Quantification of Carbon Assimilation of Plants in Simulated and In Situ Interiorscapes

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Abstract. Interiorscape plants have many documented benefits, but their potential for carbon sequestration is not clear. This study was undertaken to quantify the amount of carbon assimilation under growth chamber conditions designed to mimic the photosynthetic photon flux (PPF) levels and temperatures of typical indoor environments and to quantify the amount of carbon assimilation in situ in a representative interiorscape composed of a variety of plant species and sizes. Quantitative data were obtained in 1) growth chambers with a typical range of PPF levels encountered indoors (≈10, 20, and 30 μmol m−2 s−1); and 2) in situ conditions in an interiorscape. Under growth chamber conditions, most species exhibited positive dry mass accumulation and carbon sequestration but Sanseveria and Dracaena ‘Janet Craig’ exhibited consistent dry mass loss throughout the 10 weeks under simulated conditions. Carbon content was lower in herbaceous species (e.g., Sanseveria aureus, 38% of dry mass) compared with woody ones (e.g., Ficus benjamina, 43%). PPF-saturated net photosynthetic rates of plants were low, ranging from 3.4 to 7.0 μmol m−2 s−1, whereas their light compensation points ranged from 8 to 78 μmol m−2 s−1. In situ, plants exhibited varying dry mass gain, largely dependent on size. In general, a large plant and/or species with a higher amount of woody tissue in their above- or belowground organs (e.g., 4.6 m high arborescent plant) sequestered more carbon than small and/or herbaceous species. This study is the first to provide quantitative data of carbon sequestration in interiorscape environments.

Reduction of the “carbon footprint,” increase in the energy efficiency of a building, and other environmentally friendly initiatives have gained considerable public and industry recognition through the Leadership in Energy and Environmental Design certification system administered by the U.S. Green Building Council (USGBC, 2011). Within this system, credits are given for the use of indoor plants because of their phytoremediation quality [removal of harmful volatile organic compounds (Yang et al., 2009)] and psychological benefits (Bringslimark et al., 2007; Lohr et al., 1996). There appears to be no published research on the aspect of indoor air quality: the impact of plants on removal of carbon dioxide from indoor environments. The principal question is whether carbon dioxide removal by indoor plants is of sufficient magnitude to substantiate claims for a significant impact on indoor air quality.

Photosynthetic activity results in the uptake of CO₂ from the indoor environment because the photoassimilates are used for new growth and maintenance of existing tissues and organs. Because PPF is the driving force behind photosynthesis, generally more photoassimilates are produced as the PPF level increases. Indoor environments typically have low PPF levels, making PPF the most limiting factor for photosynthesis. The PPF levels in typical commercial interiorscape installations range from more than 40 μmol m−2 s−1 (rated as a “good” level by interiorscapers), 35 to 30 μmol m−2 s−1 (“medium” PPF), or 25 to 15 μmol m−2 s−1 (“low” PPF) (Manaker, 1981). Under such conditions, plants have variable photosynthetic rates, mainly depending on the ambient PPF levels.

Although photosynthesis is the basic physiological process underlying carbon sequestration, the total amount of carbon sequestered by plants cannot be determined directly from leaf photosynthesis measurements, because leaf measurements do not integrate the whole plant, do not take into account diurnal variations in photosynthesis, and do not account for nighttime respiration (van Iersel and Bugbee, 2000). A more reliable way to determine carbon sequestration is to measure the increase in the total amount of carbon present in the plants. Such data would be valuable both under simulated conditions and in interiorscapes, because there is a lack of quantitative data on plant performance in situ. Our goal was to collect quantitative information that can be used to help predict the magnitude of carbon sequestration by...
plants in interiorscapes. The specific objectives of this study were to: 1) quantify the photosynthetic activity and carbon sequestration of common interiorscape plants under simulated environments, replicating typical interiorscape conditions; and 2) quantify the amount of carbon assimilation in situ in a commercial interiorscape composed of a variety of plant species and sizes.

Materials and Methods

Simulated environment

Plant material. The study extended over a period of 16 months, from Feb. 2009 to June 2010, to accommodate the number of species and cultivars used. Consecutive shipments of finished plant material (Spathiphyllum ‘Sweet Chico’ Aglaonema spp., Sanseveria trifasciata ‘Hahnii’, Chamaedorea elegans, Dracaena marginata, Dracaena godseffiana ‘Florida Beauty’, Dracaena deremensis ‘Lemon Lime’, and Dracaena deremensis ‘Janet Craig’) were obtained from a wholesale producer in Florida. All of these species were grown in round, 10-cm diameter pots, whereas Spathiphyllum was also grown in 15-cm diameter pots. Ctenanthe oppenheimiana, Ficus repens, Hedera helix, Scindapsus aureus, Philodendron scandens, and Dizygotheca elegantissima were clonal material obtained from plants maintained at the University of Georgia greenhouse and rooted under mist. Ficus benjamina was also obtained from cuttings of plants grown in-house. These cuttings were grown for different lengths of time, referred hereto as F. benjamina “immature” and F. benjamina “mature,” the latter for 8 weeks longer to allow more woody growth to occur. Pachira aquatica was shipped as unrooted tip cuttings from a commercial supplier and was subsequently rooted under mist in a greenhouse. All clonal material was rooted in 10-cm diameter pots, the same size as the shipped finished plants.

Regardless of the origin of the plant material (shipped finished or grown in-house), plants were placed in a double-polyethylene Quonset-style greenhouse for acclimatization. Plants were placed in a double-polyethylene material (shipped finished or grown in-house), was shipped as unrooted tip cuttings.

A l l c l o n a lm a t e r i a lw a sr o o t e di n1 0 - c m 

15-cm diameter pots. Fertilizer solutions were stored in plastic barrels (210 L) and pumped into the water-tight trays of the ebb-and-flow system using submersible pumps (NK-2; Little Giant, Nebraska). Fertilizer solutions were stored in plastic barrels (210 L) and pumped into the water-tight trays of the ebb-and-flow system using submersible pumps (NK-2; Little Giant, Nebraska).

Table 1. Dry mass, growth, and carbon sequestration of foliage species and cultivars as affected by PPF level.

| Species                      | PPF (μmol·m⁻²·s⁻¹) | Final biomass (g) | Biomass increase (g) | Relative growth rate (mg·g⁻¹·d⁻¹) | Carbon sequestered (g) |
|------------------------------|--------------------|-------------------|----------------------|------------------------------------|------------------------|
| Aglaonema spp.              |                    |                   |                      |                                    |                        |
| H                            | 35.0               | 19.0              | 11.1                 | 7.5                                |                        |
| M                            | 28.6               | 12.6              | 8.4                  | 5.0                                |                        |
| L                            | 21.1               | 5.1               | 6.4                  | 1.9                                |                        |
| Significance                 |                    |                   |                      |                                    |                        |
| H                            | 27.7               | 9.5               | 5.7                  | 4.0                                |                        |
| M                            | 24.4               | 6.3               | 3.8                  | 2.6                                |                        |
| L                            | 22.7               | 4.6               | 2.9                  | 1.9                                |                        |
| Chamaedorea elegans         |                    |                   |                      |                                    |                        |
| H                            | 33.3               | 17.8              | 9.0                  | 7.3                                |                        |
| M                            | 33.1               | 17.6              | 9.2                  | 7.2                                |                        |
| L                            | 27.3               | 11.8              | 6.6                  | 4.8                                |                        |
| Significance                 |                    |                   |                      |                                    |                        |
| H                            | 8.9                | 4.2               | 8.8                  | 1.9                                |                        |
| M                            | 7.5                | 2.8               | 6.3                  | 1.2                                |                        |
| L                            | 6.0                | 1.3               | 3.3                  | 0.5                                |                        |
| Dizygotheca elegantissima   |                    |                   |                      |                                    |                        |
| H                            | 11.7               | 5.5               | 8.4                  | 2.3                                |                        |
| M                            | 11.7               | 5.5               | 8.6                  | 2.3                                |                        |
| L                            | 8.5                | 2.3               | 3.8                  | 0.9                                |                        |
| Significance                 |                    |                   |                      |                                    |                        |
| H                            | 13.5               | 0.7               | —x                   | —                                  |                        |
| M                            | 12.2               | 0.6               | —                    | —0.2                               |                        |
| L                            | 11.0               | 1.7               | —                    | —0.7                               |                        |
| Dracena deremensis ‘Lemon Lime’ | 21.5        | —1.7             | —                    | —1.1                               |                        |
| M                            | 20.5               | 2.7               | —                    | —1.1                               |                        |
| L                            | 18.2               | 4.9               | —                    | —1.9                               |                        |
| Dracena deremensis ‘Janet Craig’ | 11.0        | 4.3               | 8.0                  | 1.9                                |                        |
| M                            | 23.4               | 0.8               | —                    | —0.6                               |                        |
| L                            | 21.5               | 1.0               | —                    | —0.2                               |                        |
| Ficus benjamina immature     |                    |                   |                      |                                    |                        |
| H                            | 5.3                | 3.0               | 11.5                 | 1.3                                |                        |
| M                            | 5.3                | 3.0               | 11.0                 | 1.3                                |                        |
| L                            | 4.3                | 2.0               | 8.6                  | 0.8                                |                        |
| Significance                 |                    |                   |                      |                                    |                        |
| H                            | 11.0               | 4.3               | 8.0                  | 1.9                                |                        |
| M                            | 9.7                | 3.0               | 6.1                  | 1.3                                |                        |
| L                            | 8.3                | 1.6               | 3.9                  | 0.7                                |                        |
| Ficus benjamina mature       |                    |                   |                      |                                    |                        |
| H                            | 4.1                | 1.3               | 5.3                  | 0.5                                |                        |
| M                            | 4.1                | 1.3               | 5.2                  | 0.5                                |                        |
| L                            | 4.1                | 1.3               | 4.9                  | 0.5                                |                        |
| Significance                 |                    |                   |                      |                                    |                        |
| H                            | 2.2                | 1.4               | 2.1                  | 0.6                                |                        |
| M                            | 2.1                | 1.3               | 2.0                  | 0.5                                |                        |
| L                            | 1.7                | 0.9               | 1.0                  | 0.4                                |                        |
| Hedera helix                 |                    |                   |                      |                                    |                        |
| H                            | 4.6                | 33.1              | 21.2                 | 13.8                               |                        |
| M                            | 34.6               | 24.9              | 17.8                 | 10.4                               |                        |
| L                            | 27.6               | 18.0              | 14.1                 | 7.5                                |                        |
| Significance                 |                    |                   |                      |                                    |                        |
| H                            | 6.4                | 3.3               | 9.0                  | 1.3                                |                        |
| M                            | 5.3                | 2.2               | 6.1                  | 0.9                                |                        |
| L                            | 4.9                | 1.7               | 4.6                  | 0.7                                |                        |
| Sansevieria trifasciata ‘Hahnii’ | 24.7          | —4.3             | —                    | —1.6                               |                        |
| M                            | 21.6               | —7.4              | —                    | —2.8                               |                        |
| L                            | 18.7               | —10.3             | —                   | —3.9                               |                        |
| Significance                 |                    |                   |                      |                                    |                        |
| H                            | 9.6                | 8.2               | 21.0                 | 3.2                                |                        |
| M                            | 7.2                | 5.8               | 17.2                 | 2.3                                |                        |
| L                            | 6.7                | 5.3               | 16.1                 | 2.0                                |                        |
| Significance                 |                    |                   |                      |                                    |                        |

(Continued on next page)
Table 1. (Continued) Dry mass, growth, and carbon sequestration of foliage species and cultivars as affected by PPF level.\(^a\)

| Species                      | PPF (µmol m\(^{-2}\) s\(^{-1}\)) | Final biomass (g) | Biomass increase (g) | Relative growth rate (mg g\(^{-1}\) d\(^{-1}\)) | Carbon sequestered (g) | Significance |
|------------------------------|----------------------------------|-------------------|----------------------|-----------------------------------------------|-------------------------|--------------|
| Spathiphyllum 'Sweet Chico' (15 cm) |                                  |                   |                      |                                               |                         |              |
| H                           | 17.8                             | 4.9               | 5.3                  | 2.1                                           |                         |              |
| M                           | 14.6                             | 1.7               | 2.7                  | 0.7                                           |                         |              |
| L                           | 14.4                             | 1.5               | 2.4                  | 0.6                                           |                         |              |

| Spathiphyllum 'Sweet Chico' (15 cm) |                                  |                   |                      |                                               |                         |              |
| H                           | 280.5                            | 132.5             | 9.0                  | 56.4                                          |                         |              |
| M                           | 272.3                            | 124.3             | 8.6                  | 52.9                                          |                         |              |
| L                           | 264.2                            | 116.2             | 8.1                  | 49.4                                          |                         |              |

| Significance                | NS                               | NS                | NS                   | NS                                            |                         |              |

\(^a\)The following parameters were included: final biomass [initial and accumulated after 10 weeks (70 d) of growth under simulated conditions], biomass increase (shoot and root dry mass accumulated only during the 10 weeks under three PPF levels), relative growth rate/day [(ln(final mass) – ln(initial mass)] / 70 d), and grams carbon sequestered during the 10 weeks [calculated by multiplying biomass increase by percent carbon (data from Table 3). PPF levels of 30, 20, or 10 µmol m\(^{-2}\) s\(^{-1}\) are referred to as high (H), medium (M), or low (L). Values are the mean per plant (n = 6). Spathiphyllum size refers to a 4-inch pot (10 cm) and 6-inch pot (15 cm).

\(^b\)Negative values represent loss of biomass.

\(^c\)Missing values: calculation was not performed as a result of negative numbers for biomass increase.

\(^d\)Negative values represent loss of biomass.

\(^*\)Non-significant linear effects of PPF on species; \(^**\)significant linear effect of PPF on species; \(^***\)highly significant linear effect of PPF on species.

\(^e\)Significance NS NS NS NS

\(^f\)Significance ** ** *** **

\(^g\)Significance NS NS NS NS

\(^h\)Significance NS NS NS NS

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Fig. 2. Growth response of selected foliage species grown under three photosynthetic photon flux (PPF) levels for a period of 10 weeks.

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AG-6; Myron L Co., Carlsbad, CA). Medium fertility levels were found to be within appropriate levels on all testing dates (EC: 1.3 to 1.6 dS m\(^{-1}\); pH: 5.5 to 6.5) (Reed, 1996).

Tissue and media samples were sent to MicroMacro Laboratories (Athens, GA) for analysis at the end of the greenhouse acclimatization period. Macro- and micronutrient tissue levels were found to be within appropriate ranges based on general recommendations for foliage plants (Mills and Jones, 1996).

Simulated environment. After acclimatization in the greenhouse, plants were placed in a growth chamber, where they were grown under one of three PPF levels, low, medium, or high PPF (30, 20, and 30 µmol m\(^{-2}\) s\(^{-1}\), respectively) and grown for a period of 10 weeks. The greenhouse was located on the University of Georgia Experiment Station in Griffin, GA. The medium and low PPF levels were achieved by placing plants under black shade cloth supported by small wood frames 30 (width) × 60 (height) × 90 (length) cm\(^{3}\). The high PPF level was the ambient PPF in the growth chamber. PPF was provided by a mixture of metal halide and high-pressure sodium lamps. PPF measurements were made with a handheld quantum sensor (LI-190). Plants were grown under a 12-h photoperiod and 21 °C day/18 °C night air temperatures. They were irrigated weekly and fertilized biweekly (75 ppm nitrogen, 24N–8P–16K).

Measurements. The following data were taken from plants subsequently placed under a simulated environment. A group of six plants per species served as the source for “initial” data such as number of leaves, shoot and root mass, carbon content, and leaf area. These plants had been subjected to acclimatization in the greenhouse, plants were placed on all plants (with the exception of number of leaves for Ficus benjamina, Spathiphyllum 15 cm size, and Ficus repens) after 10 weeks of growth under simulated interiorscape conditions. Whole plant leaf areas were taken on all plants (with the exception of number of leaves for Ficus benjamina, Spathiphyllum 15 cm size, and Ficus repens) after 10 weeks of growth under simulated interiorscape conditions. Whole plant leaf areas were taken on all plants (with the exception of number of leaves for Ficus benjamina, Spathiphyllum 15 cm size, and Ficus repens) after 10 weeks of growth under simulated interiorscape conditions. Whole plant leaf areas were taken on all plants (with the exception of number of leaves for Ficus benjamina, Spathiphyllum 15 cm size, and Ficus repens) after 10 weeks of growth under simulated interiorscape conditions.
(two plants of each species per shade structure; a total of three species and six plants under each structure at one time). The three PPF treatments within each replicate were placed within the space allocated to the replicate, and the six replicates were then placed in a randomized complete block design. Linear regression analysis of each morphological parameter was performed using SAS® Enterprise Guide® Version 4.02 (SAS Institute, 2010) with PPF being the independent variable. Analyses were performed separately for each individual species.

**Photosynthesis.** Photosynthesis PPF response curves were measured before plants were placed under simulated interiorscape conditions but after acclimatization had been completed. A leaf was placed in a cuvette of the leaf photosynthesis system (CIRAS-1; PP Systems, Amesbury, MA) and exposed to progressively higher PPF (≈0, 10, 20, 30, 40, 50, 75, 100, 250, 500, 750, 1000, 1500, and 2000 μmol·m⁻²·s⁻¹). Net photosynthesis (Pₙ) was measured on the most recently matured leaf, midway between the midrib and leaf margin, and midway between the petiole and leaf tip. Dark respiration (Rₖ), maximum quantum yield (the slope of the PPF response curve at a PPF of 0 μmol·m⁻²·s⁻¹), and light-saturated gross photosynthesis (Pₐmax) were estimated from:

\[
Pₙ = Pₐmax \left(1 - e^{(-\text{quantum yield})(PPF)/Pₐmax}\right) - Rₖ
\]

The light compensation point was determined by solving this equation for the PPF at which Pₙ = 0 μmol·m⁻²·s⁻¹. Light-saturated Pₙ was calculated as Pₐmax – Rₖ (Burton et al., 2007).

**In situ environment**

The in situ environment was located in a public office building located at Galleria 200, Cobb Parkway, Atlanta, GA, and managed by Foliage Design Systems, Inc. The size of the interiorscape planting was ≈95 m² and consisted of in-ground planters and individual plants in containers. Carbon gain of the plants in situ was assessed by collecting clippings and senesced foliage for a period of 12 months. Because the interiorscape was managed with the goal to maintain a stable plant size, senesced leaves and shoot clippings (stems with attached foliage) could be used as a proxy for plant growth. Each plant was assigned to a section within the interiorscape complete with PPF-level information taken at the plant canopy level. Some sections contained multiple species, whereas other sections contained a single species; for example, six plants of *Brassaia* in 18.9-L pots comprised a section (Fig. 1, Section 4), whereas a single 4.6-m *Ficus benjamina* planted with an underplanting of *Scindapsus* comprised a different section (Fig. 1, Section 1). The majority of plants had been maintained for a minimum of 5 years and some as long as 7 years. Senesced foliage and stem and foliar clippings from each species were collected monthly and placed in paper bags with
Results and Discussion

Simulated environment

Biomass and carbon accumulation. With the exception of S. trifasciata ‘Hahnii’, Dracaena ‘Janet Craig’, Dracaena ‘Lemon Lime’, and Dracaena marginata, all species showed positive dry mass accumulation under all three PPF levels (Table 1; Fig. 2). There was a positive correlation between PPF and biomass increase for most species, even those that had a net decrease in biomass at some or all PPF levels, indicating increasing growth at higher PPF. Relative growth rate and carbon sequestration exhibited similar correlations with PPF. Among plants in 10-cm pots, the two species represented by different size levels (33.1 g) and the highest RGR (21.2 mg mol−1 C1 g−1 d−1). ‘Sweet Chico’ tended to have a higher RGR than immature plants, whereas smaller ‘Sweet Chico’ tended to have a higher RGR than larger plants. Among plants in 10-cm pots, carbon than smaller plants. More mature plants tended to accumulate more mass and mg

Table 2. Growth and morphological characteristics of foliage species and cultivars as affected by PPF level under simulated conditions. *Continued on next page*
Table 2. Growth and morphological characteristics of foliage species and cultivars as affected by PPF level under simulated conditions.*

| Species            | PPF (μmol m⁻² s⁻¹) | Shoot/root ratio | Shoot mass (g) | Root mass (g) | Leaf area (cm²) | Leaf area ratio (cm² g⁻¹) |
|--------------------|--------------------|------------------|----------------|--------------|-----------------|---------------------------|
| Scindapsus aureus  | H                  | 1.6              | 4.7            | 2.7          | 380             | 87.0                      |
|                    | M                  | 2.1              | 3.4            | 1.7          | 375             | 110                       |
|                    | L                  | 2.0              | 2.6            | 2.0          | 324             | 130                       |
|                    | Significance       | NS               | *              | NS           | **              | *                         |
| Spathiphyllum ‘Sweet Chico’ (10 cm) | H                  | 1.1              | 2.2            | 3.6          | 1014            | 460                       |
|                    | M                  | 1.4              | 1.6            | 1.0          | 773             | 485                       |
|                    | L                  | 1.5              | 1.5            | 0.9          | 813             | 541                       |
|                    | Significance       | NS               | *              | NS           | **              | *                         |
| Spathiphyllum ‘Sweet Chico’ (15 cm) | H                  | 0.2              | –7.1          | 139.3        | 1319           | —                         |
|                    | M                  | 0.2              | –8.3          | 132.4        | 969             | —                         |
|                    | L                  | 0.2              | –10.0         | 125.9        | 566             | —                         |
|                    | Significance       | NS               | NS            | **           | *               | NS                        |

*Shoot-root ratio was calculated from total shoot and root mass, whereas leaf area, shoot and root mass, and leaf area ratio are estimates of the new growth during the period that the plants were in the growth chamber. PPF levels of 30, 20, or 10 μmol m⁻² s⁻¹ are referred to as to as high (H), medium (M), or low (L). Values are the mean per plant (n = 6).

Values are the mean per plant (n = 2). NS and * represent non-significant and significant linear effects of PPF levels at P = 0.05, 0.01, and 0.001, respectively. 

PPF = photosynthetic photon flux.

Table 3. Shoot tissue carbon concentration for various foliage species as affected by PPF (arranged from highest to lowest average values for all three PPF levels).*

| Species            | Percent carbon          |
|--------------------|------------------------|
|                    | 30 μmol m⁻² s⁻¹ | 20 μmol m⁻² s⁻¹ | 10 μmol m⁻² s⁻¹ | Significance |
| F. benjamina mature | 43.82            | 43.25            | 43.09            | NS           |
| H. helix           | 42.26            | 43.45            | 43.30            | NS           |
| F. benjamina immature | 43.38          | 42.56            | 42.26            | NS           |
| D. elegantissima   | 44.56            | 42.08            | 42.33            | *            |
| Spathiphyllum ‘Sweet Chico’ | 42.83         | 42.55            | 42.21            | NS           |
| C. elegans         | 42.14            | 41.73            | 42.34            | NS           |
| P. aquatica        | 41.78            | 41.79            | 41.47            | NS           |
| Dracaena ‘Florida Beauty’ | 41.34        | 41.16            | 41.17            | NS           |
| C. oppenheimiana   | 41.11            | 40.79            | 40.95            | NS           |
| D. ‘Janet Craig’   | 41.13            | 41.04            | 40.60            | NS           |
| D. marginata       | 41.13            | 41.15            | 40.40            | NS           |
| D. ‘Lemon Lime’    | 40.24            | 39.92            | 41.15            | NS           |
| F. repens          | 40.38            | 40.22            | 40.11            | NS           |
| P. scandens        | 40.73            | 39.50            | 40.45            | NS           |
| Aglaonema spp.     | 39.68            | 39.91            | 40.37            | *            |
| S. aureus          | 39.21            | 39.53            | 37.25            | NS           |
| Sansevieria ‘Hahnii’ | 38.48           | 38.02            | 37.69            | NS           |

*Values are the mean per plant (n = 2). NS and * represent non-significant and significant linear effects of PPF at P = 0.05. 

PPF = photosynthetic photon flux.

greater accumulation of dry matter in roots and shoots, whereas the highest (46% shade, 1080 μmol m⁻² s⁻¹) and lowest PPF levels (92% shade, 60 μmol m⁻² s⁻¹) resulted in reductions in dry matter accumulation. Another shade-obligate species, Geogenanthenus undatus C. Koch & Linden, exhibited 30% higher total biomass when grown under 130 compared with 50 μmol m⁻² s⁻¹ (Burton et al., 2007). Because of the low PPF levels in the growth chambers, we expected growth of all species to increase with increasing PPF levels and this was confirmed by our findings (Tables 1 and 2).

Carbon concentration. Shoot carbon concentration (Table 3) ranged from 37.2% to 44.6% and tended to be lower in herbaceous species (e.g., S. aureus, 38% of dry mass) compared with woody ones (e.g., F. benjamina, 43%). Carbon concentration of most species was not significantly affected by the PPF level (except for D. elegantissima and Aglanema, which showed opposite responses to PPF).

Biomass allocation and partitioning. Most species exhibited an increase in shoot mass and leaf area with increasing PPF; however, the trend was significant only in Aglaonema, C. elegans, C. oppenheimiana, F. repens, H. helix, P. aquatica, S. trifasciata ‘Hahnii’, and S. aureus (Table 2). Shoot mass significantly increased in D. godseffiana, D. elegantissima, D. marginata, F. benjamina immature and mature, and P. scandens, whereas leaf area significantly increased in Spathiphyllum ‘Sweet Chico’ in 15-cm pots. Most species exhibited an increase in root mass with increasing PPF; however, the trend was significant in Aglaonema, C. elegans, C. oppenheimiana, D. godseffiana ‘Florida Beauty’, D. deremensis ‘Lemon Lime’, D. deremensis ‘Janet Craig’, D. marginata, F. repens, and Spathiphyllum ‘Sweet Chico’ in 15-cm pots. With respect to shoot-to-root ratio, plants fell into one of three groups: species that increased their shoot-to-root ratio with increased PPF (significant in C. elegans, F. repens, and P. aquatica; non-significant in C. oppenheimiana, F. benjamina immature, H. helix, P. scandens, and S. trifasciata ‘Hahnii’), species that lowered their shoot-to-root ratio with increased PPF (significant in Spathiphyllum ‘Sweet Chico’ in 10-cm pots; non-significant in Aglaonema, D. elegantissima, D. godseffiana ‘Florida Beauty’, D. deremensis ‘Lemon Lime’, D. deremensis ‘Janet Craig’, F. benjamina mature, and S. aureus), and species in which shoot-to-root ratio did not change (D. marginata and Spathiphyllum ‘Sweet Chico’ in 15-cm pots).

With respect to LAR, species fell into one of two groups: species that increased their LAR with increased PPF (significant in C. oppenheimiana, F. repens, and H. helix; non-significant in Aglaonema and D. godseffiana ‘Florida Beauty’) and species that lowered their LAR (significant in F. benjamina immature and mature, P. aquatica, S. aureus, and S. ‘Sweet Chico’ in 10-cm pots; non-significant in C. elegans, D. elegantissima, D. deremensis ‘Janet Craig’, and P. scandens).

Light has been shown to change dry mass accumulation and partitioning in both sun and shade plants. Plants grown under low light generally allocate a larger fraction of their biomass to their shoots and leaves compared with plants grown under high light (Taiz and Zeiger, 2010). Leaf morphology also changes with plants grown under low light developing thinner leaves than plants grown under high light (Makinod et al., 1997). However, eight genotypes of Pisum sativum L., a sun plant, behaved differently when grown under different light levels (100% to 25% of full sun); four allocated more mass to the shoot, whereas the rest decreased their allocation to the shoot in response to decreasing light (Achter et al., 2009), indicating that there is genotypic variation in responses to light, even within a single species. A tropical pioneer woody species, Croton urucurana Baill, had higher shoot dry weight and higher leaf area when grown under 30% of full sun compared with full sun (Alves de Alvarenga et al., 2003). Two tropical forest species, Warburgia ugangensis and Polyscias fulva, showed increased leaf area and higher leaf numbers when grown under PPF levels of less than 42% of full sun compared with 65% of full sun (Kinyamario et al., 2008).

In the present study, some species exhibited their responses to the three different PPF levels, whereas others did not. This could be explained by differences in their inherent genotypic, physiological, morphological, and anatomical characteristics. Most plants used in interioriescapes are of tropical origin and can adapt to grow in low

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Table 4. Photosynthetic features of selected foliage species as determined from photosynthesis – PPF response curves.\textsuperscript{a}

| Species               | Dark respiration (µmol·m\(^{-2}\)·s\(^{-1}\)) | Maximum net photo synthesis (µmol·m\(^{-2}\)·s\(^{-1}\)) | Maximum gross photosynthesis (µmol·m\(^{-2}\)·s\(^{-1}\)) | Maximum quantum yield (mol·mol\(^{-1}\)) | Light compensation point (µmol·m\(^{-2}\)·s\(^{-1}\)) |
|-----------------------|-----------------------------------------------|-------------------------------------------------|-------------------------------------------------|---------------------------------|------------------------|
| C. oppenheimiana      | 0.80                                          | 6.80                                            | 7.60                                            | 0.058                           | 15                     |
| F. benjamina          | 0.46                                          | 4.83                                            | 5.29                                            | 0.022                           | 22                     |
| H. helix              | 0.55                                          | 7.07                                            | 7.62                                            | 0.069                           | 8                      |
| P. scandens           | 0.38                                          | 5.49                                            | 6.09                                            | 0.007                           | 56                     |
| S. aureus             | 0.60                                          | 3.45                                            | 3.83                                            | 0.015                           | 41                     |
| F. repens             | 0.83                                          | 3.51                                            | 4.34                                            | 0.012                           | 78                     |

\textsuperscript{a}Values are the mean per plant (n = 2 to 4).

PPF = photosynthetic photon flux.

PPF environments (Conover and Poole, 1981). Some of these species are known to tolerate full sun (e.g., *F. benjamina*), whereas others are shade-obligate (e.g., *Aglaonema*).

From the present study conducted under simulated conditions, several general trends for plant behavior could be inferred for foliage species when placed under typical interiorscape light levels. For the initial 10-week period, plants would grow, adding new and/or larger leaves. Depending on the species, this increase would come from stored reserves and/or photosynthesis. *Sansevieria* and *Dracena deremensis* would tend to use up stored reserves, mostly from their roots and possibly add several new leaves. *Dracena marginata* would exhibit positive biomass accumulation but lose leaves. This is possibly related to different strategies of coping with low PPF: species that defoliate with more ease (e.g., *D. marginata*) initially lose leaves, whereas species that do not defoliate (i.e., *D. deremensis*) spent their reserves to develop new leaves and increase leaf area. Most foliage species would increase their LAR as a means to acclimate to lower PPF levels.

Photosynthetic performance. We were able to collect photosynthesis PPF response curves for only six of the species; photosynthetic rates of the other species were too low to be measured accurately. \( P_{\text{gmax}} \) ranged from 3.8 µmol·m\(^{-2}\)·s\(^{-1}\) for *P. scandens* to 7.6 µmol·m\(^{-2}\)·s\(^{-1}\) for *C. oppenheimiana* and *H. helix* (Table 4; Fig. 3). Such \( P_{\text{gmax}} \) rates are comparable to those of shade-obligate species like *Geoncophyllum undatus* ‘Inca’ and *Smilacina racemosa* (\( P_{\text{gmax}} \) of 3.4 and 3.9 µmol·m\(^{-2}\)·s\(^{-1}\), respectively) (Burton et al., 2007; Hull, 2002). The light compensation point ranged widely among species, from 8 µmol·m\(^{-2}\)·s\(^{-1}\) for *H. helix* to 78 µmol·m\(^{-2}\)·s\(^{-1}\) for *F. repens*. These light compensation points are generally higher than that reported (11 µmol·m\(^{-2}\)·s\(^{-1}\)) (Giorgioni and Neretti, 2010). The maximum quantum yield varied from 0.007 mol·mol\(^{-1}\) for *P. scandens* to 0.069 mol·mol\(^{-1}\) for *H. helix*. This 10-fold variation in maximum quantum yield is consistent with the finding the even within the Araceae family, there are large differences in maximum quantum yield among species (0.0014 to 0.112 mol·mol\(^{-1}\)) (Giorgioni and Neretti, 2010).

In situ environment

The total aboveground biomass accumulated by the plants in the interiorscape was 42,672 g, of which 39,312 g (92%) was contributed by just a few woody plants (4.6-m and 3.7-m *F. benjamina*, 3-m *Ficus ‘Alii’*, 1.2-m *Podocarpus*, and 2.4-m *Dracena reflexa*) (Table 5). In general, within a particular species, the biomass that was removed reflected the location (PPF level) and size of container where the plant was growing; i.e., the amount of foliage and clippings collected from *F. benjamina* increased with increasing PPF and container size, whereas that of *Podocarpus* increased with increasing PPF.

In practical terms, if the PPF level was adequate and if space allowed, a plant would continue to accrue biomass until pruning/repotting was necessary. The single *Howea* palm in the study, although showing only 1 g of clippings, had likely accumulated considerably more dry weight than recorded. However, because there was no necessity to trim the plant (and it had not outgrown its location), only a small amount of clippings was collected.

It is important to recognize that the senesced foliage and shoot clippings constitute only part of the biomass accumulation and growth of the interiorscape plants. Biomass was accrued in the new leaves, stems, and...
Table 5. Dry mass of senesced foliage and shoot clippings of plants collected from an ≈95-m² interiorscape.

| Species/size                                      | PPF (μmol·m⁻²·s⁻¹) | No. of plants | Dry mass (g) |
|--------------------------------------------------|---------------------|---------------|--------------|
| 4.6-m *F. benjamina* (planter size: 1.2 m W × 0.6 m H) | 70                  | 1             | 11,173       |
| 4.6-m *F. benjamina* (planter size: 1.2 m W × 0.6 m H) | 50                  | 1             | 9,207        |
| 3.7-m *F. benjamina* (planter size: 0.6 m W × 0.8 m H) | 70                  | 1             | 4,281        |
| 3.7-m *F. benjamina* (planter size: 0.6 m W × 0.8 m H) | 40                  | 1             | 2,964        |
| 2.4-m *Dracaena reflexa*                           | 80                  | 1             | 4,540        |
| 3-m *Ficus 'Alii'* (planter size: 1.2 m W × 0.6 m H) | 50                  | 3             | 6,195        |
| 1.2-m *Podocarpus* (planter size: 0.9 m W × 0.2 m H) | 80                  | 2             | 225          |
| 1.2-m *Podocarpus* (planter size: 0.9 m W × 0.2 m H) | 80                  | 2             | 197          |
| 1.2-m *Podocarpus* (planter size: 0.9 m W × 0.2 m H) | 70                  | 2             | 181          |
| 1.2-m *Podocarpus* (planter size: 0.9 m W × 0.2 m H) | 60                  | 2             | 150          |
| 1.2-m *Podocarpus* (planter size: 0.9 m W × 0.2 m H) | 40                  | 2             | 77           |
| 1.2-m *Podocarpus* (planter size: 0.9 m W × 0.2 m H) | 40                  | 2             | 72           |
| *Trichilia*                                       | 15                  | 1             | 48           |
| *Howea fosteriana*                                | 80                  | 1             | 1            |

**Woody plant total** | 39,312

*Brassia* (planter size 18.9 L) | 35                  | 6             | 202          |
*Brassia* (planter size 18.9 L) | 20                  | 6             | 47           |
*Dracaena ‘Janet Craig’*        | 30                  | 10            | 24           |
*Aspidistra*                     | 50                  | 10            | 191          |
*Aspidistra* (8 months)          | 4                   | 5             | 40           |
*Aspidistra* (8 months)          | 0.5                 | 5             | 19           |
*Aglaoenema*                     | 80                  | 10            | 181          |
*Aglaoenema*                     | 80                  | 5             | 103          |
*Aglaoenema* (8 months)          | 40                  | 5             | 69           |
*Aglaoenema* (8 months)          | 10                  | 6             | 60           |
*Aglaoenema* (8 months)          | 1                   | 6             | 37           |
*Zamioculcas*                    | 80                  | 5             | 7            |
*Scindapsus* (planter size: 1.2 m W × 0.6 m H underplanting of *F. benjamina*) | 70                  | 5             | 198          |
*Scindapsus* (planter size: 1.2 m W × 0.6 m H underplanting of *F. benjamina*) | 50                  | 5             | 153          |
*Scindapsus* (planter size: 0.6 m W × 0.8 m H underplanting of *F. benjamina*) | 70                  | 4             | 382          |
*Scindapsus* (planter size: 0.6 m W × 0.8 m H underplanting of *F. benjamina*) | 40                  | 4             | 141          |
*Scindapsus* (planter size: 0.9 m W × 0.2 m H underplanting of *Podocarpus*) | 70                  | 5             | 105          |
*Scindapsus* (planter size: 0.9 m W × 0.2 m H underplanting of *Podocarpus*) | 60                  | 5             | 90           |
*Scindapsus* (planter size: 0.9 m W × 0.2 m H underplanting of *Podocarpus*) | 40                  | 10            | 339          |
*Scindapsus* (planter size: 0.9 m W × 0.2 m H underplanting of *Podocarpus*) | 30                  | 10            | 437          |
*Ficus repens* (underplanting of *Podocarpus*) | 80                  | 20            | 290          |
*Ficus repens* (underplanting of *Podocarpus*) | 40                  | 6             | 10           |
*Hedera helix* (whole plant; planter size: 1.2 m W × 0.6 m H underplanting of *F. ‘Alii’*) | 50                  | 5             | 214          |

Total | 42,672

*Except where noted, values represent data from 12 months. The last column represents the total dry mass of all plants of that species in that location (as listed under No. of plants). Except where planter size listed, plants were in ground containers.

1 The entire plant was removed from the planting.

2 Photosynthetic photon flux; W = width; H = height.

**Conclusions**

Carbon fixation in an interiorscape was dominated by a few large plants. Over time larger plants (which are generally woody species) accumulated significantly larger quantities of dry mass (and carbon) compared with smaller, herbaceous species. Although positive carbon gains were demonstrated both under simulated and in situ conditions, the reduction in ambient carbon dioxide levels by interiorscape plants is not likely to substantiate claims for a significant impact on indoor air quality. Interiorscape plants have been documented to remove volatile organic compounds (VOCs), and it is this aspect that should serve as a basis for the claim for improvement of indoor air quality. Carbon dioxide assimilation provides corollary information to the VOC removal and a more complete assessment of plants’ benefits to the interiorscape environment.

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