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Long-Term Effects of Elevated Carbon Dioxide Concentration on Sour Orange Wood Specific Gravity, Modulus of Elasticity, and Microfibril Angle

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Abstract

The carbon dioxide (CO_2) concentration of Earth's atmosphere continues to rise. Plants in general are responsive to changing CO_2 concentrations, which suggests changes in agricultural productivity in the United States and around the world. The ability of plants to absorb CO_2 during photosynthesis and then store carbon in their structure or sequester it in the soil has potential for mitigating the rate of rise of atmospheric CO_2 concentration. Since 1987, Bruce Kimball and coworkers at the USDA Agricultural Research Service in Phoenix, Arizona, have maintained a greenhouse gas experiment using sour orange trees maintained in a CO_2-enriched environment. These trees were harvested in 2005. During the final massive harvest, many different properties and characteristics of the woody biomass for these sour orange trees were studied. This report focuses only on the mechanical property evaluation of modulus of elasticity (MOE), specific gravity, and microfibril angle. In this study of CO_2-exposed sour orange trees, CO_2 did not significantly affect specific gravity of sour orange trees. Exposure to CO_2 did not significantly affect MOE of sour orange trees. Exposure to CO_2 did, however, seem to influence microfibril angle development. Minor interactions between CO_2 and cardinal direction affected the MOE and were caused by experimental difference in chamber construction.

Keywords: Elevated CO_2 exposure, sour orange, properties, MOE, fibril angle, specific gravity

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Introduction

The carbon dioxide (CO_2) concentration of Earth's atmosphere continues to rise, and general circulation models predict a consequent global warming and changes in precipitation patterns (IPCC 2001). Plants in general are responsive to changing CO_2 concentrations, which portends changes in agricultural productivity in the United States and around the world. At the same time, the ability of plants to absorb CO_2 during photosynthesis and then store the carbon in their structure or sequester it in the soil, or both, has potential for mitigating the rate of rise of atmospheric CO_2 concentration. Increasing atmospheric CO_2 concentration portends possible global changes in climate and especially in the growth of plants. Since 1987, Bruce Kimball and coworkers at the USDA Agricultural Research Service (ARS) in Phoenix, Arizona, have maintained a greenhouse gas experiment using sour orange trees maintained in a CO_2-enriched environment (Idso and others 2001). These sour orange trees are unique and valuable specimens of plant material. Plans to relocate the ARS laboratory forced an end to this experiment in January 2005, and the trees were harvested and prepared for extensive testing to optimize information obtained from this long-term experiment. At the harvest date in February 2005, they had been grown from seedling stage in elevated CO_2 continuously for 17 years. No similar project that started with tree seedlings comes close to this duration.

During the final harvest, leaf biomass and area, branch classes, and trunk diameter were determined. Soil and root core samples were taken for determination of fine root biomass, soil nutrients, soil microbes, and arbuscular mycorrhizal fungi. Using backhoes and hoses, root biomass was removed and measured. Finally, wood samples from the trunks of the trees were taken for determination of bulk and micro specific gravity, strength, cellular anatomy, and biochemical composition of the woody material. The latter information is particularly important because of implications for changed lignin and other compounds to alter resistance to decomposition and sequester soil carbon. The USDA Forest Service Forest Products Laboratory (FPL) assisted in the analysis of wood samples to determine if CO_2-enriched trees showed (a) higher wood specific gravity and modulus of elasticity, resulting in greater strength at both micro and bulk scales, (b) longer wood fibers and thicker cell walls, (c) increased lignin concentration and altered molecular composition and bonding of lignin, (d) increased chemical extractives and fuel value or fixed carbon and volatile content (in proximate analysis) of wood, and (e) improved dimensional stability of wood. This report focuses only on the mechanical property evaluation.

Background

The long-term responses of trees to elevated CO_2 are especially crucial to (1) slowing down the rate of atmospheric CO_2 increase, (2) determining the character of future forested natural ecosystems and their spread across the landscape, and (3) determining the productivity of future agricultural tree crops. This important link between trees, climate, future natural ecosystems, and tree crop productivity led to the initiation of a long-term CO_2-enrichment experiment on sour orange trees in 1987 (Idso and others 1991). Sour orange is an ornamental tree often used for root stocks in commercial citrus orchards because of its disease and frost resistance.

Eight sour orange trees (*Citrus aurantium* L.) were grown from seedling stage in four identically vented, open-top, clear-plastic-wall chambers at Phoenix, Arizona (Idso and others 1991) (Figure 1). The trees were planted directly into the ground (Avondale loam) (Kimball and others 1992) in July 1987. The four chambers were constructed around pairs of trees. Initially, the chambers were 5.3 m long by 2.6 m

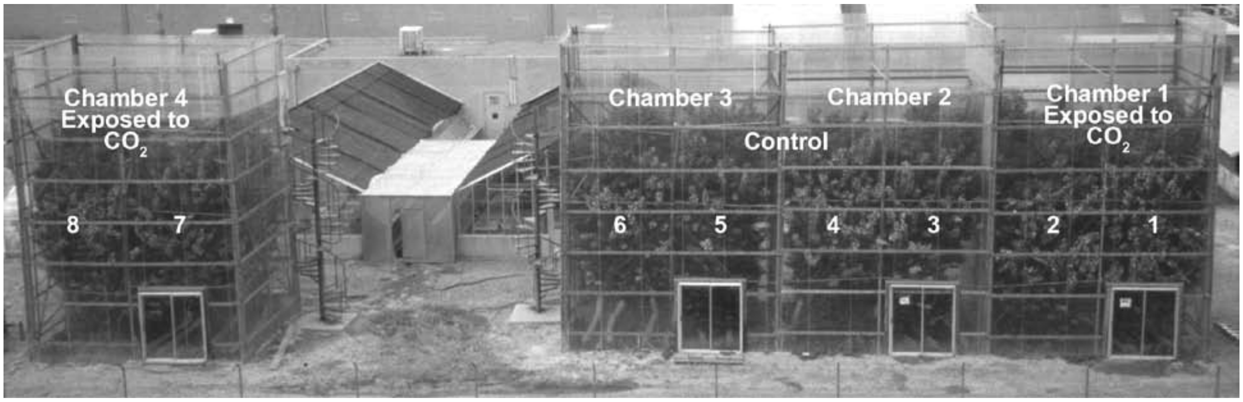

Figure 1—A 2001 aerial view of the sour orange enriched-CO_2 and control growth chambers, with tree numbers labeled.

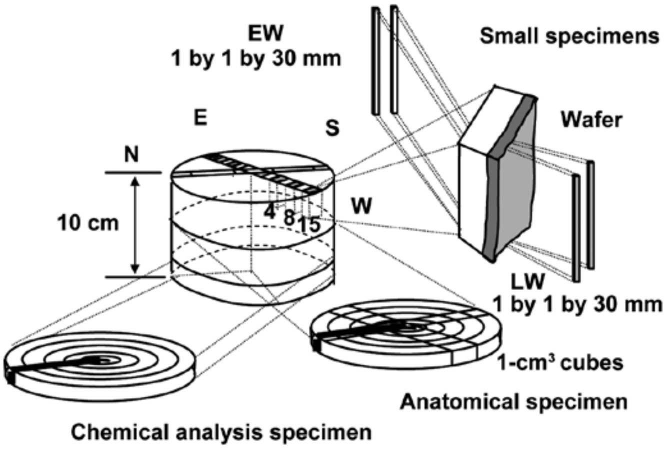

Figure 2—Cutting procedure for disks harvested.

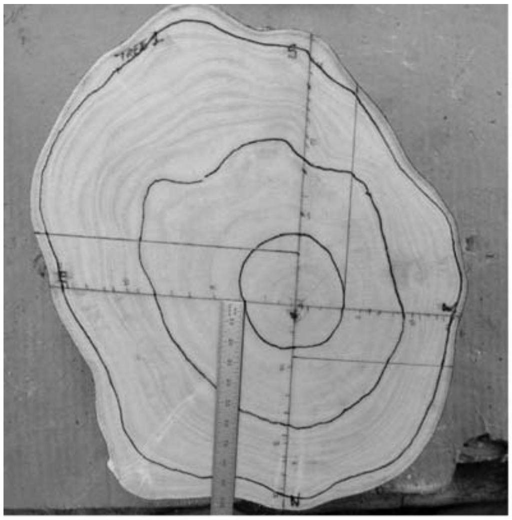

Figure 3—Cutting pattern marked on disk from tree 1.

wide by 2.0 m high. As the plants grew, the chambers were periodically enlarged until their final dimension of 6.3 m long by 5.1 m wide by 9.0 m high. The target CO_2 concentration of the enriched chambers was 300 parts per million (ppm) above that of the CO_2 concentration in the ambient chambers (about 370 ppm) (Keeling and Whorf 2005). If current atmospheric trends continue, this level of CO_2 concentration may be reached by 2060. The automatic CO_2 sampling and control system is described by Kimball and others (1992). Except for short periods of chamber enlarging and very infrequent mechanical problems, enrichment was continuous for 24 h per day since November 1987. The trees were fertilized and flood irrigated similar to practice in commercial orchards so as to maintain ample nutrients and soil moisture. The sour orange trees were highly responsive to the 300-ppm increase in CO_2, with growth and fruit production increases of about 75% each year over the past 6 years.

A 100-mm segment was taken from the trunk of each of the eight trees starting at 500-mm height above ground. The cardinal directions (north, south, east, and west) and tree number were marked on the segments, the samples were sealed in plastic bags for shipment, and then all eight disks were shipped to FPL.

Specimen Preparation

The disks received from Arizona were cut into various specimens, shown in Figure 2. Specimens for mechanical and anatomical testing were prepared in the FPL carpenter shop. Figure 3 shows the marking of the disk from tree 1 prior to cutting.

Three general types of samples were prepared and tested: (a) small rectangular specimens (approximately 1 by 1 by 30 mm) of earlywood (EW) and latewood (LW) extracted from the cardinal directions for rings 4, 8, and 15; (b) a 1-cm^3 sectioning cube for all four cardinal direction of rings 4, 8, and 15 to determine anatomical characteristics; and (c) a sample used for chemical analysis.

Table 1—Test matrix

	Height 0.5 m	Treatments CO_2, Control	Direction N, E, S, W	Ring 4, 8, 15	Wood EW, LW	Replicates	Test MOE, SG
Tests	1	2	4	3	2	5	1
Exposed (tree 1, 2, 7, 8)	4	4	4, 4, 4, 4	16, 16, 16	48, 48	240, 240	480
Unexposed (trees 3, 4, 5, 6)	4	4	4, 4, 4, 4	16, 16, 16	48, 48	240, 240	480
Total	8	8	32	96	192	960	960

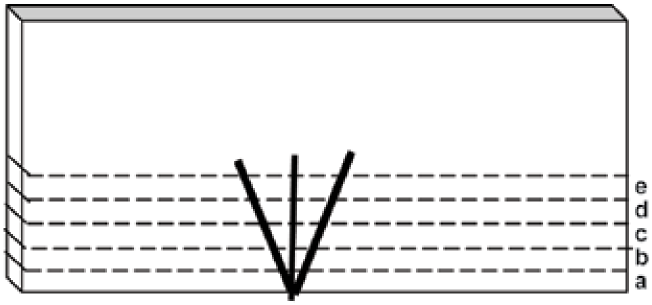

Figure 4—Marking scheme for wafer.

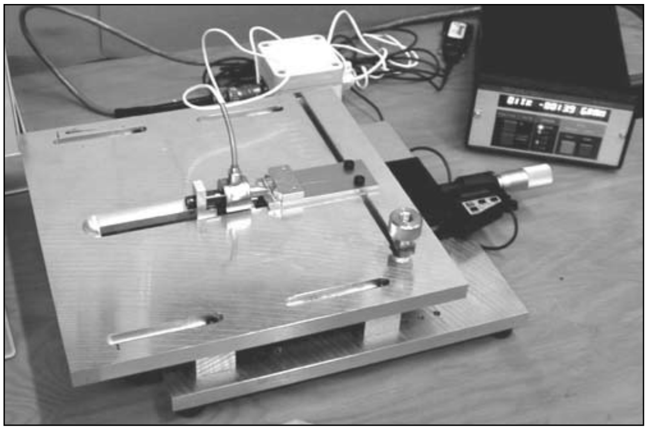

Figure 5—Micro-mechanical test equipment.

Tree number and cardinal directions were marked on each segment. For example, tree 1, north, ring 8, earlywood was marked SO1N08E.

The planned test matrix for the study is shown in Table 1. A total of 960 tests were planned.

Testing Methods

Earlywood and latewood properties for rings 4, 8, and 15 were measured from sections taken from the eight trees. Samples were prepared from the green logs by an FPL pattern maker having extensive experience with the unique characteristics of wood and specimen preparation. Each wafer manufactured had an arrow drawn on the tangential surface to track the progression of 1- by 1- by 30-mm specimens prepared (Figure 4). Four to five specimens were prepared from each wafer. The material once manufactured was stored in a conditioning room at 73°F and 65% relative humidity (RH) for 6 months.

Testing began in early May 2006. For each tree ring and wood type combination, an envelope was opened and the technician was to reconstruct the arrow pattern marked at time of manufacture. The tip of the arrow was labeled A, the next piece B, …, and E at the base of the arrow. Specimens were then marked with a colored dot to differentiate each: (a) blue dot (or streak), (b) red dot (or three small dots), (c) small black dot (small dot), (d) green dot (or two dashes), (e) yellow dot.

For micro-mechanical testing, specimens were placed with the tip of the arrow on the top and the dots placed on the right-hand side of specimen. Specimens were tested with the marked side facing the test head and the dot closest to the tester. The specimens were loaded in 10-g increments by rotating the micrometer to a maximum of 50 g. A computer interfaced with the load cell and micrometer was used to record load and deflection for each increment. This information was then used to determine modulus of elasticity (MOE) for the specimen.

The width of each specimen was measured by a digital micrometer with the marked side facing up. This measurement was the base of the specimen. The specimen was rotated 90° so the mark was facing the micrometer, and the height of the specimen was determined. The length of the specimen was also determined with a digital caliper. Finally, the pre-test weight of the sample was measured and recorded.

Moisture content (MC), specific gravity (SG, oven dry weight/volume at time of test), and bending stiffness–MOE were determined for 955 specimens. The MOE was measured using a micro-testing device (Kretschmann and others 2002) (Figure 5). Microfibril angles (MFAs) were measured on a sub-sample of 48 specimens with X-ray diffraction using the methods described by Verrill and others (2001, 2006).

Results and Discussion

A complete summary of sample size, mean, and standard deviations of MOE, MC, and SG for earlywood and

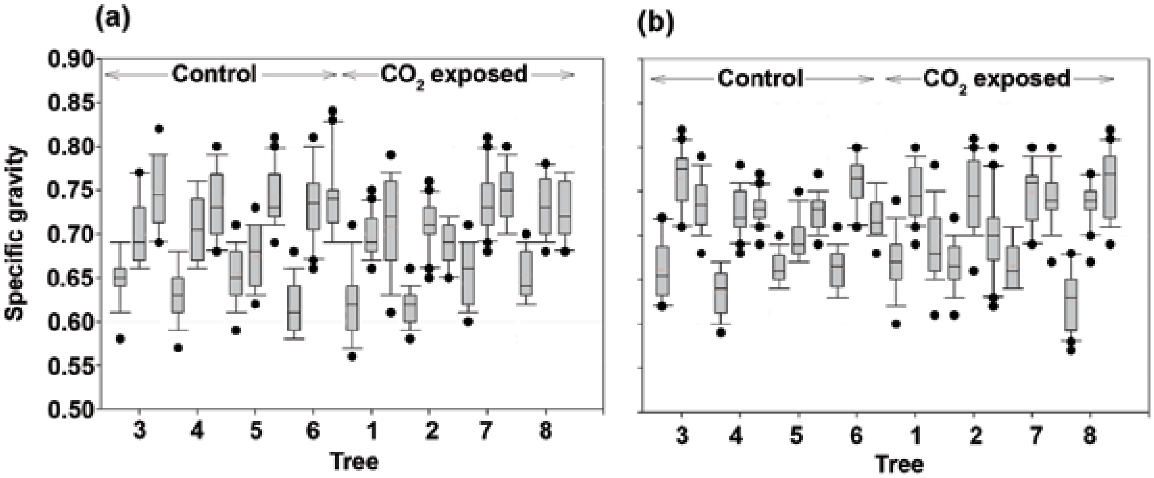

Figure 6—Box plots for specific gravity of (a) earlywood and (b) latewood samples for the various trees. The first box plot for a tree represents all data for ring 4, the second ring 8, and the last ring 15. Box plots show 5th, 25th, 50th, 75th, and 95th percentiles and extreme points. Dashed lines represent mean values.

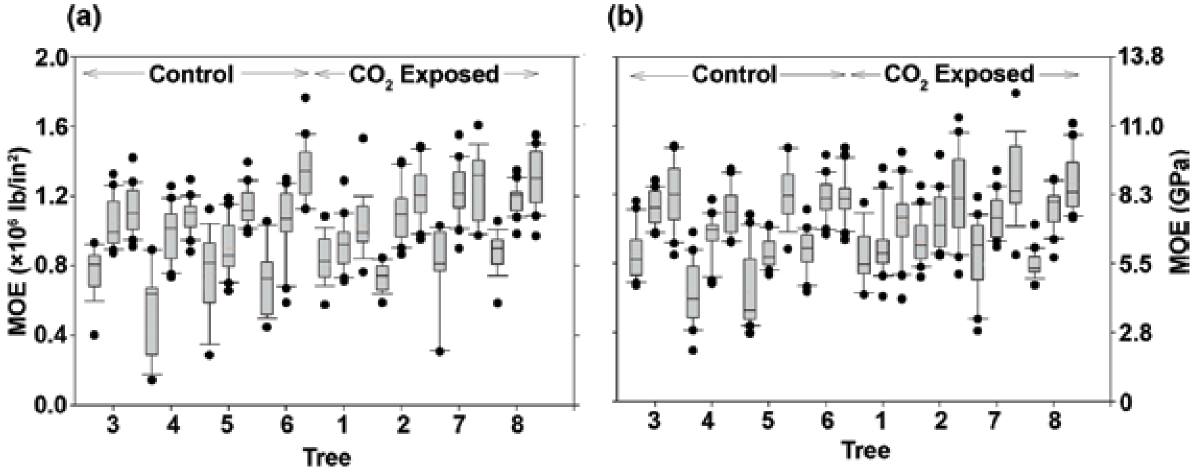

Figure 7—Box plots for modulus of elasticity for (a) earlywood and (b) latewood samples. Box plots show 5th, 25th, 50th, 75th, and 95th percentiles and extreme points. Dashed lines represent mean values.

latewood from the various trees is given in Appendix A. Results were analyzed to determine if statistical differences existed between the CO_2-enriched and the control material. The FPL statistical group was consulted to ensure that appropriate statistical tests were conducted.

Statistical Analysis

Statistical significance was calculated using SAS general linear models (GLM) procedure with CO_2 exposure, chamber, tree, cardinal direction, ring, and type of wood as classes. The CO_2 exposure, cardinal direction, ring, and wood were treated as fixed variables; sample repetition, chamber, and tree were defined as random variables. The first step was to determine if the physical gap (pathway) between chambers 3 and 4 had a statistically significant impact on MOE and specific gravity. No statistical difference was determined between chambers relative to the tree when compared with tree-to-tree variability for CO_2 exposure. This preliminary analysis of variance indicated that the sour orange trees could be treated as a split plot design.

Further analysis of the data indicated no significant difference between replicate samples and the various cardinal directions for a ring. Box plots for SG and MOE for CO_2-exposed and control trees by ring for earlywood and latewood are shown in Figures 6 and 7. The box plots show 5th, 25th, 50th, 75th, and 95th percentiles and extreme points. Dashed lines in the plots represent mean values. The first box plot for a tree represents all data for ring 4, the second ring 8, and the last ring 15.

The results of our split plot design analysis are shown in Table 2.

Table 2—Statistical significance of various class combinations[a]

	MOE		Specific gravity	
Effect	Pr > *F*	Sig.	Pr > *F*	Sig.
CO_2	0.2995		0.9073	
Card Dir	0.8882		0.5643	
Ring	<0.001	***	<0.001	***
Wood	0.5436		0.0087	**
Card Dir*Ring	0.1920		0.3477	
Card Dir*Wood	0.1784		0.6433	
Ring*Wood	0.2352		0.0472	*
Card Dir*Ring*Wood	0.5497		0.6850	
CO_2*Card Dir	0.0477	*	0.4213	
CO_2*Ring	0.4724		0.3194	
CO_2*Wood	0.2226		0.6449	
CO_2*Card Dir*Ring	0.7884		0.7249	
CO_2*Card Dir*Wood	0.9013		0.7103	
CO_2*Ring*Wood	0.4426		0.5223	
CO_2*Card Dir*Ring*Wood	0.0372	*	0.5907	

[a] Levels of significance are labeled *, **, and ***, representing the 0.05, 0.01, and 0.001 levels, respectively.

Specific Gravity

Specific gravity showed no statistically significant difference between trees exposed to CO_2 and control trees. Only ring and type of wood were significant at the 0.01 level (Table 2). Figure 6 shows that specific gravity for earlywood and latewood in all trees has a very significant increase between rings 4 and 8. For earlywood (Figure 6a), a smaller increase occurs between rings 8 and 15, whereas for latewood (Figure 6b), specific gravity is consistently higher than for ring 4 but may increase or decrease marginally from ring 8 to ring 15 in the latewood. Specific gravity of the latewood is consistently higher than that of earlywood. This pattern in wood development has been observed for years and is to be expected. What is different is that for these data, no statistical difference was found overall between the exposed and the control trees. Elevated CO_2 did not seem to affect specific gravity.

Modulus of Elasticity

Modulus of elasticity showed no statistically significant difference between trees exposed to CO_2 and control trees. Only ring was significant at the 0.01 level (Table 2). Figure 7 shows that MOE for earlywood and latewood in all trees shows a very significant increase between rings 4 and 8. A smaller increase occurs between rings 8 and 15 for earlywood (Figure 7a) than for latewood (Figure 7b). MOE is consistently higher in ring 8 than in ring 4 but may increase proportionally less from ring 8 to ring 15 than is observed in the earlywood, which is expected given its higher SG. Latewood MOE is consistently higher than earlywood MOE. A slight interaction was found between cardinal direction and ring, which may be explained as an artifact of chamber construction (see Growth Rate section). This pattern in wood development has been observed for years and is to be expected. What is different is that for these data, no statistical difference was found overall between the exposed and the control trees.

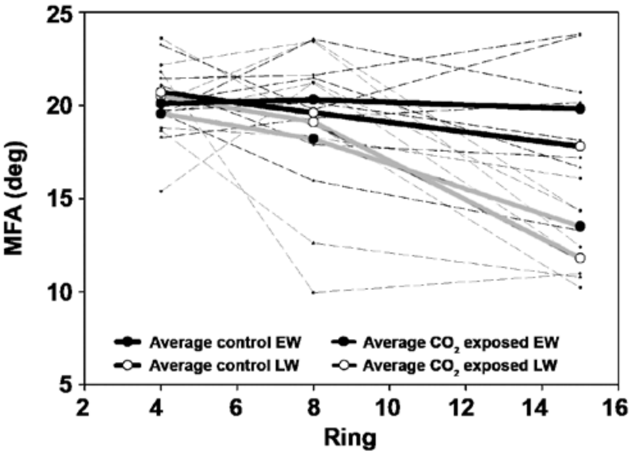

Figure 8—Plot showing the results of limited microfibril angle measurements. Heavier solid lines represent average for the control trees, lighter solid lines represent CO_2-exposed material.

Microfibril Angle

Microfibril angle test results for the sub-sample of sour orange specimens are summarized in Appendix B and shown graphically in Figure 8. Because this is a limited sample of MFA, statistically based conclusions were not possible. However, Figure 8 shows that MFA in the control trees remains relatively constant all the way out to ring 15, whereas MFA for CO_2-exposed trees changes significantly between rings 8 and 15. This suggests that the length of juvenility is reduced in the CO_2-exposed tree.

Growth Rate

Close examination of disks for all trees showed an obvious slowing of growth rate at 8 to 10 rings from the pith (Figure 9). Growth rate of the control trees (trees 3 to 6) might slow a bit sooner (rings 7 or 8) than that of the CO_2-exposed (trees 1, 2, 7, 8). The earlier reduction in growth rate may result from leafy material reaching the walls of the two control chambers sooner.

Differences in chamber solar exposure may have affected MOE values, resulting in minor interaction between cardinal direction and exposure detected in MOE. The physical gap (pathway) between chambers 3 and 4 (Figure 1) seems to have affected growth rate for the outside portions of the chambers. Growth over the 16 rings was significantly greater for the east and south cardinal directions of chamber 1 and the east, south, and west cardinal directions of chamber 4 than for the inner two chambers (Figure 10).

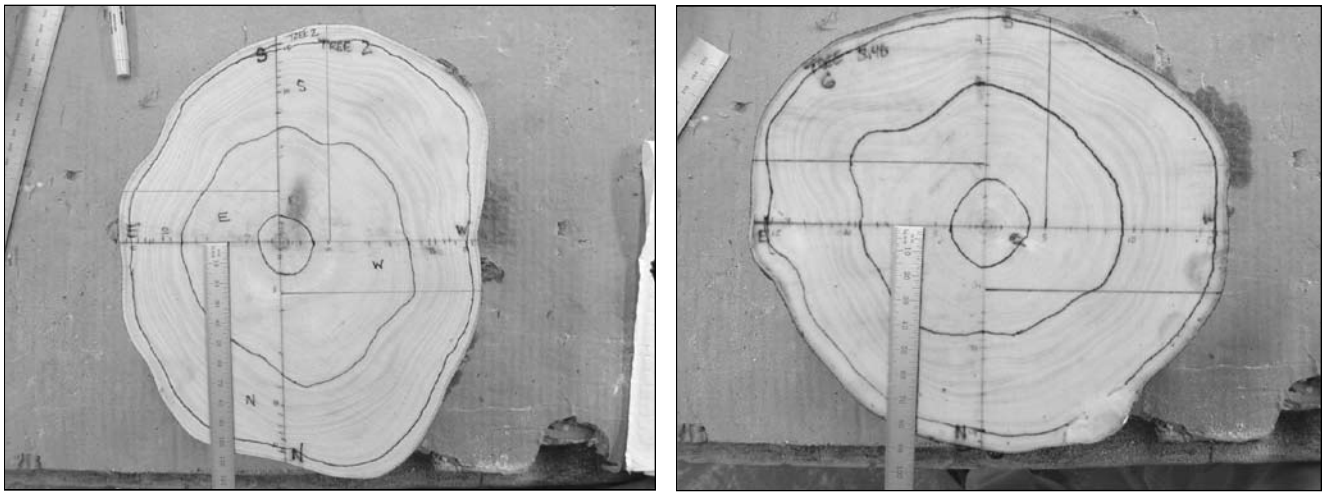

Figure 9—Disks from trees 2 and 6.

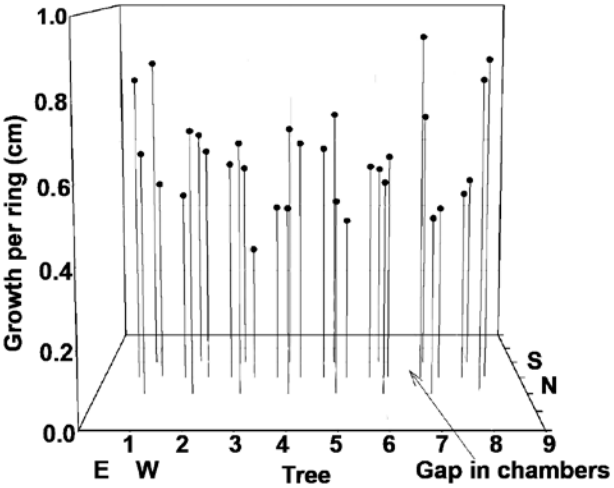

Figure 10—Plot of average growth rate for the four cardinal directions for each tree.

Conclusions

The following conclusions may be drawn from the property data developed in this study of CO_2-exposed sour orange trees:

- Exposure to CO_2 did not significantly affect specific gravity of sour orange trees.
- Exposure to CO_2 did not significantly affect modulus of elasticity of sour orange trees.
- Exposure to CO_2 did seem to influence microfibril angle development by reducing the length of juvenility.
- Minor interactions between CO_2 and cardinal direction affected modulus of elasticity and were caused by experimental difference in chamber construction.

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Appendix A—Summary of sample size, mean MOE, standard deviation, mean MC, and mean SG for each tree tested[a]

Sub sample	EW Ring 4	LW Ring 4	EW Ring 8	LW Ring 8	EW Ring 15	LW Ring 15	All EW	All LW	All
Tree 1	20	19	20	20	19	20	59	59	118
	5.75 (0.834)	5.77 (0.837)	6.34 (0.919)	6.14 (0.891)	7.07 (1.026)	7.15 (1.037)	6.37 (0.924)	6.36 (0.923)	6.37 (0.924)
	0.99 (0.144)	1.01 (0.147)	0.96 (0.139)	1.19 (0.172)	1.20 (0.174)	1.42 (0.206)	1.17 (0.169)	1.34 (0.194)	1.25 (0.181)
	9.5	10.3	9.8	10.3	10.0	10.7	9.8	10.4	10.1
	0.62	0.67	0.70	0.75	0.71	0.69	0.67	0.70	0.69
Tree 2	20	20	20	20	20	20	60	60	120
	5.03 (0.730)	6.37 (0.924)	7.59 (1.101)	7.19 (1.043)	8.35 (1.211)	8.25 (1.197)	6.99 (1.014)	7.27 (1.055)	7.13 (1.034)
	0.52 (0.075)	0.90 (0.130)	1.12 (0.163)	1.13 (0.164)	1.08 (0.157)	1.70 (0.247)	1.71 (0.248)	1.48 (0.215)	1.60 (0.232)
	10.1	10.6	11.3	10.2	10.4	10.5	10.6	10.4	10.5
	0.62	0.67	0.71	0.74	0.69	0.70	0.67	0.70	0.69
Tree 3	20	20	20	20	20	20	60	60	120
	5.30 (0.768)	5.88 (0.853)	7.21 (1.045)	7.76 (1.126)	7.72 (1.120)	8.18 (1.187)	6.74 (0.978)	7.28 (1.056)	7.01 (1.017)
	0.89 (0.129)	0.96 (0.139)	0.94 (0.137)	0.68 (0.099)	0.92 (0.133)	1.30 (0.188)	1.39 (0.201)	1.41 (0.205)	1.42 (0.206)
	8.9	9.1	10.0	10.0	9.0	9.9	9.3	9.6	9.5
	0.65	0.66	0.70	0.77	0.75	0.74	0.70	0.72	0.71
Tree 4	20	20	20	20	20	20	60	60	120
	3.65 (0.529)	4.27 (0.620)	6.83 (0.990)	6.67 (0.968)	7.49 (1.086)	7.59 (1.101)	5.98 (0.868)	6.18 (0.896)	6.08 (0.882)
	1.59 (0.231)	1.25 (0.182)	1.05 (0.153)	0.81 (0.117)	0.65 (0.094)	0.94 (0.136)	2.04 (0.296)	1.73 (0.251)	1.89 (0.274)
	9.0	9.56	9.9	10.1	10.2	8.7	9.7	9.4	9.6
	0.62	0.64	0.71	0.73	0.73	0.73	0.69	0.70	0.69
Tree 5	20	20	20	20	20	19	60	59	119
	5.07 (0.736)	4.40 (0.638)	6.21 (0.900)	5.92 (0.858)	7.85 (1.138)	8.25 (1.197)	6.37 (0.924)	6.15 (0.892)	6.27 (0.909)
	1.73 (0.251)	1.45 (0.211)	1.12 (0.162)	0.58 (0.084)	0.72 (0.104)	1.12 (0.162)	1.69 (0.245)	1.93 (0.280)	1.81 (0.262)
	9.3	9.4	9.9	10.0	9.8	10.3	9.7	9.9	9.8
	0.65	0.66	0.67	0.70	0.74	0.73	0.69	0.69	0.69
Tree 6	20	20	20	20	20	20	60	60	120
	4.96 (0.719)	6.03 (0.875)	7.26 (1.053)	8.14 (1.181)	9.32 (1.351)	8.18 (1.186)	7.18 (1.041)	7.45 (1.080)	7.32 (1.061)
	1.23 (0.178)	0.81 (0.117)	1.38 (0.200)	0.83 (0.120)	1.15 (0.167)	0.88 (0.127)	2.18 (0.316)	1.30 (0.189)	1.80 (0.260)
	10.1	10.3	10.0	10.3	11.0	11.3	10.3	10.6	10.5
	0.62	0.66	0.74	0.76	0.74	0.72	0.70	0.72	0.71
Tree 7	20	20	20	20	19	19	59	59	118
	5.52 (0.801)	5.98 (0.867)	8.43 (1.223)	7.42 (1.076)	8.83 (1.281)	8.1 (1.278)	7.58 (1.099)	7.38 (1.070)	7.47 (1.084)
	1.48 (0.215)	1.52 (0.220)	1.04 (0.151)	0.83 (0.121)	1.32 (0.192)	1.57 (0.227)	1.96 (0.284)	1.76 (0.255)	1.85 (0.269)
	11.0	11.3	10.4	10.7	10.5	10.8	10.6	10.9	10.8
	0.66	0.67	0.74	0.75	0.75	0.74	0.71	0.72	0.72
Tree 8	20	20	20	20	20	20	60	60	120
	5.77 (0.837)	5.50 (0.797)	8.16 (1.184)	7.75 (1.124)	8.96 (1.300)	8.69 (1.261)	7.63 (1.107)	7.32 (1.061)	7.47 (1.084)
	1.25 (0.182)	0.54 (0.078)	0.61 (0.088)	0.80 (0.116)	1.14 (0.165)	1.17 (0.169)	1.70 (0.247)	1.61 (0.233)	1.65 (0.24)
	10.8	10.6	11.5	12.1	11.1	10.3	11.2	11.0	11.1
	0.65	0.63	0.73	0.74	0.73	0.76	0.70	0.71	0.71
All	160	159	160	160	158	158	478	477	955
	5.13 (0.744)	5.53 (0.801)	7.25 (1.052)	7.12 (1.033)	8.20 (1.190)	8.14 (1.180)	6.86 (0.994)	6.92 (1.004)	6.89 (0.999)
	1.40 (0.202)	1.30 (0.189)	1.27 (0.184)	1.14 (0.166)	1.25 (0.182)	1.36 (0197)	1.83 (0.266)	1.66 (0.241)	1.75 (0.254)
	9.8	10.1	10.4	10.5	10.2	10.3	10.2	10.3	10.24
	0.64	0.66	0.71	0.74	0.73	0.73	0.69	0.71	0.70
Chamber 1	40	39	40	40	39	40	119	119	238
	5.39 (0.782)	6.07 (0.881)	6.96 (1.010)	6.67 (0.967)	7.73 (1.121)	7.70 (1.117)	6.68 (0.969)	6.82 (0.989)	6.75 (0.979)
	0.86 (0.125)	0.99 (0.144)	1.21 (0.176)	1.26 (0.183)	1.30 (0.188)	1.64 (0.238)	1.49 (0.216)	1.48 (0.215)	1.48 (0.215)
	9.8	10.4	10.6	10.3	10.2	10.6	10.2	10.4	10.3
	0.62	0.67	0.70	0.75	0.69	0.70	0.67	0.70	0.69
Chamber 2	40	40	40	40	40	40	120	120	240
	4.47 (0.649)	5.08 (0.737)	7.01 (1.017)	7.22 (1.047)	7.61 (1.103)	7.89 (1.144)	6.36 (0.923)	6.73 (0.976)	6.54 (0.949)
	1.52 (0.221)	1.37 (0.199)	1.01 (0.146)	0.92 (0.134)	0.79 (0.115)	1.15 (0.167)	1.78 (0.258)	1.67 (0.242)	1.73 (0.251)
	9.0	9.3	10.0	10.0	9.6	9.3	9.5	9.5	9.5
	0.64	0.65	0.70	0.75	0.74	0.74	0.69	0.71	0.70

Sub sample	**EW Ring 4**	**LW Ring 4**	**EW Ring 8**	**LW Ring 8**	**EW Ring 15**	**LW Ring 15**	**All EW**	**All LW**	**All**
Chamber 3	40	40	40	40	40	39	120	119	239
	5.01 (0.727)	5.21 (0.756)	6.73 (0.976)	7.03 (1.019)	8.58 (1.244)	8.21 (1.191)	6.78 (0.983)	6.81 (0.987)	6.78 (0.984)
	1.48 (0.215)	1.43 (0.207)	1.34 (0.195)	1.33 (0.193)	1.20 (0.174)	0.99 (0.143)	1.98 (0.287)	1.76 (0.255)	1.87 (0.271)
	9.7	9.9	9.9	10.1	10.4	10.8	10.0	10.3	10.1
	0.64	0.66	0.71	0.73	0.74	0.72	0.69	0.71	0.70
Chamber 4	40	40	40	40	39	39	119	119	238
	5.65 (0.819)	5.74 (0.832)	8.29 (1.203)	7.58 (1.100)	8.90 (1.291)	8.75 (1.269)	7.61 (1.103)	7.34 (1.065)	7.47 (1.084)
	1.37 (0.198)	1.15 (0.167)	0.85 (0.124)	0.83 (0.120)	1.21 (0.176)	1.36 (0.197)	1.83 (0.265)	1.68 (0.243)	1.75 (0.254)
	10.9	11.0	11.0	11.4	10.8	10.5	10.9	11.0	10.9
	0.66	0.65	0.73	0.74	0.736	0.750	0.71	0.71	0.71
Control	80	80	80	80	80	79	240	239	479
	4.74 (0.688)	5.14 (0.746)	6.87 (0.997)	7.12 (1.033)	8.09 (1.174)	8.051.167	6.57 (0.953)	6.77 (0.982)	6.67 (0.967)
	1.52 (0.220)	1.39 (0.202)	1.19 (0.173)	1.14 (0.165)	1.12 (0.163)	1.08 (0.157)	1.89 (0.274)	1.71 (0.248)	1.81 (0.262)
	9.3	9.6	10.0	10.1	10.0	10.0	9.8	9.9	9.8
	0.64	0.66	0.70	0.74	0.74	0.73	0.69	0.71	0.70
Exposed CO$_2$	80	79	80	80	78	79	238	238	476
	5.52 (0.800)	5.91 (0.857)	7.63 (1.107)	7.13 (1.034)	8.32 (1.206)	8.22 (1.192)	7.14 (1.036)	7.08 (1.027)	7.12 (1.032)
	1.14 (0.165)	1.08 (0.157)	1.24 (0.180)	1.15 (0.167)	1.38 (0.200)	1.59 (0.231)	1.73 (0.251)	1.60 (0.232)	1.66 (0.241)
	10.4	10.7	10.8	10.8	10.5	10.6	10.6	10.7	10.6
	0.64	0.66	0.72	0.74	0.72	0.72	0.69	0.71	0.70
All	160	159	160	160	158	158	478	477	955
	5.77 (0.744)	5.53 (0.801)	7.25 (1.052)	7.12 (1.033)	8.20 (1.190)	8.14 (1.180)	6.86 (0.994)	6.92 (1.004)	6.89 (0.999)
	1.25 (0.202)	1.30 (0.189)	1.27 (0.184)	1.14 (0.166)	1.25 (0.182)	1.36 (0.197)	1.83 (0.266)	1.66 (0.241)	1.75 (0.254)
	9.9	10.1	10.4	10.4	10.3	10.3	10.2	10.3	10.2
	0.64	0.66	0.71	0.74	0.73	0.73	0.69	0.71	0.70

[a] Sample size (no.)
Mean MOE (GPa (×10^6 lb/in^2))
Std. dev. (GPa (×10^6 lb/in^2))
Mean MC (%)
Mean SG

Appendix B—Microfibril angle estimates determined by X-ray diffraction

Sub sample	EW Ring 4	LW Ring 4	EW Ring 8	LW Ring 8	EW Ring 15	LW Ring 15
Tree 1	21.8	19.5	9.9	21.2	11.0	11.8
Tree 2	15.4	18.6	21.2	12.6	14.4	10.8
Tree 3	21.4	23.2	21.6	19.8	23.8	23.8
Tree 4	19.7	20.1	20.1	21.5	18.1	16.7
Tree 5	19.6	18.3	15.9	19.3	16.7	13.3
Tree 6	19.5	21.1	23.5	17.9	20.7	17.2
Tree 7	18.8	23.6	18.3	19.0	16.1	10.2
Tree 8	22.2	20.2	23.4	23.5	12.4	14.3