intensity was maintained automatically for an interval of 3-5 minutes to allow responses to stabilise and a meaningful reading to be obtained before increasing to the next step of intensity. The CO\textsubscript{2} concentration produced in the chamber is the resultant of photosynthesis and any leaf respiration occurring over that interval. Thus the readings recorded are in terms of CO\textsubscript{2} flux (net reduction or increase in CO\textsubscript{2} concentration), as micro-moles CO\textsubscript{2} per m\textsuperscript{2} leaf surface per second (µmol CO\textsubscript{2} m\textsuperscript{-2} s\textsuperscript{-1}).

The full range of light intensities was tested in order to estimate the range or limits of the intrinsic capacity of the photosynthetic apparatus of each species to respond to increasing intensities. When any plant (especially a shade plant) is exposed to intensities above the light saturating level for photosynthesis, it will often show inhibition of the process, referred to as photoinhibition. Full sunlight can be expected to photoinhibit most indoor plants chronically if they are placed in locations that receive direct sunlight. If there is no relief from such exposures, yellowing, bleaching or death of leaves and then of the plant may result. Acute photo-inhibition can also sometimes result if a leaf is exposed to short-term high light intensities during the day. From the data light response curves (LRCs) were graphed, and utilised: (a) to assess and compare the overall light responsiveness of the species under the two acclimatisation regimes, (b) to act as the basis for determining light intensities to be used in the subsequent whole-potted-plant chambers trials, and (c) to allow a general comparison of the maximum rate of photosynthesis of which the species were capable.

Figure 1 Li-COR leaf chamber IRGA (envsupport.licor.com)
2.4. Measurements of whole-potted-plant CO₂ fluxes

The aims of the whole-chamber PPM testing were (a) to find the light intensity that must be exceeded for net CO₂ reduction to be reliably achieved in the species concerned and, (b) to compare the total CO₂ removal capacities from each species after glasshouse or laboratory (i.e. indoor) light acclimatisation. A Perspex test chamber, 60x60x60 cm (216 L) (Figure 2) was used for the trials, with a portable IRGA CO₂ monitor (TSI IAQ-CALC, TSI Inc., MN, USA) set to record CO₂ concentrations at 1-minute intervals. A small chamber fan was used to maintain air circulation. A number of light sources were used to attain the various intensities required, including: ambient laboratory lighting with modified shading for the chamber to achieve levels below 10 µmol m⁻² s⁻¹; a variable-intensity bank of 5 Wotan ‘daylight’ incandescent tubes, used for intensities between 10 and 100 µmol m⁻² s⁻¹; and a 500 W sodium arc discharge lamp for intensities between 100 and 350 µmol m⁻² s⁻¹. All light levels were measured using a LI-COR light meter recording PAR. This is an important consideration, as photographic-type light meters measure overall light intensity, of whatever wavelength, not PAR.

![Figure 2 Whole plant test chambers](image)

Four replicates were used for each species from each light acclimatisation regime. The potted-plant was placed in the chamber, which was then sealed and CO₂ concentration readings continued over a 40 min period. This period was selected because it was found that after this interval, chamber CO₂ levels could become so low that removal rates tailed off, and chamber humidity rose to levels that could affect stomatal function and photosynthesis. All whole plant chamber trials were performed at the ambient CO₂ level at that time (mean over experimental period: 435±23 ppm). For every plant, CO₂ fluxes at two or three light intensities were measured, as follows:

(a) at 350 µmol m⁻² s⁻¹, this being the intensity at which the LRC results had shown was the point at which about 60% of maximum CO₂ uptake rates were obtained across the test species. In addition, this was the maximum intensity found within 0.5 m of any indoor light source within the two building investigated in our office studies (Burchett et al., 2010), and thus it represented a practical maximum indoor lighting intensity;

(b) at 10 µmol m⁻² s⁻¹, which was about the normal, ‘well-lit’ (for occupants) office light level found during our office study;
(c) as necessary, a third light intensity was tested, the level being equal to the PPM-LCP for the species, if that was not equal to what had been found with either of the light levels in (b) above. This light intensity was estimated experimentally from the leaf LRCs, the intensity then adjusted until the change in chamber CO₂ concentration over the 40 minute test period was about zero (± 2%). This light intensity provided an estimate of the minimum light level at or above which the potted plant-microcosm will act as a net remover of CO₂.

For each replicate tested, data were adjusted for minor differences in ambient CO₂ concentrations in the laboratory by expressing changes in the chamber air in terms of percentages of initial CO₂ concentration recorded over time.

2.5. **Other plant parameters**

The efficiency of the CO₂ removal capacities of the test species was also calculated per plant leaf areas, which were measured using a leaf area meter. Shoot fresh weights, and dry weights after 24 h in a hot-air oven at 65°C, were also used in the comparisons.

2.6. **Data analysis**

Means and standard errors of the means (SEMs) were calculated for CO₂ removal data for every species from each light acclimatisation regime. LRCs for all species are presented as graphs, as were the results from the PPM test chamber trials. From the data CO₂ removal was calculated per day (24 h illumination). To determine whether the acclimatisation regimes gave significantly different results when plants were tested at the two or three test light intensities, removal rates were taken as being significantly different if the 95% confidence intervals for the mean values did not overlap. CO₂ removal capacities were also calculated on the basis of leaf area, and leaf fresh and dry weights.
3. Results and discussion

3.1. Leaf-measured CO2 fluxes

3.1.1 Light response curves

The set of LRC graphs for the 9 species are presented in Figures 3 to 11. In 7 of the species from the glasshouse regime, and in 3 species from laboratory-acclimatisation, CO2 removal rates (μmol CO2 m⁻² leaf area s⁻¹), continued to rise with increasing light intensities up to 2000 μmol m⁻² s⁻¹. These results indicate a general short-term ability to respond right up to the intensity of full sunlight. However, in C. elegans (Fig. 9) removal rates in the laboratory-acclimatised plants were higher than in those from the glasshouse throughout the sequence of light intensities, and the maximum removal rate in this species was recorded at 1000 μmol m⁻² s⁻¹, followed by a decline at 2000 μmol m⁻² s⁻¹. These responses indicated acute photoinhibition at the highest intensity, and a chronic photoinhibition from being kept in the glasshouse, apparently moderate though its light regime was. Higher rates of removal in laboratory-acclimatised plants were also found in Ag. commutatum (Fig. 10), however this species did not show any acute photoinhibition at the highest intensity. D. ‘Compacta’ plants from glasshouse-acclimatisation (Fig. 11) showed one of the lowest CO2 removal rates at 2000 μmol m⁻² s⁻¹, but third highest in removal rates among plants with laboratory-acclimatisation, which indicates photoinhibition under glasshouse conditions; however no CAM-type shut-down response was evidenced.

A summary comparison of LRCs among the 9 species is presented in Table 2. Overall the LRCs were significantly lower in laboratory-acclimatised plants than in those from the glasshouse treatment, with reductions in CO2 removal of often 50% or more in laboratory-held plants. In other words, considerable down-regulation of photosynthetic activity was evidenced from the LRCs from the two acclimatisation regimes. In all species, from both acclimatisation regimes, the rises in the rates of CO2 removal started to slope off at about 50 μmol m⁻² s⁻¹ (Figs. 3-11). In 7 of the 9 species (exceptions being H. forsteriana and Ca. australis) at 350 μmol m⁻² s⁻¹, plants from the glasshouse regime showed removal rates that were 50% or more of their maximum rates, and for laboratory-kept plants rates were 60% or more of their maximum rates. That is, for most species and light treatments removal rates were approaching light saturation values at that intensity. The differences in LRCs from the two light-acclimatisation regimes suggest that, for most of the species, a possible management technique for maximising indoor CO2 removal would be to rotate plants back to the nursery glasshouse on a regular basis for periods of up-regulatory recovery, though that would presumably be a costly means of achieving the desired result.

Most of the CO2 removal rates obtained in these leaf-based trials are very small compared with those reported for many high-light plants, e.g. rice cultivars (27-37 μmol CO2 m⁻² s⁻¹; Bacarin et al., 2008); the Mopane tree (15–22 μmol m⁻² s⁻¹; Veenendall et al., 2008); Eucalyptus grandis (20–25 μmol m⁻² s⁻¹) or Grevillea robusta (11–14 μmol m⁻² s⁻¹) (Shem et al., 2009). However, they are in the same range as recorded for an understorey population of Quercus ilex (evergreen or holly oak) (0.5–3 μmol m⁻² s⁻¹), and for other indoor species, e.g. Philodendron spp. (1.4–6.3 μmol m⁻² s⁻¹) (Giorgioni and Neretti, 2009).
Table 2: From leaf-based LRCs, comparisons of maximum net CO₂ removal (µmol CO₂ m⁻² s⁻¹) in 9 test species; and light compensation points (LCPs) (µmol m⁻² s⁻¹) under the two acclimatisation regimes, glasshouse (GH) and laboratory (Lab). (Means ± SEM; n = 16).

<table>
<thead>
<tr>
<th>Species/PAR / CO₂ removal – (µmol m⁻² s⁻¹)</th>
<th>2000 GH</th>
<th>2000 Lab</th>
<th>350 GH</th>
<th>350 Lab</th>
<th>LCP GH</th>
<th>LCP Lab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acclimatisation regime</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>D. lutescens</strong></td>
<td>7.18±0.80</td>
<td>4.21±1.13</td>
<td>3.86±1.10</td>
<td>1.77±1.14</td>
<td>3.2</td>
<td>1.8</td>
</tr>
<tr>
<td><strong>F. benjamina</strong></td>
<td>5.37±0.21</td>
<td>3.14±1.43</td>
<td>1.51±0.01</td>
<td>0.38±0.10</td>
<td>5.3</td>
<td>1.8</td>
</tr>
<tr>
<td><strong>As. elator</strong></td>
<td>2.90±0.60</td>
<td>2.00±0.70</td>
<td>2.15±0.70</td>
<td>1.40±0.67</td>
<td>2.2</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>H. forsteriana</strong></td>
<td>2.45±0.34</td>
<td>0.40±0.28</td>
<td>1.45±0.30</td>
<td>0.36±</td>
<td>4.3</td>
<td>9.0</td>
</tr>
<tr>
<td><strong>Ca. australe</strong></td>
<td>2.43±0.21</td>
<td>0.44±0.11</td>
<td>1.5±0.01</td>
<td>0.38±0.10</td>
<td>4.1</td>
<td>9.1</td>
</tr>
<tr>
<td><strong>C. elegans</strong></td>
<td>2.25±0.37</td>
<td>*3.35±0.35 (at 1000 PAR)</td>
<td>1.90±0.33</td>
<td>2.25±0.27</td>
<td>2.7</td>
<td>2.4</td>
</tr>
<tr>
<td><strong>Ag. commutatum</strong></td>
<td>1.25±0.32</td>
<td>*1.86±0.16</td>
<td>0.49±0.19</td>
<td>1.05±0.14</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td><strong>D. ‘Compacta’</strong></td>
<td>1.50±0.27</td>
<td>0.78±0.20</td>
<td>0.83±0.16</td>
<td>0.43±0.15</td>
<td>14.5</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>A. robusta</strong></td>
<td>0.71±0.78</td>
<td>0.40±1.1</td>
<td>0.37±1.1</td>
<td>0.48±1.1</td>
<td>5.8</td>
<td>8.0</td>
</tr>
</tbody>
</table>

3.1.2 Leaf based light compensation points
The leaf-chamber based light compensation points (LCPs) (intensity at which CO₂ flux equals zero) in glasshouse-acclimatised plants of 8 of the species were below 6 µmol m⁻² s⁻¹. D. ‘Compacta’ was the exception, recording an LCP of 14.5 µmol m⁻² s⁻¹. For laboratory-acclimatised plants, 7 of the 9 species had LCP values below 2.5 µmol m⁻² s⁻¹. The remaining species however, H. forsteriana and Ca. australe, had values that were higher than those for the glasshouse-acclimatised treatment, the low-light acclimatisation seeming to dampen initial light response in these species. Values for LCPs of ≤ 2 µmol m⁻² s⁻¹ are at or below one thousandth the intensity of full sunlight – i.e. photosynthesis is initiated and net CO₂ reduction accomplished just a fraction above darkness. In general these values are comparable with those reported for leaf-based measurements of other understory species, e.g. weed species under a eucalypt plantation with LCPs of from 4.85 to 7.14 µmol m⁻² s⁻¹, and light saturation points of only 155 to 237 µmol m⁻² s⁻¹ (Shem et al., 2008).

The last 6 species listed in Table 2 recorded maximum removal rates ranging from 1.5 to 2.9 µmol CO₂ m⁻² s⁻¹. The values were only about 50% of that of F. benjamina, and 40% of the reductions recorded in D. lutescens. Considered in isolation, the results could be taken to indicate that these top three species would be the most suitable choice for development for indoor CO₂ reduction. But data from leaf-chamber tests do not take into account the continuous respiratory CO₂ emissions of the non-green plant parts and the potting mix microbiota, which together play a major role in determining the net CO₂ removal capability of the potted-plant microcosm as a whole. The results from the whole-pot-and-plant chamber trials, described in the next section, show a rather different situation from that suggested by the leaf data alone.
Figure 3. Light response curves of *Dracaena lutescens* from two light-acclimatisation treatments, glasshouse (GH) and laboratory (LAB). (Means ±SEM; n=16)

Figure 4. Light response curves of *Agathis robusta* from two light-acclimatisation treatments, glasshouse (GH) and laboratory (LAB). (Means ±SEM; n=16)
Figure 5. Light response curves of *Ficus benjamina* from two light-acclimatisation treatments, glasshouse (GH) and laboratory (LAB). (Means ±SEM; n=16)

Figure 6. Light response curves of *Aspidistra elator* from two light-acclimatisation treatments, glasshouse (GH) and laboratory (LAB). (Means ±SEM; n=16)
Figure 7. Light response curves of *Howea forsteriana* from two light-acclimatisation treatments, glasshouse (GH) and laboratory (LAB). (Means ±SEM; n=16)

Figure 8. Light response curves of *Castanospermum australe* from two light-acclimatisation treatments, glasshouse (GH) and laboratory (LAB). (Means ±SEM; n=16)
Figure 9. Light response curves of *Chamaedorea elegans* from two light-acclimatisation treatments, glasshouse (GH) and laboratory (LAB). (Means ±SEM; n=16)

Figure 10. Light response curves of *Aglaonema commutatum* from two light-acclimatisation treatments, glasshouse (GH) and laboratory (LAB). (Means ±SEM; n=16)
1.1. Measurement of whole-potted-plant CO₂ fluxes

3.2.3 Estimating critical light intensities
The aims of this component of the study were to compare whole plant responses to the highest and lowest levels of indoor light intensities (PAR), and to estimate the light intensity (PAR) at which the photosynthetic CO₂ removal of the plant shoots would be exactly balanced by the respiratory CO₂ emissions of the non-green plant parts and the potting mix microorganisms. At this light intensity there would be no change in the CO₂ concentration in a test chamber containing the potted-plant; it is thus the critical intensity which must be exceeded with this species to achieve any net CO₂ removal, i.e. the potted-plant microcosm’s light compensation point, PPM-LCP. From the results of our preliminary studies with other species (Burchett et al., 2009; Brennan, 2011), we expected that at 10 µmol m⁻² s⁻¹ the CO₂ concentrations in the test chamber were likely to show little change over the test period (40 min). However, where an increase in chamber CO₂ concentrations of more than 2% were recorded during the test period (i.e. rates of respiratory emissions were exceeding rates of CO₂ removal), plants were tested at a third light intensity which from the leaf-chamber data it was indicated might result in positive CO₂ reductions. The results of these trials for each species are presented in Figures 12–20.

3.2.4 CO₂ removal per potted-plant
Figures 12-20 show that, as anticipated, potted-plants tested under 350 µmol m⁻² s⁻¹ generally showed significant net PPM CO₂ removal, but at 10 µmol m⁻² s⁻¹ tended to show little change in chamber CO₂ concentration over the 40 min test period. The first species presented, H. forsteriana (Fig. 12), was tested at only two light intensities, since it showed almost zero change in chamber CO₂ concentration under this low-light test condition, from either light-acclimatisation regime. With C. elegans (Fig. 13), a more than 2% increase in CO₂ concentration was recorded in the glasshouse-acclimatised plants under 10 µmol m⁻² s⁻¹. This group was therefore also tested at 20 µmol m⁻² s⁻¹, where a zero change in CO₂ concentration
was recorded. For the remaining species also, results for two or three light intensities were tested as indicated in the graphs.

Table 3 presents a summary comparison of results from these trials, with values expressed as mg CO$_2$ removed/ PPM/d (24 h illumination). Table 3 also shows estimates for PPM-LCPs for each species and light acclimatisation regime, i.e. the critical PAR light intensity that must be exceeded for net CO$_2$ removal by the potted-plant unit to be achieved.

Of the laboratory-acclimatised plants, 4 of the 9 species showed greater CO$_2$ removals at this intensity than did those from the glasshouse treatment. However, only the first two species listed, *H. forsteriana* and *C elegans*, showed net CO$_2$ removal from both acclimisation treatments under 10 µmol m$^{-2}$ s$^{-1}$, and of glasshouse-acclimatised plants only one species, *A. robusta*, showed net CO$_2$ removal under this low intensity.

The three palm species, *H. forsteriana*, *C. elegans* and *D. lutescens* (Figs. 12, 13, 14) performed consistently well, and had among the lowest estimated PPM LCPs. Also, although *Ca. australe* is categorised by the horticultural industry as a medium/high-light plant (Table 1), this species (Fig 15) on the whole showed a good response to low indoor light conditions, with low PPM-LCPs. On the other hand, *As. Elator* and *Ag. commutatum* (Figs. 16,17), although known to be able to ‘survive under a stairwell’, did not show positive removal responses when laboratory-acclimatised and tested at 10µmol m$^{-2}$ s$^{-1}$. *F. benjamina* (Fig. 18) performed adequately at a third test light level of 30 µmol m$^{-2}$ s$^{-1}$. But the results for *A. robusta* (Fig. 20) suggest it would be unsuitable for long-term indoor use for CO$_2$ remediation, having too high a light requirement to stay in condition for extended periods indoors. *D. ‘Compacta’* (Fig. 19) is also regarded as a reliable plant for very low-light situations, but it appeared to require higher light levels than all other species apart from *A. robusta* to start to achieve net CO$_2$ removal. However, this species was later confirmed to have a smaller surface area than most of the other species, and when removal performances for all species were computed per unit leaf area, perspectives changed once more, as discussed below.

The estimated PPM-LCPs are tentative only, requiring further investigation. However they provide some interim guidelines for minimum intensities which should be exceeded, whether attained by positioning or by specific plant lighting installation.
Table 3: Calculated CO$_2$ removal rates (mg) per potted-plant microcosm [PPM] per day (lit 24 h), at 2 test light levels, after acclimatisation at 2 light regimes, glasshouse (GH) and laboratory (Lab); and the estimated likely critical light intensity (PPM light compensation point [LCP]) ($\mu$mol PAR m$^{-2}$ s$^{-1}$) which must be exceeded for consistent CO$_2$ removal under indoor conditions. (Means±SEM; n=4)

<table>
<thead>
<tr>
<th>Species</th>
<th>Acclim. Cond.</th>
<th>PAR (Near Saturating)</th>
<th>mg CO$_2$ removed/ PPM/d</th>
<th>PAR Low/ Var.</th>
<th>mg CO$_2$ removed/ PPM/d</th>
<th>Estimated ‘PPM LCP’ PAR ($\mu$mol m$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>H. forsteriana</em></td>
<td>GH</td>
<td>350</td>
<td>3685±0.04</td>
<td>10</td>
<td>-228±0.04</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Lab</td>
<td>350</td>
<td>*4025±0.04</td>
<td>10</td>
<td>*93±0.04</td>
<td>&lt;10</td>
</tr>
<tr>
<td><em>C. elegans</em></td>
<td>GH</td>
<td>350</td>
<td>2840±0.04</td>
<td>20</td>
<td>88±0.04</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Lab</td>
<td>350</td>
<td>2640±0.04</td>
<td>10</td>
<td>*125±0.04</td>
<td>10</td>
</tr>
<tr>
<td><em>D. lutescens</em></td>
<td>GH</td>
<td>350</td>
<td>2755±0.04</td>
<td>10</td>
<td>-173±0.04</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Lab</td>
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<td>1825±0.04</td>
<td>10</td>
<td>-112±0.04</td>
<td>20</td>
</tr>
<tr>
<td><em>Ca. australi</em></td>
<td>GH</td>
<td>350</td>
<td>867±0.04</td>
<td>10</td>
<td>45±0.04</td>
<td>10</td>
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<tr>
<td></td>
<td>Lab</td>
<td>350</td>
<td>*1425±0.04</td>
<td>20</td>
<td>-127±0.04</td>
<td>25</td>
</tr>
<tr>
<td><em>As. elator</em></td>
<td>GH</td>
<td>350</td>
<td>1410±0.04</td>
<td>25</td>
<td>170±0.04</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Lab</td>
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<td>*2160±0.04</td>
<td>20</td>
<td>-125±0.04</td>
<td>25-30</td>
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<td><em>Ag. commutatum</em></td>
<td>GH</td>
<td>350</td>
<td>1150±0.04</td>
<td>25</td>
<td>69±0.04</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Lab</td>
<td>350</td>
<td>*1760±0.04</td>
<td>10</td>
<td>-63±0.04</td>
<td>25</td>
</tr>
<tr>
<td><em>F. benjamina</em></td>
<td>GH</td>
<td>350</td>
<td>1125±0.04</td>
<td>30</td>
<td>130±0.04</td>
<td>25</td>
</tr>
<tr>
<td></td>
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<td>445±0.04</td>
<td>30</td>
<td>-46±0.04</td>
<td>35</td>
</tr>
<tr>
<td><em>D. ‘Compacta’</em></td>
<td>GH</td>
<td>350</td>
<td>2060±0.03</td>
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<td>126±0.04</td>
<td>50</td>
</tr>
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<td>Lab</td>
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<td>795±0.04</td>
<td>50</td>
<td>98±0.04</td>
<td>50</td>
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<tr>
<td><em>A. robusta</em></td>
<td>GH</td>
<td>350</td>
<td>1350±0.04</td>
<td>50</td>
<td>-31±0.04</td>
<td>&gt;&gt;60</td>
</tr>
<tr>
<td></td>
<td>Lab</td>
<td>350</td>
<td>317±0.04</td>
<td>270</td>
<td>*102±0.04</td>
<td>&gt;&gt;60</td>
</tr>
</tbody>
</table>

*CO$_2$ removal greater in laboratory-acclimatised plants than from the glasshouse treatment.
Figure 12. Changes in test-chamber CO$_2$ concentrations in (a) glasshouse and (b) laboratory acclimatised *Howea forsteriana* plants, sampled at 10 and 350 μmol m$^{-2}$s$^{-1}$. (Means ± SEM; n=4).
Figure 13. Changes in test-chamber CO$_2$ concentrations in (a) glasshouse and (b) laboratory acclimatised Chamaedorea elegans plants, sampled at 10, 20 and 350 μmol m$^{-2}$ s$^{-1}$. (Means ± SEM; n=4).
Figure 14. Changes in test-chamber CO\(_2\) concentrations in (a) glasshouse and (b) laboratory acclimatised Dracaena lutescens plants, sampled at 10 and 350 \(\mu\)mol m\(^{-2}\) s\(^{-1}\). (Means ± SEM; n=4).
Figure 15. Changes in test-chamber CO₂ concentrations in (a) glasshouse and (b) laboratory acclimatised *Castanospermum austral* plants, sampled at 10, 20 and 350 µmol m⁻² s⁻¹. (Means ± SEM; n=4).
Figure 16. Changes in test-chamber CO₂ concentrations in (a) glasshouse and (b) laboratory acclimatised *Aspidistra elator* plants, sampled at 10 and 350 µmol m⁻² s⁻¹. (Means ± SEM; n=4).
Figure 17. Changes in test-chamber CO₂ concentrations in (a) glasshouse and (b) laboratory acclimatised Aglaonema commutatum plants, sampled at 10 and 350 μmol m⁻² s⁻¹. (Means ± SEM; n=4).
Figure 18. Changes in test-chamber CO$_2$ concentrations in (a) glasshouse and (b) laboratory acclimatised Ficus benjamina plants, sampled at 10 and 350 µmol m$^{-2}$s$^{-1}$. (Means ± SEM; n=4).
Figure 19. Changes in test-chamber CO₂ concentrations in (a) glasshouse and (b) laboratory acclimatised *Dracaena deremensis* ‘Compacta’ plants, sampled at 10, 50 and 350 μmol m⁻² s⁻¹. (Means ± SEM; n=4).
Figure 20. Changes in test-chamber CO₂ concentrations in (a) glasshouse and (b) laboratory acclimatised *Agathis robusta* plants, sampled at 10, 50 or 270, and 350 μmol m⁻² s⁻¹. (Means ± SEM; n=4).
3.2.5 \textit{CO}_2 \text{removal per unit leaf area}

The universal functional unit of interior plant horticulture is the potted-plant, of a size indicated from its pot diameter (150, 200, 300 mm, etc.). But since \text{CO}_2 removal is achieved solely by the green shoots of the plant, performance needs to be measured in terms of \text{CO}_2 removal per unit leaf area. Table 4 presents leaf areas for all species, and data from the whole-chamber trials (Figs. 12-20) expressed as net mg \text{CO}_2 removed per m$^2$ leaf area per day (lit 24 h). On this basis of calculation \textit{D. lutescens} appears to be the most effective species, with a maximum net \text{CO}_2 removal rate under an intensity of 350 \textmu mol m$^{-2}$ s$^{-1}$ that was one third higher than that of \textit{D. ‘Compacta’} in second place, and more than twice as high as the third-placed species, \textit{A. elator}. The result for \textit{D. ‘Compacta’} suggests that the small \text{CO}_2 removal rates recorded for this species on a per PPM basis (Table 3) are in part explained by its comparatively small leaf area. \textit{D. lutescens} has a similarly small leaf area and its removal performance was the highest recorded on a leaf area basis. The cellular photosynthesis rates in these species are clearly very high.

Table 4 also presents the number of 200 mm pots of each species needed to provide 1 m$^2$ of leaf surface. The differences in numbers among the species reflect not only their obvious diversity of plant morphology, but also differences in basic leaf physiology. Such functional variation depends in part on factors relating to differences in the photosynthetic apparatus \textit{per se}, but also arises from variables such as density and size of the stomates, and other leaf surface attributes affecting gaseous diffusion rates into the leaf, together with the efficacy of the diffusion pathways among the cells inside the leaf.

The \text{CO}_2 removal performance data based on leaf areas have practical implications for the design of interior plantscape installations, both of potted arrangements and of vertical gardens/plant walls, the latter having continuous supporting fabric and hydroponics flows rather than comprising discrete pots of standard sizes.
Table 4: Leaf areas and calculated CO₂ removal rates per m² leaf area per day (mg/m²²/d) (lit 24 h), at 2 test light levels, after acclimatisation at 2 light regimes, glasshouse (GH) and laboratory (Lab); and number of plants needed per m² leaf area. (Means±SEM; n=4)

<table>
<thead>
<tr>
<th>Species</th>
<th>Acclim. Cond.</th>
<th>Leaf area (m²)</th>
<th>PAR (Near Saturat-ing)</th>
<th>mg CO₂ removed/ m² leaf/d</th>
<th>PAR Low/ Var.</th>
<th>mg CO₂ removed/ m² leaf/d</th>
<th>No. 200 mm pots for 1 m² leaf area</th>
</tr>
</thead>
<tbody>
<tr>
<td>D. lutescens</td>
<td>GH</td>
<td>0.211±0.02</td>
<td>350</td>
<td>13035±1.7</td>
<td>10</td>
<td>-821±1.8</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>Lab</td>
<td>350</td>
<td>8640±1.8</td>
<td>10</td>
<td>-529±1.8</td>
<td></td>
<td>&quot;</td>
</tr>
<tr>
<td>D. ‘Compacta’</td>
<td>GH</td>
<td>0.216±0.02</td>
<td>350</td>
<td>9525±2.2</td>
<td>50</td>
<td>585±2.3</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>Lab</td>
<td>350</td>
<td>3675±2.3</td>
<td>50</td>
<td>-452±2.4</td>
<td></td>
<td>&quot;</td>
</tr>
<tr>
<td>As. elator</td>
<td>GH</td>
<td>0.233±0.06</td>
<td>350</td>
<td>6095±0.63</td>
<td>25</td>
<td>728±0.63</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>Lab</td>
<td>350</td>
<td>9270±0.62</td>
<td>20</td>
<td>-538±0.65</td>
<td></td>
<td>&quot;</td>
</tr>
<tr>
<td>F. benjamina</td>
<td>GH</td>
<td>0.208±0.02</td>
<td>350</td>
<td>5410±2.2</td>
<td>30</td>
<td>625±2.0</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>Lab</td>
<td>350</td>
<td>2140±2.2</td>
<td>30</td>
<td>-221±2.2</td>
<td></td>
<td>&quot;</td>
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<tr>
<td>H. forsteriana</td>
<td>GH</td>
<td>0.745±0.10</td>
<td>350</td>
<td>4945±0.36</td>
<td>10</td>
<td>-307±0.37</td>
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<tr>
<td></td>
<td>Lab</td>
<td>350</td>
<td>5405±0.36</td>
<td>10</td>
<td>125±0.36</td>
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</tr>
<tr>
<td>A. robusta</td>
<td>GH</td>
<td>0.409±0.03</td>
<td>350</td>
<td>3300±1.4</td>
<td>50</td>
<td>-76±1.4</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Lab</td>
<td>350</td>
<td>775±1.5</td>
<td>270</td>
<td>249±1.4</td>
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<td>&quot;</td>
</tr>
<tr>
<td>Ag. commutatum</td>
<td>GH</td>
<td>0.454±0.02</td>
<td>350</td>
<td>2535±1.9</td>
<td>25</td>
<td>185±0.59</td>
<td>2.2</td>
</tr>
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<td></td>
<td>Lab</td>
<td>350</td>
<td>3882±1.9</td>
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<td>-137±1.9</td>
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<td>&quot;</td>
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<tr>
<td>C. elegans</td>
<td>GH</td>
<td>1.240±0.05</td>
<td>350</td>
<td>2290±0.79</td>
<td>20</td>
<td>71±0.80</td>
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<tr>
<td></td>
<td>Lab</td>
<td>350</td>
<td>2130±0.80</td>
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<td>101±0.76</td>
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<td>Ca. australe</td>
<td>GH</td>
<td>0.524±0.06</td>
<td>350</td>
<td>1655±0.56</td>
<td>10</td>
<td>86±0.59</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>Lab</td>
<td>350</td>
<td>2720±0.58</td>
<td>20</td>
<td>-242±0.59</td>
<td></td>
<td>&quot;</td>
</tr>
</tbody>
</table>

3.2.6 CO₂ removal per unit shoot weight
Since photosynthetic CO₂ removal is directly proportional to leaf area for a given species under the same environmental conditions, potted-plant net CO₂ removal results (Table 3) can also be calculated on the basis of rates per unit fresh or dry weight of leaf tissue (Table 5). Once removal rates per leaf area and leaf weights have been determined for the species, shoot weights from other specimens of the same maturity can presumably offer a simple method for industry to estimate leaf area. Direct leaf area measurements require either more tedious methods or specialised instrumentation. Fresh weight/dry weight ratios are also included in Table 5, the values indicating something of the water content/succulence of the foliage, and conversely the amounts of fibrous tissue in the leaf structure. Fresh weights depend not only on the basic leaf structure in the species, but also on the level of hydration at the time of weighing. Potted-plants need to be watered and allowed to drain before excising for weight estimation, so that consistent results can be assured.
Table 5: Fresh weights (FWT), dry weights (DWT) and FWT/DWT ratios of shoots, and mg CO$_2$ removed/g FWT/d, and g DWT/d (lit 24 h) for 9 species, for plants acclimatised under two light regimes and tested selected light intensities. (Means ± SEM; n = 4)

<table>
<thead>
<tr>
<th>Species</th>
<th>Accli. Cond.</th>
<th>PAR</th>
<th>FWT/shoot</th>
<th>mg CO$_2$ removed/g FWT/d</th>
<th>DWT/shoot</th>
<th>mg CO$_2$ removed/g DWT/d</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>D. lutescens</em></td>
<td>GH 350</td>
<td>32±3.6</td>
<td>86±9.7</td>
<td>11±0.7</td>
<td>245±15</td>
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<tr>
<td></td>
<td>Lab 350</td>
<td>57±6.4</td>
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</tr>
<tr>
<td></td>
<td>GH 10</td>
<td>-5.4±0.6</td>
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<td>-15.5±0.9</td>
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</tr>
<tr>
<td></td>
<td>Lab 10</td>
<td>-3.5±0.4</td>
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<td>-10.0±0.6</td>
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<tr>
<td><em>D. ‘Compacta’</em></td>
<td>GH 350</td>
<td>77±5.7</td>
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<td>11.5±0.8</td>
<td>181±13.5</td>
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<tr>
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<td>70±5.2</td>
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<td></td>
<td>GH 50</td>
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<tr>
<td></td>
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<tr>
<td><em>As. elator</em></td>
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<td></td>
<td>19±1.8</td>
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<tr>
<td></td>
<td>Lab 30</td>
<td>-1.3±0.1</td>
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<td></td>
<td>-6.7±0.7</td>
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</tr>
<tr>
<td><em>H. forsteriana</em></td>
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<td>69±9.7</td>
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<td>40±5.6</td>
<td>93±13</td>
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<tr>
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<td>59±8.3</td>
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<tr>
<td></td>
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<td>-5.8±0.8</td>
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<tr>
<td></td>
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<tr>
<td><em>A. robusta</em></td>
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<tr>
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<td>10±0.7</td>
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<tr>
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<td>GH 50</td>
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<tr>
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<tr>
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</tr>
<tr>
<td></td>
<td>GH 20</td>
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</tr>
<tr>
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<td></td>
<td>3.0±0.4</td>
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</tr>
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<td><em>Ca. australis</em></td>
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<td>132±15</td>
<td>6.5±0.8</td>
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</tr>
<tr>
<td></td>
<td>Lab 350</td>
<td>3.8±0.4</td>
<td></td>
<td></td>
<td>11±1.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GH 10</td>
<td>0.1±0.0</td>
<td></td>
<td></td>
<td>0.3±0.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lab 20</td>
<td>-0.3±0.0</td>
<td></td>
<td></td>
<td>-1.0±0.1</td>
<td></td>
</tr>
</tbody>
</table>
3.3. **Summary of findings**

It is well established in plant science literature that every species and cultivar has its idiosyncratic photosynthetic characteristics. The goal of this study was to profile these characteristics in the 9 test indoor species, from two light-acclimatisation regimes, by measuring their responses to exposure to a range of test light intensities (PAR).

3.3.1 **Leaf-chamber estimates of CO₂ fluxes**

Leaf-chamber measurements of CO₂ fluxes with IRGA instrumentation are very useful for providing comparisons of photosynthetic performance among different species, and/or within one species under a range of different environmental conditions. Both types of comparison were investigated in the leaf-chamber trials (Table 2, Figs 3-11). The main findings were as follows:

- Eight the 9 species, in the short-term (minutes) tested, responded by increasing CO₂ removal rates with increasing light intensities up to the equivalent of full sunlight (2000 µmol m⁻² s⁻¹);

- however, the majority of species, from either light acclimation regime, reached some 50-65% of maximum CO₂ removal rates at a test light intensity of 350 µmol m⁻² s⁻¹, which in not surprising in ‘indoor’, shade tolerant plants;

- at 350 µmol m⁻² s⁻¹ every species showed different maximum removal rates, values from the glasshouse-acclimatised treatment ranging from 1.5 to 7.2 µmol CO₂ removed m⁻² s⁻¹, and in the laboratory-acclimatised group from 0.4 to 4.2 µmol CO₂ m⁻² s⁻¹. The results add information on the species-specific diversity of indoor plant photosynthetic capabilities;

- all but 2 species showed significant down-regulation of photosynthetic activity when acclimatised indoors. The exceptions were *C. elegans* and *Ag. commutatum*, which displayed greatest shade tolerance, or extreme sensitivity to high light;

- the mean LCP for glasshouse-treated plants of 8 species (i.e. apart from *D. ‘Compacta’*) was 3.7 µmol m⁻² s⁻¹, and for laboratory-acclimatised plants, 4.0 µmol m⁻² s⁻¹. The results indicate that in these species the light-acclimatisation conditions have little effect on altering LCP values, although in individual species indoor-acclimatisation could produce either a small increase or decrease in the critical intensity.
3.3.2 Whole-potted-plant chamber estimates of CO₂ removal

Leaf-based values for CO₂ removal rates and LCPs do not provide a direct indication of net CO₂ fluxes of the plant as a whole because they do not measure respiratory emissions from other tissues or root-zone microorganisms. Whole-potted-plant test-chamber trials are therefore also essential in investigating CO₂ fluxes in the PPM. The results (Table 3, Figs. 12-20) showed that:

- at a test intensity of 350 µmol m⁻² s⁻¹ all species, from both acclimatisation regimes, showed significant CO₂ removal, the three top performing species being the three palms, *H. forsteriana*, *D. lutescens* and *C. elegans*;
- at 350 µmol m⁻² s⁻¹ 4 of the 9 species showed higher removal levels in the laboratory-acclimatised treatment than from the glasshouse;
- at a test intensity of 10 µmol m⁻² s⁻¹, plants of 6 species from the glasshouse regime showed net CO₂ removal, although at levels only about one tenth those obtained from tests under 350 µmol m⁻² s⁻¹;
- at 10 µmol m⁻² s⁻¹, plants of only 4 species from the laboratory regime showed net CO₂ removal; and at this test intensity only 1 species, *D. ‘Compacta’*, showed net CO₂ removal in plants from both acclimatisation regimes. *H. forsteriana* and *C. elegans* showed CO₂ removal in the laboratory-acclimatised groups, and *C. australe* in the glasshouse-acclimatised plants; all other species required a third, somewhat higher intensity (generally 20 – 50 µmol m⁻² s⁻¹) for CO₂ removal to be achieved from either light-acclimatisation regime.

3.3.3 Potted-plant CO₂ removal per unit leaf area and weight

The CO₂ removal by any plant is directly proportional to the area of healthy mature leaves. When calculated on the basis of CO₂ removal per m² leaf area (Table 4), the comparative performances of the 9 species appear quite different from those computed on a per PPM basis (Table 3). As well, the values for leaf areas per plant, or numbers of pots needed to provide 1m² leaf area, further revealed the differences in photosynthetic activity or efficiency among the test species.

As a final step, a correlation analysis was performed for the factors of CO₂ removal per plant, light intensity, leaf area per plant, and fresh and dry weights of the plants (Table 6). No statistically significant, taxonomically independent relationships were detected between leaf area, fresh weight or dry weight, and CO₂ removal, adding further confirmation that species-specific behaviour is the primary determinant of photosynthetic capacity indoors, as in natural habitats. Perhaps more surprisingly, across all species, acclimatisation conditions and test light levels, there was also no correlation between light level and photosynthetic rate, which again emphasises the centrality of species-specific behaviour in determining CO₂ removal capacity and responses. For ease of comparison, Figure 21 presents in summary form the PPM CO₂ fluxes for all species and both acclimatisation treatments at every test light intensity applied. Overall the results of the tests reinforce the conclusion that the CO₂ removal responses of any species cannot be predicted; they must to be empirically tested.
Table 6: Pearson product moment correlation analyses for associations between mean CO$_2$ removal rate and mean plant size variables. Data are the correlation coefficients above the p-value. FWT: fresh weight; DWT: dry weight.

<table>
<thead>
<tr>
<th>Variable</th>
<th>DWT/plant</th>
<th>Light level for test</th>
<th>Leaf area/plant</th>
<th>mg CO$_2$ removed/plant/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWT/plant</td>
<td>0.913</td>
<td>0.012</td>
<td>0.344</td>
<td>-0.071</td>
</tr>
<tr>
<td></td>
<td>0.000</td>
<td>0.937</td>
<td>0.017</td>
<td>0.630</td>
</tr>
<tr>
<td>DWT/plant</td>
<td>—</td>
<td>0.012</td>
<td>0.348</td>
<td>-0.007</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>0.937</td>
<td>0.015</td>
<td>0.961</td>
</tr>
<tr>
<td>Light level for test</td>
<td>—</td>
<td>—</td>
<td>0.013</td>
<td>0.812</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>—</td>
<td>0.929</td>
<td>0.000</td>
</tr>
<tr>
<td>Leaf area/plant</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.212</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.147</td>
</tr>
<tr>
<td>mg CO$_2$ removed/plant/h</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
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</table>
Figure 21. Potted-plant test-chamber CO₂ removal (µmol CO₂ m⁻² s⁻¹), in laboratory and glasshouse acclimatised plants of 9 species, tested at various light intensities (µmol m⁻² s⁻¹). (Means ± SEM; n = 4)
4. Significant to industry

The installation of ‘vertical gardens’, ‘living walls’, ‘plant walls’, ‘green walls’ or ‘green zones’ are underway in the developed world (e.g. Darlington et al., 2000; BEDP, 2009). The major emphasis for such living structures to date has been for their beneficial aesthetic and psychological purposes, although there is also now a growing appreciation that they have air cleansing properties as well. The German company, Indoor Landscaping, describes their plant-wall work as “a connection between man, enclosed spaces and open nature... Nature should become tangible for people even within buildings; our plants change with the seasons, they age within the architecture enhanced in character and charm...[with plantings] which clean the air, create sound barriers and obviously have an amazing visual impact” (Oppenheim, 2010). More flexible installations based on potted-plant groupings, in walls or towers of shelves, or in ‘hedges’ along filing cabinets or other space dividers, can be utilised to achieve similar results (Figures 21, 22). As Birkeland (2009) puts it, ‘eco-retrofitting’ can be used to redesign our city spaces to achieve sustainable urban settlements of the future. Such retrofits can be constructed more effectively when appropriate indoor plants can be matched with appropriate indoor lighting conditions, so as to attain significant reductions in HVAC power consumption, along with other air-cleansing plant functions.

The technology of lighting systems for interior plant cultivation is already highly advanced, especially in the northern hemisphere, because of the need for continuous greenhouse cultivation of fruit, vegetable and ornamental crops (Massa et al., 2008; Hogewoning et al., 2010; Nederhoff, 2011). The glasshouse and tissue culture growth cabinet lighting technology could readily be developed and applied to the light intensity needs of indoor plantings in urban buildings, since any lighting, particularly with targeted broad-spectrum LED lighting for indoor plantings, would require orders of magnitude less energy than HVAC systems consume to provide the same amount of air freshening.

Such eco-retrofits would make a significant contribution to the triple bottom line of sustainability in Australia and elsewhere – i.e. for environmental, social and economic benefit (Wu et al., 2008; Weinmaster, 2009; Yeh and Chung, 2009; Kolokotsa et al., 2010). The lighting requirements could be fulfilled by lighting frames over the plant installations, either mobile or wall/ceiling mounted. The financial cost of installing such arrangements, and maintaining the plants, would together be far less than for other building fittings.
5. Recommendations for future R&D

Our results, from over 100 offices, indicate that an indoor light intensity of about 10 µmol m\(^{-2}\) s\(^{-1}\) is accepted as adequate for building occupants, though intensities ranged from 5 to 30 µmol m\(^{-2}\) s\(^{-1}\). The results of this study indicate that at the lower end of this range, in a sealed building with an HVAC system the potted-plant microcosm would in general not be able to achieve enough net CO\(_2\) removal to make a significant improvement to indoor air quality. This intensity is only about 5 µmol m\(^{-2}\) s\(^{-1}\) above what the results above showed was the average leaf LCP value across the 9 species tested (Table 2). The estimated PPM-LCPs for 6 the test species, from both light-acclimatisation treatments (Table 3) ranged from 10 to 25 µmol m\(^{-2}\) s\(^{-1}\). Of the remaining 3 species, *F. benjamina* PPM-LCPs were estimated at 25 and 35 µmol m\(^{-2}\) s\(^{-1}\) for the two acclimatisation regimes respectively; for *D. ‘Compacta’*, 50 µmol m\(^{-2}\) s\(^{-1}\); and for *A. robusta*, unknown but considerably over 50 µmol m\(^{-2}\) s\(^{-1}\), since a test intensity of 270 µmol m\(^{-2}\) s\(^{-1}\) resulted in only a modest net CO\(_2\) reduction, in laboratory-acclimatised plants (Table 3). The estimated potted-plant microcosm light compensation points (PPM-CLPs) were from two to ten times higher than those of the leaf-chamber based CLPs (cf Tables 2 and 3).

- The development of indoor plants for routine building CO\(_2\) reduction will involve preliminary individual testing species and varieties of interest.

- Since in plant research investigations, leaf-chamber photosynthetic data are far more commonly reported than data from whole-plant chamber studies, it is suggested that, when testing an untried indoor species, a ‘pot-factor’ of about x10 might be applied to leaf-based CLP data as the putative critical minimum light intensity that would be a suitable starting point for further testing of net CO\(_2\) removal performance of the whole potted-plant microcosm (PPM).

- The shaded glasshouse used here for the higher light-acclimatisation regime, had average intensities of 50-100 µmol m\(^{-2}\) s\(^{-1}\); and the leaf-based light response curves (LRCs, Figures 3-11) on the whole showed steady increases in leaf-chamber CO\(_2\) removal under intensities in the range. Future studies on indoor plant species could well concentrate on CO\(_2\) removal responses in stepped intensities in the range 15 to 100 µmol m\(^{-2}\) s\(^{-1}\).

- To provide a database of plants with their ideal and effective range of light intensities and predicted CO\(_2\) removal rates, which could be used to inform government policy and green building codes etc.

- Collaborative studies of horticulturists with plant lighting engineers and interior designers are indicated, to produce attractive, effective, indoor plant arrangements for retro-fitting our city buildings to reduce their energy and cost loads and the carbon-footprint of the city.
6. Recommendations for Industry

World research, including studies conducted in this laboratory, have demonstrated that indoor plants have strong air cleansing capacities, reducing all types of urban air pollutants including those always found in higher concentrations indoor, namely VOCs and CO\textsubscript{2}. VOC removal is continuous, i.e. in light and dark (24/7). All species we have tested work about equally well, because it is the microorganisms of the potting mix that are the primary agents of VOC removal, the plant contributing nourishment to the microbes – if the plant is healthy the substrate microorganisms will be healthy too. In contrast, CO\textsubscript{2} reduction is accomplished only by green shoots, and only with adequate light, which is very often not adequately supplied for plants indoors. But the results of this study show that the situation for indoor plants can be improved with a moderate increase in lighting levels and suitable spectra, which can be supplied by appropriate use of horticultural fluorescent and/or LED lighting.

Plant walls, hedges, ‘break-out’ zones and the like are gaining recognition as beneficial both to business image and the health and performance of building occupants, and the exigencies of climate change concerns and the need to develop more sustainable cities, are placing more emphasis on seeking innovative, non-polluting solutions. Plant walls etc. can be readily retro-fitted into city buildings with mobile installations and lighting frames. Indoor plants represent a low-cost, non-polluting, easily maintained, element of the built environment that can be developed for maximum benefit to indoor environmental quality and sustainable city functioning. Indoor plant presence has been also shown to improve worker performance by some 12 per cent (Lohr et al., 1996; Knight and Alexander, 2010), which also reduced the cost of plant installation substantially.
7. Technology transfer

The UTS team have been actively involved in technology transfer of information derived from this research. We list activities we have undertaken in association with this project.

**Talks/Seminars**

We have made numerous presentations on our indoor plant research:

- Brisbane meeting of Green Infrastructure Australia (Oct. 2010)
- Gold Coast Conference of the National Interior Plantscape Association (Oct. 2010)
- In January 2011, the research team provided a session at a UTS science summer school for entering year 11 students from disadvantaged areas, the sessions concentrating on the significance of urban plants, and in particular indoor plants. Participants were each given a potted palm at the end of the session, supplied by Ambius.
- We gave approximately 40 radio/magazine interviews associated with the NGIA campaign, launched ‘To improve your plant/life balance’ and the advice to ‘Put a plant on your desk’.
- M. Burchett was interviewed for an article on indoor plants featured in the *Wall Street Journal*.
- F. Torpy and M. Burchett together gave a talk on the topic in June 2011, in the UTS Public Lecture series.
- M. Burchett has been invited to present findings of UTS indoor plant research at the Cities Alive Conference on urban green infrastructure, to be held in Philadelphia Nov/Dec. 2011.

**Industry publications**

Contributions to newsletters of the National Interior Plantscape Association.

**Peer-reviewed international journals**

We are preparing the research material as papers for submission to international scientific journals.

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Résumés of Research Team Members

*Adjunct Prof Margaret Burchett* has over 40 years experience as a plant ecophysiologist, with particular expertise in plant responses to air and soil pollution, and the use of plants to remediate pollution effects. She has produced over 200 publications, in peer-reviewed journals, conference proceedings and professional and industry media. Among other interests, she has for some 15 years led research of the UTS Plants and Indoor Environmental Quality Group in the Faculty of Science.

*Dr Fraser Torpy* is a microbial ecologist with expertise in plant-fungal symbiosis, bioremediation of indoor air quality, clinical mycology, and experimental design and data analysis. He has been a post-doctoral researcher in the UTS Plants and Indoor Environmental Quality group for 10 years. He lectures in the School of the Environment, and also has collaborative research on arbuscular mycorrhizas and photosynthesis dynamics with other Departmental colleagues.

*Dr Lou de Filippis* is a horticultural scientist with special interests in molecular biodiversity, soil dynamics, composts and amendments, and physiology. He has recently returned from study leave in Germany, which has provided new perspectives on European cultivation techniques.

*Mr Jason Brennan* holds a BSc degree in Environmental Sciences from UTS, with particular interests in plant science and mycology. He has recently graduated from the UTS MSc program, working in the Plants and Indoor Environmental Quality group. He has been actively involved in the plant CO₂ removal studies.

*Mr Peter Irga* is currently enrolled as an Honours candidate in biotechnology and environmental science at UTS. Employed as a part-time research assistant, he has carried out a number of the light response trials reported here.