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Sensitivity and Photosynthetic Response of Indoor Plant Species to Ozone Exposure Duration

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Abstract. This study was conducted to determine the effect of ozone in eight species of indoor foliage plants (*Cissus rhombifolia* Vahl, *Hedera helix* L., *Spathiphyllum wallisii* Regel, *Syngonium podophyllum* Schott 'Albo-Virens', *Dieffenbachia* 'Marrianne', *Ficus benjamina* L. 'Hawaii', *Pachira aquatica* Aubl., and *Scindapsus aureus* Engler) in relation to their sensitivity and physiological responses. The indoor plants grown under controlled environment chambers were exposed to 120 ppb ozone which is typically found in indoor conditions for 2, 4, or 8 hr/d for 25 d. Of the eight foliage plants, only *Cissus rhombifolia* displayed distinct foliar injuries within a few days after initial exposure. The severeness of the symptoms such as leaf necrosis and distortion of mesophyll cells was positively correlated with ozone treatment period. No significant differences were observed in the chlorophyll content and chlorophyll fluorescence (Fv/Fm) between control plants and ozone treated plants. Ozone treatment resulted in significant decreases in photosynthetic rate in *Cissus rhombifolia*, *Dieffenbachia*, *Pachira aquatica*, and *Scindapsus aureus*. There were significant differences in carbon fixation among the indoor plants used in this study, *Dieffenbachia*, and *Pachira aquatica* had ozone tolerant carbon fixation systems that did not exhibit changes in photosynthetic rate with increasing CO_2 concentration. *Cissus rhombifolia* was considered the most sensitive species to ozone among the eight foliage plants due to severe visual injury *Dieffenbachia*, *Pachira aquatica*, and *Scindapsus aureus* were classified as ozone sensitive species due to their inhibition of photosynthesis by ozone. The remaining species (*Spathiphyllum wallisii*, *Ficus benjamina* and *Hedera helix*) were more tolerant to ozone and thereby potentially better suited for indoor air phytoremediation.

***Additional key words*:** apparent quantum yield, chlorophyll content, chlorophyll fluorescence, CO_2 fixation efficiency, foliar injury symptoms

Introduction

Increasing population density, industrialization and transport related-activities, especially in developing countries during the past 25 years, has resulted in a dramatic increase in air pollutants (Ashmore et al., 2005; Fiscus et al., 2005) such as ozone, nitrogen oxides, volatile organic compounds and dust that are deleterious to human and plant health (Hill et al., 1970; Jones, 1999). The evidence showing that air pollutants are closely related to the aggravation of chronic diseases has been reported; for example, there is a strong causative link between ozone exposure and asthma (Petroeschevsky et al., 2001; Trasande and Thurston, 2005).

Ozone was identified as the primary phytotoxic constituent in smog, a form of air pollution, which was first reported to cause injury to vegetation in 1944 (Middleton et al., 1950; Richards et al., 1968). Ozone is a powerful oxidant that is known to corrode plastics, metals, textiles, and rubber products (Boubel et al., 1994) as well as causing extensive injury to plants. Concentrations high enough to cause injury to a wide cross-section of plants result from photochemical reactions in the lower atmosphere (Fiscus et al., 2005; Hill et al., 1970). Ozone is considered as a secondary air pollutant in that it is predominately formed *via* photolysis of nitrogen oxides and volatile hydrocarbons emitted in the exhaust of internal combustion engines. The average concentration of tropospheric ozone in 2000 was 50 $nmol \cdot mol^{-1}$, which was approximately the threshold for injury to ozone sensitive plants (Fuhrer et al., 1997). While ozone in the external environment has been the focus, elevated indoor ozone concentration is also a serious problem because with urbanization people spend most of their time indoors. Ozone within buildings arises *via* the diffusion of the gas from the exterior and from interior sources. Ozone can also be generated from air purifiers and office electronic devices or equipments (e.g., copy machines, faxes, and laser printers) (Allen et al., 1978; Leovic et al., 1996). Seriousness of ozone as a pollutant was reviewed in several recent papers (Ashmore, 2005; Fiscus et al., 2005).

The concentration of ozone in the troposphere is strongly modulated by plants and their growing environment. There is a significant flux of atmospheric ozone into plants where it is both deposited on the surface and absorbed. Absorbed ozone

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can be modulated by a wide range of factors (Grünhage et al., 2000) however, its fate within the plant is not entirely clear. Many plants appear to have the ability to detoxify ozone; however, above a critical internal concentration, irreversible damage occurs resulting in a cross-section of symptoms from surface discoloration to reduced yield (Hill et al., 1970).

According to plant species, the sensitivity to ozone varies widely (Fiscus et al., 2005; Fuhrer et al., 1997; Heagle, 1989; Hill et al., 1970). In addition, cultivar, stage of development, and a wide range of environmental factors like ambient CO_2 concentration can affect the sensitivity of plants to ozone (Fiscus et al., 1997; Fuhrer and Booker, 2003; Guidi et al., 2000; Heagle et al., 1999). A number of studies have reported the symptoms and physiological changes associated with ozone damage in horticultural, agronomic and forestry crops and natural vegetation (Heagle, 1989; Hill et al., 1970; Lee et al., 2002). However, there is still limited information available on the effect of ozone on indoor plants. Moreover, while there have been a number of studies on the use of plants to eliminate various indoor air pollutants (Han and Lee, 2002; Hong, 2000; Park et al., 1998; Son et al., 2000, Wolverton et al., 1989), only a small number have addressed plant injury or their air purification efficacy (Han and Lee, 2002; Park et al., 1998). Thus, assessment of these parameters in a wide range of indoor plants is required. In this study, we assessed the sensitivity of a cross-section of indoor plants to ozone by monitoring visible and anatomical symptoms and changes in selected physiological responses with exposure duration.

Materials and Methods

Plant materials

Eight species of popular indoor foliage plants (*Cissus rhombifolia* Vahl, *Dieffenbachia* 'Marrianne', *Ficus benjamina* L. 'Hawaii', *Hedera helix* L., *Pachira aquatica* Aubl., *Scindapsus aureus* Engler, *Spathiphyllum wallisii* Regel, and *Syngonium podophyllum* Schott 'Albo-Virens'), which are widely used in the interior spaces of commercial buildings and homes were assessed for sensitivity to ozone. Plants were purchased from a grower in the Kyunggi Province of Korea, repotted in either 12 or 18 cm diameter pots containing Sunshine Mix #1 (SunGro Chemicals, Los Angeles, CA, USA) and acclimatized for $\geq$ 6 months in a greenhouse at Kon-Kuk University, Seoul, Korea. The plants were grown under shade cloth (~60% shade) at 200±50 μmol·m^{-2}·s^{-1} PPF, 40 ± 10% RH and 25 ± 5ºC and were fertilized every 5 d with an aqueous solution of 200 ppm liquid fertilizer (N:P:K=24:7:5; SunGro Chemicals, Los Angeles, CA, USA).

Ozone treatment

Plants were exposed to ozone in a walk-in growth chamber located at the Department of Forest Genetic Resources, Korea Forest Research Institute, Suwon, Korea. The ozone concentration selected (120 ppb) was in the upper range of the concentration commonly encountered in indoor environment (Weschler et al., 1989; Zhang et al., 1994) and equal to or greater than recommended air quality limits (i.e., 60-120 ppb in the U.S. and Japan) (Weschler, 2000). Ozone was generated using a Model H450 Corona Discharge Ozone Generator (Harim Engineering, Inc., Seoul, Korea) and atmospheric oxygen, mixed with air using a Teledyne API Model 701 Zero Air Generator (API, Inc., San Diego, CA, USA). The generated ozone was released inside the chamber by a Model H800 Gas-Exposing System (Harim Engineering, Inc., Seoul, Korea) and the level was monitored by a Model 400 Photometric O_3 Analyzer (API, Inc., San Diego, CA, USA) (Lee et al., 2001) and maintained using a computerized control system with application *via* the Pulse Width Modulated (PWM) method. The experimental design was organized into control and treatment groups with three replications. Control groups were exposed to atmosphere devoid of ozone. Treated groups were exposed to 120 ppb of ozone for 2 hr (13:00 to 15:00), 4 hr (12:00 to 16:00) or 8 hr (10:00 to 18:00) per day and the ozone treatments were maintained for 25 d. During the treatment period the plants were maintained at 300 μmol·m^{-2}·s^{-1} PPFD, a 13/11 hr (day/night) photoperiod, 60 ± 10% RH, and 25 ± 3ºC.

Visible and anatomical injury

Visible symptoms of ozone injury were photographed using an Olympus C-4000 (Olympus America, Inc., Melville, NY, USA). Leaf material for anatomical analysis (10 × 10 mm sections) was fixed in FAA solution for 24 hr, dehydrated in *n*-butanol for 64 hr using new solution every 8 hr, and embedded in paraffin with xylene at 58-60ºC. Embedded samples were dissected into 8 μm sections using a microtome and the paraffin removed using xylene. The samples were then stained with safranin and fastgreen and observed under a CH-2 light microscope (Olympus America, Inc., Melville, NY, USA).

Chlorophyll content

Chlorophyll content was measured in 1 cm^2 vein-free leaf samples taken from leaves devoid of injury symptoms. Leaf samples were soaked in 10 ml of 100% dimethyl sulfoxide and incubated at 65ºC for 3 hr to extract the pigments (Hiscox and Israelstam, 1979). The absorbance of the extracted solution was measured at 663 and 645 nm using a Shimadzu-1600 UV-Spectrophotometer (Shimadzu, Kyoto, Japan). Chlorophyll a and b content per unit leaf area were calculated according to Arnon (1949) and corrected for the extraction solution volume and sample leaf area.

Chlorophyll fluorescence

To determine the sensitivity of foliage plants to ozone, chlorophyll fluorescence was used because Fv/Fm reflects the

maximum quantum yield in a photochemical reaction. Chlorophyll fluorescence was measured in control and 2, 4, 8 hr ozone treated plants of *C. rhombifolia*, *H. helix*, *S. wallisii*, and *S. podophyllum* 'Albo-Virens'. Leaves were selected in the morning after the last day of treatment (i.e., 25 d) and kept in the dark 20 min. Measurements were performed using an OS5-FL Modulated Fluorometer (Opti-Sciences, Tyngsboro, MA, USA). Fv was obtained by subtraction of the Fm value from Fo.

Photosynthesis

Light response curves were obtained by measuring photosynthetic rates at different light intensities at the end of the ozone treatments and *A*/*Ci* curves by measuring the rate of photosynthesis at different mesophyll CO_2 concentrations using a Li-6400 portable photosynthetic analyzer (LI-COR Bioscience, Lincoln, NE, USA). The light intensity response curve was obtained by measuring the rate of air flux into the leaf chamber under conditions of 250 μmol·s^{-1} air flow rate, 400 μmol CO_2·mol^{-1}, 25ºC and photosynthetic photon flux densities (PPFD) of 0, 25, 50, 75, 100, 150, 300, and 600 μmol·m^{-2}·s^{-1}. Photosynthetic rate, measured at different light intensities, yielded a light response curve from which the light compensation points, light saturation points, apparent quantum yields, and photosynthetic rates were calculated (Kim et al., 2001; Kim and Lee, 2001).

A/*Ci* curves were obtained at a light intensity of 700 μmol·m^{-2}·s^{-1} of PPFD and CO_2 concentrations of 0, 50, 100, 200, 400, 700 and 1000 μmol CO_2·mol^{-1} within the leaf chamber. Carbon dioxide compensation point, photorespiration, maximum photosynthetic rate, and carboxylation efficiency were then calculated from this information (Kim and Lee, 2001; Kim et al., 2001).

Data analysis

Data were analyzed by ANOVA using standard statistical software (SAS Institute, Cary, NC, USA) with the means separated by Duncan's test.

Results and Discussion

Visible leaf injury symptoms

Among the eight foliage plants tested, *Cissus rhombifolia* was the most sensitive to ozone. Necrotic lesions were only observed in *Cissus rhombifolia* (Fig. 1). The symptom started to appear on the 4th day in the 8 hr treatment. The color of the lesions darkened appreciably by the 14th day and began to widen from the 20th day onward, spreading over much of the leaf area and eventually becoming necrotic. Plants exposed for 4 hr and 2 hr treatments began to develop brown lesions by the 6th day and 9th day, respectively. Therefore, visible foliar injury in *Cissus rhombifolia* increased with ozone exposure time. In the previous studies, chlorosis and necrosis were induced by ozone on upper leaf surfaces and become progressively more severe with increasing exposure duration (Davis and Coppolono, 1976; Keen and Taylor, 1975). Compared with ozone bioindicator species such as *Spinacia oleracea* L., *Ipomoea purpurea* Roth., and *Nicotina tabacum* L. which show visible foliar injuries under continuous 150 ppb ozone after 192, 48, and 24-48 hr, respectively (Hur et al., 1995), *Cissus rhombifolia* is more sensitive to ozone in that 120 ppb ozone for 8 hr per day was enough to induce foliar injury symptom in this plant. Given all the information related to visible data, visible symptoms are known to be a good indicator of species sensitivity to ozone (Adams et al., 1988; Lee et al., 2002).

Cross-sectional analysis of *Cissus rhombifolia* leaves exposed to ozone showed lots of damage in mesophyll cells and epidermal cells on the abaxial leaf surface (Fig. 2). The damage was a typical injury induced by ozone and consistent with that

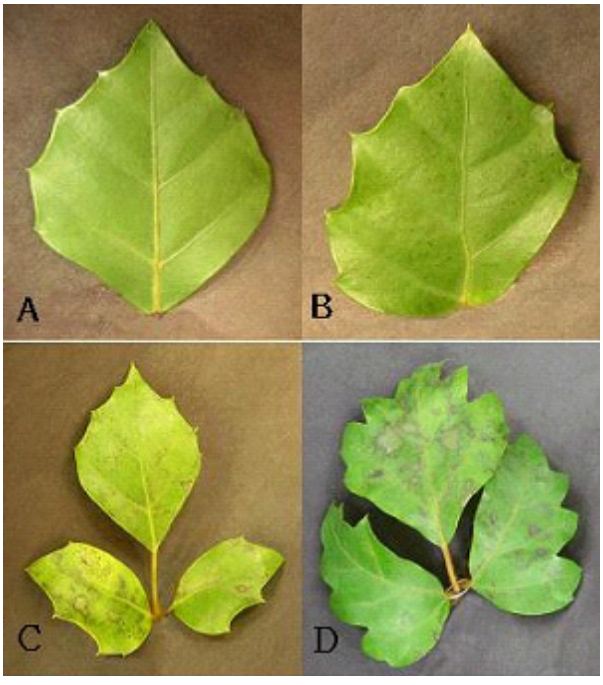

Fig. 1. Foliar injury symptoms of leaves of *Cissus rhombifolia* exposed to 120 ppb ozone for 25 d: A) control; B) 2 hr·d^{-1}; C) 4 hr·d^{-1}; and D) 8 hr·d^{-1}.

Fig. 2. Light microscope vertical cross-sections (100×) of *Cissus rhombifolia* leaves exposed to 120 ppb ozone for 25 d: A) leaf devoid of visible surface injury symptoms; and B) leaf with extensive surface injury symptoms.

described in previous studies (Evans et al., 1996).

Changes in chlorophyll content and fluorescence

There were significant differences in the content of chlorophyll a and b and the ratio among plant species (Table 1). However, ozone treatment period at 120 ppm ozone did not significantly affect either parameter, although there was a trend that chlorophyll content appeared to decrease along with increased

Table 1. Effect of daily ozone exposure duration (0, 2, 4 and 8 hr·d^{-1} at 120 ppb ozone for 25 d) on chlorophyll content and fluorescence of eight indoor plant species.

Species	Exposure duration (h/d)	Chlorophyll content (g·cm^{-2})			Chlorophyll a/b	Fv/Fm
		a	b	a+b		
Cissus rhombifolia	0	0.0285	0.0087	0.0372	3.45	0.729
	2	0.0279	0.0080	0.0360	3.42	0.717
	4	0.0271	0.0079	0.0350	3.39	0.726
	8	0.0277	0.0077	0.0353	3.35	0.696
Hedera helix	0	0.0338	0.0072	0.0408	4.94	0.722
	2	0.0325	0.0068	0.0372	4.83	0.717
	4	0.0328	0.0070	0.0353	4.83	0.711
	8	0.0331	0.0070	0.0428	4.54	0.706
Spathiphyllum wallisii	0	0.0449	0.0077	0.0526	6.01	0.754
	2	0.0444	0.0077	0.0524	5.86	0.764
	4	0.0446	0.0075	0.0521	5.85	0.752
	8	0.0449	0.0072	0.0521	5.84	0.705
Syngonium podophyllum	0	0.0366	0.0064	0.0432	5.94	0.746
	2	0.0360	0.0062	0.0405	5.78	0.753
	4	0.0358	0.0056	0.0404	5.52	0.739
	8	0.0350	0.0057	0.0406	5.70	0.722
Dieffenbachia 'Marrianne'	0	0.0341	0.0072	0.0413	4.93	
	2	0.0385	0.0076	0.0461	4.79	
	4	0.0324	0.0074	0.0397	4.52	
	8	0.0307	0.0069	0.0377	4.49	
Ficus benjamina	0	0.0430	0.0065	0.0494	7.12	
	2	0.0358	0.0051	0.0407	7.31	
	4	0.0409	0.0064	0.0472	6.84	
	8	0.0437	0.0065	0.0505	6.74	
Pachira aquatica	0	0.0227	0.0042	0.0272	4.96	
	2	0.0221	0.0046	0.0269	4.73	
	4	0.0202	0.0037	0.0227	5.02	
	8	0.0216	0.0043	0.0259	5.07	
Scindapsus aureus	0	0.0246	0.0044	0.0236	5.27	
	2	0.0200	0.0036	0.0226	5.39	
	4	0.0231	0.0043	0.0256	5.03	
	8	0.0288	0.0045	0.0350	5.31	
Species (A)		***	***	***	***	NS
Exposure time (B)		NS	NS	NS	NS	NS
A × B		NS	NS	*	NS	NS

NS,*,*** Non significant or significant at P = 0.05 or 0.001, respectively.

period of ozone treatment in several foliage plants. In the previous studies at substantially higher ozone concentrations, a distinct reduction in chlorophyll content has been reported in oriental orchids and several indoor plants (Han and Lee, 2002; Her et al., 1999). Thus, while total chlorophyll content can be an indicator of foliar injury by ozone in some cases (Davis and Coppolono, 1976), it may not be used under low ozone concentrations such as in this study. A reduction in chlorophyll fluorescence due to ozone exposure also would be indicative of damage to the light harvesting complex. However, there were also no significant differences in chlorophyll fluorescence among the species tested or ozone treatments within a species in this study (Table 1).

Light-photosynthetic and *A*/*Ci* response curves

To monitor the effect of daily ozone exposure duration on

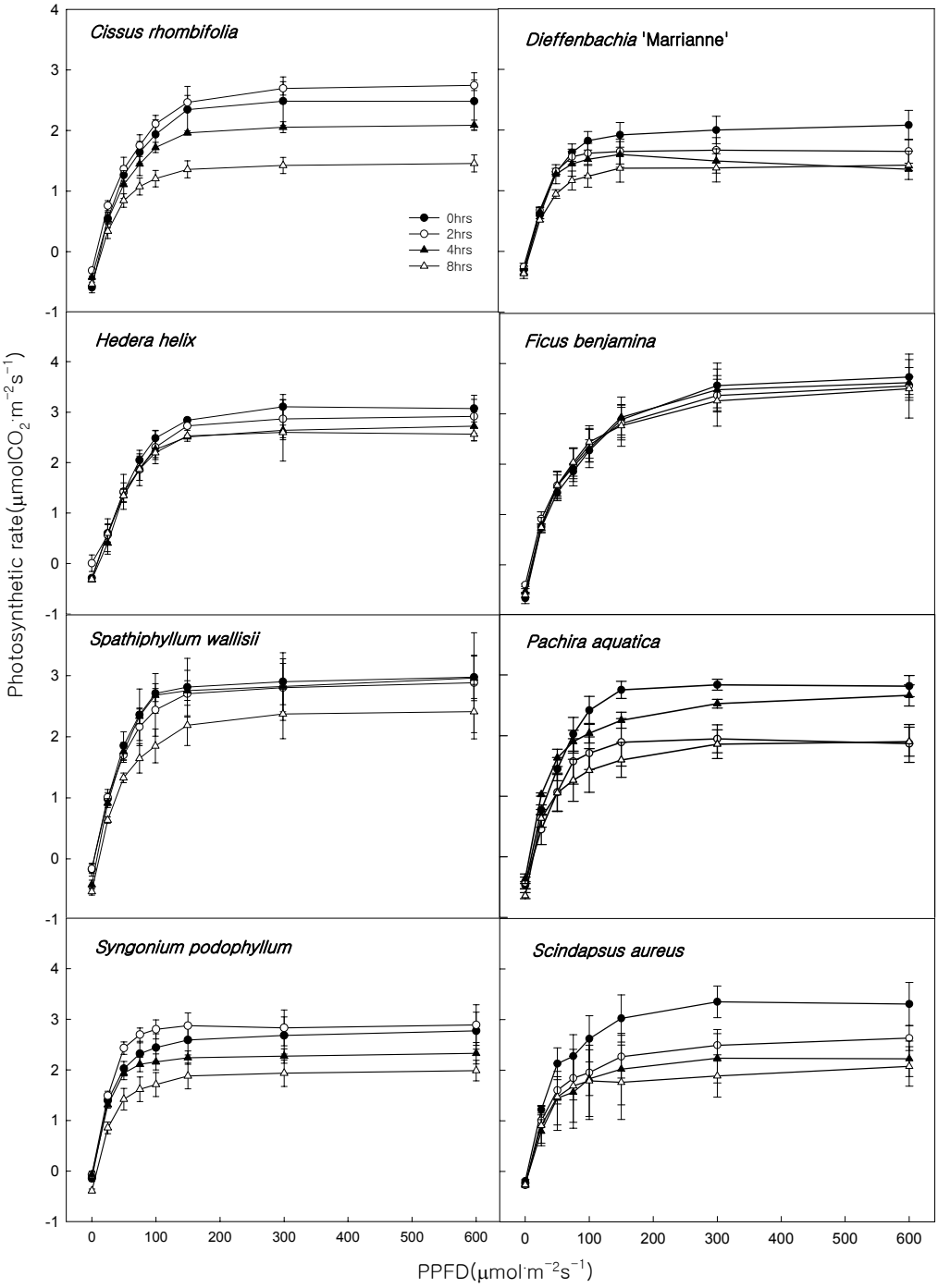

Fig. 3. Photosynthetic light response curves for indoor plant species exposed to 120 ppb ozone for 25 d: solid circles = control; open circles = 2 hr·d^{-1} exposure; solid triangles = 4 hr·d^{-1} exposure; and open triangles = 8 hr·d^{-1} exposure.

photochemical changes in each foliar plant, the photosynthetic response was plotted according to light intensity (PPFD) (Fig. 3). At low light intensities, photosynthetic rate increases in a linear manner with intensity and the response in this range is indicative of the activity of the photochemical system (Evans, 1987; Kim et al., 2001). Control treatment for *Syngonium podophyllum* had the highest level of photosynthesis in the linear range suggesting a very active photochemical system. Under saturated light intensity, factors other than light intensity modulate photosynthetic rate (e.g., the activity of enzymes involved in the dark reactions) influenced rates. In this region of the response curve, the control plants had the highest rate of photosynthesis in most of the species except for *Cissus rhombifolia* and *Syngonium podophyllum*, which showed

Table 2. Effect of daily ozone exposure duration (0, 2, 4 and 8 hr·d^{-1} at 120 ppb ozone for 25 d) on light compensation point, light saturation point, photosynthetic rate and apparent quantum yield of eight indoor plant species.

Species	Exposure duration (h/d)	Light compensation point (μmol m^{-2}s^{-1})	Light saturation point (μmol m^{-2}s^{-1})	Photosynthetic rate (μmol CO_2 m^{-2}s^{-1})	Apparent quantum yield (μmol CO_2 mol^{-1})
Cissus rhombifolia	0	10.32	73.42	2.04 ab[z]	0.033
	2	8.40	71.24	2.70 a	0.034
	4	10.76	70.27	1.74 bc	0.031
	8	10.90	71.57	1.20 c	0.026
Hedera helix	0	5.26	94.16	3.33	0.042
	2	4.17	93.83	3.26	0.040
	4	6.94	87.98	3.15	0.040
	8	7.78	87.04	2.60	0.032
Spathiphyllum wallisii	0	7.56	87.02	2.90	0.040
	2	7.06	90.31	2.81	0.041
	4	8.01	92.76	2.90	0.039
	8	11.40	93.39	2.05	0.037
Syngonium podophyllum	0	2.19	61.92	2.52	0.040 b
	2	1.92	61.47	2.62	0.053 a
	4	1.58	56.54	2.05	0.040 b
	8	5.72	63.22	1.98	0.040 b
Dieffenbachia 'Marrianne'	0	10.82	66.20	2.00 a	0.031
	2	10.54	64.07	1.53 b	0.031
	4	10.66	56.16	1.42 b	0.033
	8	11.63	51.89	1.23 b	0.031
Ficus benjamina	0	10.29	86.98	3.57	0.050
	2	10.11	84.66	3.37	0.044
	4	10.31	84.22	3.48	0.045
	8	10.72	83.38	3.26	0.044
Pachira aquatica	0	8.66	92.63	2.84 a	0.040
	2	21.48	67.32	2.17 b	0.033
	4	22.57	80.25	2.47 b	0.035
	8	13.37	61.77	2.27 b	0.036
Scindapsus aureus	0	4.67	72.53	2.90 a	0.052 a
	2	4.81	70.17	2.27 ab	0.049 a
	4	4.69	70.58	1.77 b	0.051 a
	8	4.33	68.52	1.64 b	0.033 b
Species (A)		**	***	***	***
Exposure time (B)		NS	NS	***	***
A × B		NS	NS	NS	NS

[z]Mean separation within columns by Duncan's multiple range test at P = 0.05.
NS,**,***Non significant or significant at P = 0.01 or 0.001, respectively.

slightly higher photosynthetic rates when they were exposed to ozone for 2 h per day.

Using the light response curves, the light compensation and saturation points, and apparent quantum yields were determined (Table 2). Consistent with the photosynthetic curve data, the eight foliar plants had significantly different light compensation and saturation points, though no significant effects of exposure duration were observed. In terms of photosynthetic rate, *Cissus rhombifolia*, *Dieffenbachia*, *Pachira aquatica* and *Scindapsus aureus* were sensitive to ozone treatment. The rates signifi-

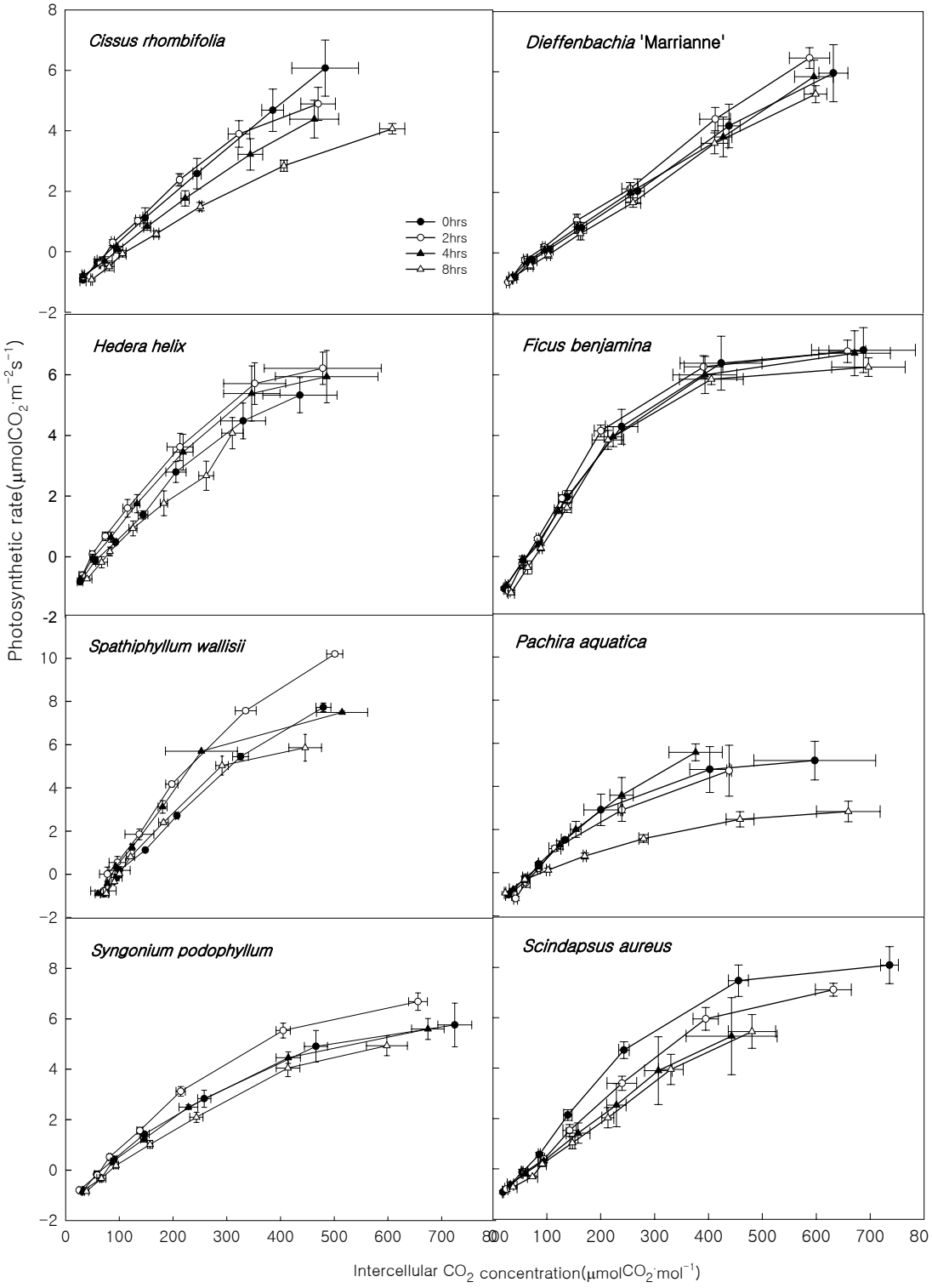

Fig. 4. Photosynthetic rate versus intercellular CO_2 concentration (*A*/*Ci* curves) for indoor plants exposed to 120 ppb ozone for 25 d: solid circles = control; open circles = 2 hr·d^{-1} exposure; solid triangles = 4 hr·d^{-1} exposure; and open triangles = 8 hr·d^{-1} exposure.

cantly declined with increased of ozone treatment period per day. While there was a significant effect among species for apparent quantum yield, differences among exposure durations within a species were generally not significantly different.

To investigate how ozone exposure time affected the carbon fixation system, *A*/*Ci* curves at different CO_2 concentrations were obtained (Fig. 4). The effect of ozone on the curves varied according to plant species. Ozone is known to decrease the amount of ribulose bisphosphate carboxylase (rubisco), the enzyme that fixes CO_2 in the C_3 reductive pentose phosphate pathway (Enyedi et al., 1992). At low CO_2 concentrations in the mesophyll cells, *A*/*Ci* curves indicate that the photosynthetic rate is dependent upon the amount of rubisco. The extinction coefficient in this linear region is the carboxylation rate,

Table 3. Effect of daily ozone exposure duration (0, 2, 4 and 8 hr·d^{-1} at 120 ppb ozone for 25 d) on CO_2 compensation point, photorespiration, photosynthetic rate, maximum photosynthetic rate and carboxylation efficiency of eight indoor plant species.

Species	Exposure duration (h/d)	CO_2 compensation point (μmol CO_2 mol^{-1})	Photorespiration rate (μmol CO_2 m^{-2}s^{-1})	Maximum photosynthetic rate (μmol CO_2 m^{-2}s^{-1})	Carboxylation efficiency (μmol CO_2 mol^{-1})
Cissus rhombifolia	0	82.22 b[z]	1.49	6.34	0.021
	2	86.45 b	1.38	5.81	0.017
	4	88.16 b	1.31	5.44	0.011
	8	169.22 a	1.34	4.57	0.008
Hedera helix	0	69.73	1.19	6.20 ab	0.017
	2	65.62	1.07	7.20 a	0.020
	4	67.15	1.21	6.96 a	0.020
	8	77.47	1.29	4.89 b	0.015
Spathiphyllum wallisii	0	112.28	1.85	7.65 b	0.026
	2	76.69	1.46	10.2 a	0.030
	4	76.77	1.97	7.59 b	0.021
	8	89.75	2.68	6.10 c	0.019
Syngonium podophyllum	0	64.19	1.04	5.71	0.016
	2	62.54	1.01	6.68	0.018
	4	66.08	1.03	5.60	0.015
	8	71.42	1.06	5.23	0.012
Dieffenbachia 'Marrianne'	0	83.39	1.21	5.85	0.013
	2	80.76	1.35	6.46	0.016
	4	83.32	1.31	5.11	0.013
	8	84.69	1.42	5.07	0.012
Ficus benjamina	0	73.79	1.67	7.62	0.027
	2	69.34	1.54	7.52	0.028
	4	73.25	1.56	7.43	0.026
	8	74.19	1.65	7.30	0.024
Pachira aquatica	0	63.27 b	1.48	5.82	0.021 a
	2	80.28 ab	1.67	5.74	0.023 a
	4	70.01 ab	1.30	5.88	0.022 a
	8	106.33 a	0.97	4.11	0.011 b
Scindapsus aureus	0	66.38	1.24	8.23	0.022
	2	73.53	1.24	7.11	0.021
	4	68.80	1.19	5.46	0.019
	8	75.52	1.27	5.45	0.014
Species (A)		**	**	***	***
Exposure time (B)		*	NS	***	***
A × B		NS	NS	NS	NS

[z]Mean separation within columns by Duncan's multiple range test at P = 0.05.
NS,*,**,***Non significant or significant at P = 0.05, 0.01, or 0.001, respectively.

reflecting the amount and/or activity of rubisco (Farquhar et al., 1980). In this region, *Dieffenbachia* and *Ficus benjamina* hardly showed differences between control and ozone treatments suggesting they had more tolerant carbon fixation systems for ozone exposure compared to the other foliar plants used in this study.

CO_2 compensation point, photorespiration rate, maximum photosynthetic rate, and carboxylation efficiency were determined from the *A*/*Ci* curves (Table 3). All the parameters were significantly different among plant species. The influence of exposure duration, however, was not reflected by consistent trends within individual species indicating that while ozone may be influencing these parameters, the effect is not pronounced. CO_2 compensation points of *Cissus rhombifolia* and Pachira aquatica exposed to 8 h of ozone treatment per day were significantly higher than controls and other ozone treatments. In addition, 8 h of ozone exposure induced a significant decrease of carboxylation efficiency in *Pachira aquatica*. Therefore, these results suggest that *Cissus rhombifolia* and *Pachira aquatica* are so sensitive to ozone treatment that their carbon fixation systems are damaged. The method of analysis in the current study, contrasting before and after treatment, may have masked temporal alterations occurring, minimizing the affects noted. Diurnal measurement would give a more precise assessment of damage to the system, as indicated by changes in selected physiological responses, and possible recovery cycles.

Categorization of species based on ozone sensitivity

Based upon the above results, *Cissus rhombifolia* was classified as the most highly sensitive species to ozone among the eight species tested. This foliage plant showed visual and anatomical injury due to ozone and also a significantly decreased photosynthetic rate with increased ozone exposure. Thus, *Cissus rhombifolia* could be used as an indicator plant for indoor ozone concentration. Several foliage plants such as *Dieffenbachia*, *Pachira aquatica* and *Scindapsus aureus* also displayed sequential decreases in photosynthetic rate as ozone duration increased. Thus, these indoor plants were classified with sensitive species to ozone. In contrast, *Hedera helix*, *Spathiphyllum wallisii*, *Syngonium podophyllum*, and *Ficus benjamina* were tolerant to ozone because there was no effect of ozone treatment on photosynthetic and carbon fixation rate in these plants, meaning that these species of foliage plants may be better suited for the purpose of indoor air cleaning. In the furture, a temporal assessment of the effect of ozone on these basic physiological processes is required in that it may provide a better understanding of the physiological responses and thereby suggest the potential of each foliage plant for removing ozone from the air.

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