Root Medium Carbon Dioxide and Oxygen Partial Pressures for Container-grown Chrysanthemums

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Abstract. Medium CO₂ and O₂ partial pressures were measured at three locations [3.8 (top layer), 7.5 (middle layer), and 10.3 (bottom layer) cm below the rim] in 15-cm-tall pots containing flowering chrysanthemums [*Dendranthema × grandiflorum* (Ramat.) Kitamura] grown in one of three root media. Average ambient medium CO₂ and O₂ partial pressures were 63 Pa and 21 kPa, respectively, and were similar in the three sampled layers in root media with an average moisture content of 50% to 60% of container capacity. Within 10 minutes after a drip-irrigation application of well water containing a titratable alkalinity to pH 4.5 of 320 mg CaCO₃/liter, the partial pressure of medium CO₂ increased to ≤1600 Pa and medium O₂ decreased to 20.5 kPa in the top and middle layers of the pot. With subirrigation, medium CO₂ partial pressures increased to ≤170 Pa and medium O₂ remained at 21 kPa. When reverse-osmosis purified water (titratable alkalinity to pH 4.5 of <20 mg CaCO₃/liter) was used instead of well water, the large increase in medium CO₂ did not occur, indicating that the bicarbonate alkalinity in the irrigation water was the source of CO₂. The high medium CO₂ partial pressure measured after irrigation was not persistent; within 180 minutes, it returned to levels averaging 45% higher (100 Pa) than that measured before the irrigation. Medium O₂ also had returned to ambient levels 180 minutes after the irrigation.

Root medium aeration is important when plants are produced in containers (Bunt, 1988; DeBoodt and Verdonck, 1971; Fonteno, 1988; Milks et al., 1989). Hanan (1964) measured O₂ partial pressures (PP) in cut-flower beds ranging from 8 to 60 cm deep and containing media with various percentages of leaf mold, loam, peat, perlite, sand, and silt. At the 5- to 7-cm depth within the beds, O₂ PP ranged from 9.8 to 21 kPa, with the highest measured in the beds containing a soilless root medium [1 peat : 1 perlite (v/v)]. Paul and Lee (1976) found that the O₂ diffusion rate correlated well with the growth of chrysanthemums in 13 root media. Fifteen percent air-filled porosity at container capacity was suggested for optimum O₂ diffusion rates and plant growth in 12-

cm-tall pots. In studies of gas exchange with soilless container root media, CO₂ PP have been largely ignored. For example, Hanan (1964) also measured CO₂ PP in several of the media in cut-flower beds but not in those containing the 1 peat : 1 perlite medium.

Medium CO₂ PP is important because of its effect on solution pH and nutrient solubility. Lindsay (1979) reported that for soils at equilibrium with CaCO₃ (calcareous), the measured pH varied from 7.3 to 8.5, depending on the CO₂ PP. Soil pH values of 8.5 in calcareous soils can be obtained only when the PP of CO₂ in the soil is similar to that measured in the ambient atmosphere (30 to 40 Pa). Because of factors such as root respiration, microbial activity, and organic matter degradation, average CO₂ PP in the soil atmosphere commonly are reported at 300 Pa, or 10 times higher than that measured in the air (Lindsay, 1979).

In the production of container-grown plants,

respiration is considered higher than that of plants grown in mineral soils because of faster plant growth rates (Paul and Lee, 1976) and higher microbial respiration because of the high organic-matter content of most soilless container media (Bunt, 1988). Muckle (1990) suggested that the accumulation of CO₂ in container media, resulting from root respiration, can reduce plant growth. However, CO₂ PP from plants grown in containers under normal production conditions are unknown. Our objectives were to determine the effects of drip irrigation and subirrigation on the medium CO₂ and O₂ PP in three root media containing fully developed chrysanthemum plants.

Materials and Methods

The three root media tested were 1) 100% Canadian sphagnum peat (Fisons professional black bale Canadian sphagnum moss peat; Sun Gro Horticulture, Bellevue, Wash.), 2) 50% sphagnum peat and 50% no. 2 vermiculite (Grace-Sierra, Marysville, Ohio), and 3) 100% no. 2 vermiculite. A wetting agent (Aquadro L; Aquatrols, Pennsauken, N.J.) was incorporated at the recommended rate (0.2 liter·m⁻³). A superfine dolomitic limestone (CaCO₃ and MgCO₃) was added to the medium before planting to increase the initial pH to 6.0. Because of the different amounts of peat added to media 1, 2, and 3, the amount of limestone incorporated was 6, 3, or 0 kg·m⁻³, respectively. Medium physical properties were determined in a 15-cm-tall × 15-cm-wide pot (1.7 liter) using the method outlined by White and Mastalerz (1966) (see Table 1).

The two irrigation methods were drip irrigation or flood subirrigation. With drip irrigation, two emitters were placed on the center of the media surface and water was applied for 5 min. Sufficient water was applied for a 30% leaching fraction. With subirrigation, pots were placed on a flood-subirrigation bench that was filled to a depth of 3 cm. The bench required 10 min to fill and 10 min to drain. The water used with both irrigation methods had a titratable alkalinity to pH 4.5 of 320 mg CaCO₃/liter (Chau, 1984).

Our experiment was conducted at Michigan State Univ., East Lansing, in a well-ventilated glass greenhouse, with constant air circulation and cement floors. Five rooted cuttings of 'Bright Golden Anne' chrysanthemum were planted into each of the root media using 15-cm-tall × 15-cm-wide plastic pots (1.7 liter). Plants were grown using the two irrigation methods for 2 weeks under long-day

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Table 1. Root-medium air space (AS), water space at container capacity (CC) in a 15-cm-tall pot, bulk density (BD) (in kilogram per cubed meter), and ambient medium CO₂ partial pressure at three layers within the same pot. Gas measurements are the mean of five pots. Least significant difference (5%) calculated using pooled SE of the data presented for CO₂ partial pressures = 10 Pa.

Medium	AS	CC	BD	Medium CO ₂ partial pressure (Pa)		
				Top	Middle	Bottom
100% peat	21	65	102	59	70	71
50% peat and 50% vermiculite	20	66	100	62	66	68
100% vermiculite	32	54	126	53	61	64

conditions (>12 h light) and 9 weeks under short-day conditions (<12 h light).

At flowering, three holes were made in each of two pots from each treatment at 3.8, 7.5, and 10.3 cm below the rim. Black vinyl tape with a bead of silicon caulk was placed over each hole to create a septum. Water was applied as a normal irrigation using one of the two methods described previously. The water content of the root medium before the irrigation was between 50% and 60% of container capacity. Gas samples were removed from the root medium before the irrigation and at 10, 20, 30, 60, 120, and 180 min thereafter with drip irrigation, and at 30, 60, 120, and 180 min after the irrigation with subirrigation using a 1-ml disposable syringe with a 22-gauge (0.64 mm) needle that was 2 cm long. We considered the possibility of outside air moving down along the pot–medium interface and contaminating the sample but thought that this threat was minimal due, in part, to the high porosity of the media relative to the sample volume. The experiment was repeated on two consecutive days with separate groups of plants for replication.

Medium CO₂ and O₂ PPs were determined using a sequential CO₂ (ADC 225–MK3 analytical infrared gas analyzer; Analytical Development Co., Hertfordshire, England) and O₂ (Ametek S–3A/II with a calcia–zirconia electrochemical detection cell; Ametek Co., Thermox Instrument Division, Pittsburgh) analyzer. With both irrigation methods, the bottom layer initially was saturated, and no gas sample was taken after the irrigation for the duration of the experiment. Root medium pH was sampled 1 week after the CO₂ analysis using the 1 medium : 2 water (v/v) method, with pH measured with an ion-specific electrode directly in the slurry.

In a second experiment, well water (titratable alkalinity to pH 4.5 of 320 mg CaCO₃/liter) or reverse-osmosis (RO) purified water (titratable alkalinity to pH 4.5 of <20 mg CaCO₃/liter) was applied to a second group of flowering chrysanthemums in pots containing medium 1 or 2. The second group of plants was grown under the same conditions and at the same time as those from Expt. 1. A gas sample was removed from the top and middle layers of the pot 10 min after the water application, and the CO₂ PP was measured as previously described.

There were two independent factors (medium and irrigation method) and two factors with equal correlation between measurements [time of sampling (time) and location within the pot (layer)]. Data were analyzed with a univariate analysis of variance for repeated measurement experiments, as suggested by Ott (1988), using general linear model (GLM) procedures of SAS (SAS Inst., Cary, N.C.) for the analysis of variance with repeated measurements. The Greenhouse–Geisser adjusted F value (Greenhouse and Geisser, 1959) was used to determine statistical significance of interactions of independent factors with time. Contrasts between the independent factors' main effects within specific time periods were calculated by the SAS GLM procedure.

Results and Discussion

Pre-irrigation CO₂ PP in the root medium at 50% to 60% of container capacity averaged 58, 66, and 68 Pa for the top, middle, and bottom layer of the pot, respectively (Table 1). The slight increase in medium CO₂ PP probably reflects the differences in water-filled porosity of the three layers as predicted by Fonteno (1988) and Milks et al. (1989). This increase over the ambient CO₂ PP measured inside the greenhouse (46 Pa) probably reflects root respiration, the root medium degradation within the pot, and the resistance within the root medium to gas diffusion. In comparison, medium O₂ PP was 21 kPa at all three layers in all root media (data not shown), similar to that measured by Hanan (1964) at 5 to 7 cm below the surface of a 50% peat and 50% perlite medium.

With drip irrigation, applying water with an alkalinity of 320 mg CaCO₃/liter caused a marked increase in medium CO₂ at two levels within the pot after 10 min, resulting in PP from 250 to 1600 Pa (Fig. 1, Tables 2 and 3). In general, the greater the peat content of the root medium, the more pronounced the increase in medium CO₂. A corresponding decrease of 0.5 kPa in the average medium O₂ PP was found in the top and middle layer after the irrigation (data not shown).

With subirrigation, medium CO₂ also increased in the top and middle layers of the pot after applying the high-bicarbonate water (Fig. 1, Table 2), but the increase was ≤10% of that measured in the same medium given drip irrigation. The trends in CO₂ evolution among root media and within the pot were consistent with the drip irrigation results, but the overall difference was less than that of drip-irrigated

Fig. 1. Top- and middle-layer CO₂ partial pressure of drip-irrigated (open symbols) and subirrigated (filled symbols) flowering chrysanthemums grown in 15-cm-tall × 15-cm-wide pots containing one of three root media. The media were 100% peat (● and ○), 50% peat and 50% vermiculite (■ and □), and 100% vermiculite (▼ and ▼). Dotted line indicates the ambient CO₂ partial pressure inside the greenhouse. Each data point represents the mean of two pots.

Table 2. Summary of the univariate analysis of variance with repeated time measurements with levels of significance for root medium CO₂ partial pressure at 0, 30, 60, 120, and 180 min at two depths within a 15-cm-tall × 15-cm-wide pot after applying irrigation water containing a titratable alkalinity to pH 4.5 of 320 mg CaCO₃/liter with drip irrigation or subirrigation. No samples were taken from subirrigated pots at 10 and 20 min after the water application. Data are presented in Fig. 1.

Variable	Independent effects		Interactions of independent effects within time		Interactions of independent effects within layer	
	df	MS ²	df	MS ²	df	MS ²
Medium (M)	2	172,815***	8	53,714***	2	6,753 ^{NS}
Irrigation method (IM)	1	938,985***	4	337,024***	1	43,739**
M × IM	2	73,882*	8	45,021***	2	2,649 ^{NS}
Error	17	13,665	68	3,414	53	4,312
Greenhouse–Geisser ε				0.27		

²Mean square from analysis of variance.

^{NS}, *, **, *** Nonsignificant or significant at $P \geq 0.05$, 0.01, or 0.001, respectively.

Table 3. Contrasts within time from the univariate analysis of variance with repeated time measurements. Data are presented in Fig. 1.

	0 vs. 30 min	30 vs. 180 min	0 vs. 180 min
Medium	***	***	NS
Irrigation method	***	***	***

NS, ***Nonsignificant or significant at $P \geq 0.001$, respectively.

media. Medium O_2 PP in the top and middle layers after the irrigation were similar to the pre-irrigation O_2 level.

The elevated CO_2 PP in the root media with drip irrigation were not expected, and the CO_2 source was not immediately clear. The possibility that the CO_2 evolved from either root respiration or microbial activity in the medium was considered first, given the differences in organic-matter content among the three media. Perhaps as water was absorbed into the root medium, the air-filled porosity and gas diffusion decreased, which caused an increase in the CO_2 PP. A second possibility was that the bicarbonate in the irrigation water was neutralized by the acidic peat to release CO_2 . The increase in medium CO_2 also may have been due to unreacted or residual lime contained in the root medium, which solubilized and reacted with the acidic peat during the irrigation, resulting in the increased CO_2 production.

When RO purified water was applied to 100% peat and 50% peat and 50% vermiculite media, there was no marked increase in CO_2 in the top or middle layers (Fig. 2). Compared to pre-irrigation medium CO_2 levels, there was an increase in the CO_2 PP 10 min after the irrigation with RO water (70 Pa), indicating that plant or medium respiration or the reaction of residual lime may have a slight effect on medium CO_2 PP during and after the irrigation. In comparison, applying well water containing $CaCO_3$ alkalinity at $320 \text{ mg} \cdot \text{liter}^{-1}$ caused an increase in medium CO_2 (≤ 1010 Pa) 10 min after the irrigation, indicating that the primary source of the increase in CO_2 (Fig. 1) was from the alkalinity in the well water.

Water absorption with subirrigation is fundamentally different from that with top-watering methods, such as drip irrigation. With subirrigation, water saturates the bottom layers first and then moves to the higher layers by capillary action. In the top and middle layer, the air-filled porosity should not have been less than that measured at container capacity. With drip irrigation, not only was more high-bicarbonate water applied to the root medium than with subirrigation (because water was leached), but the water flowed through the pore spaces of the top and middle layers. Until drainage stopped, the air-filled porosity of the top and middle layers would have been less than that measured at container capacity. The lower air-filled porosity during and after the drip irrigation could have, in part, caused the larger increase in the medium CO_2 PP compared to that measured with subirrigation.

There were differences in the pH of the root medium layer that came into contact with the applied irrigation water. The root medium pH

of the top layer of the drip-irrigated pots ranged from 5.8 to 7.3 (Table 4). In comparison, the root medium pH of the bottom layer of subirrigated pots ranged from 6.8 to 8.0. It cannot be determined from this experiment if the increase in medium CO_2 would have been similar under both irrigation methods if the root medium pH had been similar.

The high CO_2 levels quickly declined and, by 180 min after the irrigation, had decreased from an average of 820 to 90 Pa (Fig. 1, Table 3). Differences in medium CO_2 PP still remained between the two irrigation methods (drip irrigated = 110 Pa, subirrigated = 90 Pa) compared to that measured before the irrigation. However, the differences were small when compared to those measured between 30 and 180 min after the irrigation. Medium O_2 PP increased to pre-irrigation lev-

els (21 kPa) in media given drip irrigation.

In general, soilless container root media maintain high air-filled porosities in pots (DeBodt and Verdonck, 1971; Fonteno, 1988; Milks et al., 1989). At container capacity, the average air space in the three root media tested was between 21% and 32% of the total volume in a 15-cm-tall pot (Table 1). This high porosity after the irrigation allowed rapid CO_2 dispersion and re-establishment of O_2 PP to near pre-irrigation levels.

The bicarbonate alkalinity in the irrigation water, not root or microbial respiration, was the primary source of medium CO_2 in this experiment. Only limited conclusions about the effect of irrigation method on medium CO_2 PP can be made because of the water alkalinity effect and differences in the root medium pH between irrigation treatments. Further study is

Fig. 2. Top- and middle-layer CO_2 partial pressure of drip-irrigated, 15-cm-tall $\times$ 15-cm-wide pots containing flowering chrysanthemums using well water or reverse-osmosis distilled water. Gas samples were taken 10 min after the irrigation. Dotted line indicates the ambient CO_2 partial pressure inside the greenhouse. Data represent the mean of two pots containing either 100% peat or 50% peat and 50% vermiculite medium.

Table 4. Root medium pH of chrysanthemums grown in three root media using drip irrigation or subirrigation at three levels within the same pot. Root medium was sampled 1 week after the gas samples were taken. Data are means of six pots. Least significant difference (5%) calculated using pooled SE of the data presented for root medium pH = 0.4.

Medium	Medium pH					
	Drip irrigation			Subirrigation		
	Top	Middle	Bottom	Top	Middle	Bottom
100% peat	6.3	6.0	5.9	5.8	6.1	6.7
50% peat and 50% vermiculite	6.3	6.0	5.9	6.0	6.1	6.9
100% vermiculite	7.0	6.8	6.8	7.1	8.1	8.0

needed to quantify the effects of irrigation method on media CO_2 PP in container root media over the duration of a crop, not just at flowering, and to determine if the increase in medium CO_2 PP has any negative effect on plant growth. Future experiments should be performed with consideration for the effects of water alkalinity, perhaps using CaCO_3 -free water to minimize its effect on medium CO_2 PP.

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