Early Growth of Muskmelon in Mulched Minitunnels Containing a Thermal Water Tube. I. Carbon Dioxide Concentrations in the Tunnel

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ABSTRACT. Temperature modification is the most investigated environmental factor considered to affect muskmelon (*Cucumis melo* L. Reticulatus Group) growth in a mulched minitunnel production system. Until now, effects on CO₂ concentrations within the tunnel have been ignored. Experiments on production of 'Earligold' netted muskmelon were conducted in 1997, 1998, and 1999 to determine daily CO₂ concentrations for 10 mulched minitunnel and thermal water tube combinations. Carbon dioxide concentrations under nonperforated (clear or infrared-blocking polyethylene) tunnels were significantly higher (three to four times) than that of ambient air. Soil respiration under the plastic mulch was primarily responsible for increased CO₂ levels in the tunnel. Daily CO₂ concentrations in the tunnels varied little during early muskmelon growth, but fluctuated widely as the plants developed. Ventilation significantly decreased CO₂ concentrations in the tunnels but levels remained significantly above the control and perforated tunnel treatments. When using mulched minitunnels for muskmelon production, daily CO₂ concentrations should be recognized as a significant factor influencing growth.

Plastic mulch in combination with a minitunnel has been used widely to increase early production of muskmelons (*Cucumis melo* Reticulatus Group) in northern climates (Loy and Wells, 1982; Wells and Loy, 1993), including Quebec, Canada (Argall and Stewart, 1989; Jenni et al., 1998). Increased air and soil temperatures under tunnels are thought to be primarily responsible for reported increases in yield. However, yield increases using minitunnels have been inconsistent (Bonanno and Lamont, 1987; Motsenbocker and Bonanno, 1989), presumably due to excessive air temperature in the tunnel. Including a water tube in the tunnel (Jenni et al., 1998) or ventilating the tunnel (Guttormsen, 1972) has reduced excessive heating in the tunnel environment and stimulated plant growth. However, there is some debate about which factors of the mulch and minitunnel environment enhance crop growth and development.

Other environmental factors, such as CO₂ levels may have an effect on growth and development of tunneled crops. High CO₂ concentrations influence photosynthetic rates, resulting in accelerated crop growth and development (Bowes, 1993; Nederhoff and Vegter, 1994), and increased yields (Kimball, 1983). Carbon dioxide levels around the planting holes in plastic mulch were significantly higher than over the mulch itself (Hopen and Oekber, 1975; Soltani et al., 1995). This was attributed to a chimney effect, which occurs when CO₂ is forced up through the planting

holes because of increased soil respiration due to higher soil temperature (Pomazkina et al., 1996). Until now, no study has focused on daily CO₂ concentrations in the microenvironment created by mulch and minitunnel combinations. Therefore, the purpose of this study was to determine the effects of minitunnel and thermal water tube combinations on CO₂ concentrations in tunnels used for muskmelon (*Cucumis melo* Reticulatus Group) production.

Materials and Methods

MINITUNNEL EXPERIMENTS. Field experiments were conducted during the Summers 1997, 1998, and 1999 at the Horticulture Research Centre, Macdonald Campus, McGill University, Sainte Anne de Bellevue, Quebec (lat. 45° 26 'N, long .73° 56 'W). The experimental site was a Gleyed Eluviated Eutric Brunisol which was fall-ploughed, spring-harrowed, and fertilized with N, P, and K according to local recommendations (Conseil des Production Vegetales du Quebec, 1994) based on soil tests. A green embossed wavelength-selective mulch 0.025 mm (Climagro, Plastitech, St-Remi, Quebec, Canada) and drip irrigation lines were installed over the 15-cm-high soil beds 1 week before muskmelon transplanting.

In 1997, 1998, and 1999, three types of polyethylene tunnels, with and without thermal water tubes, were compared with control plots. The tunnel treatments were clear perforated (500 holes of 1 cm diameter/m², Plastitech), clear nonperforated (Plastitech), and infrared-blocking nonperforated (Polyon-Barkai, Polywest, Encinatas, Calif.) polyethylene. The combinations of tunnels and thermal tubes in 1997, 1998, and 1999 were as follows: 1) no tunnel/no thermal tube (OO), 2) no tunnel/a thermal tube (OT), 3) clear perforated polyethylene/no thermal tube (PO), 4) clear perforated polyethylene/thermal tube (PT), 5) clear nonperforated polyethylene/no thermal tube (CO), 6) clear

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Fig. 1. Modified minitunnel to allow carbon dioxide measurement without disturbing the inside microclimate. (A) Examination glove, sealed and screwed to the tunnels using plastic pieces and (B) resealable slit window.

nonperforated polyethylene/thermal tube (CT), 7) infrared-blocking nonperforated polyethylene/no thermal tube (IO), 8) infrared-blocking nonperforated polyethylene/thermal tube (IT); and in 1998 and 1999, two additional treatments were added: 9) clear nonperforated polyethylene/no thermal tube/ventilated (COV), and 10) infrared-blocking nonperforated polyethylene/no thermal tube/ventilated (IOV). The experimental design was a randomized complete block with 10 treatments and three replications. The polyethylene was stretched over 10-gauge wire hoops and soil-secured along the mulched bed to create minitunnels 8 m long $\times$ 0.8 m wide $\times$ 0.375 m high. In treatments with thermal tubes, a clear polyethylene tube, 8.0 m long $\times$ 0.32 m wide, was filled with water and placed along the inside edge of each tunnel as described by Jenni et al. (1998). In 1997, the tubes were staked on the mulch surface. However, in 1998 and 1999, the tubes were

trenched (5 cm deep and 10 cm wide) into the mulched soil bed to simplify tube placement. In 1997 and 1998, one environment consisting of a clear nonperforated tunnel without a water tube (CO) and containing no plants was included in the field experimental plots to examine daily CO_2 concentrations. For the ventilated treatments (COV and IOV), ventilation consisted of cutting 15-cm slits 1 m apart on the leeward sides of the tunnel surfaces. The tunnels were ventilated when the ratio of variable to maximum fluorescence (F_v/F_m) dropped below 0.5 for three consecutive days, indicative of plants under severe or extreme stress (Bjorkman and Demmig, 1987). Tunnels were ventilated 13 d and 10 d after transplanting in 1998 and 1999, respectively.

Seeds of 'Earligold' netted muskmelon were seeded into 7.5-cm² cell packs containing Pro-mix 'BX', a peat-based growing medium (Premier Horticulture, Riviere de Loup, Quebec, Canada) and placed in a greenhouse with days/nights of 25 to 28/18 to 20 °C and natural daylight. Seedlings received 75 mg·L⁻¹ of a 20N-8.8P-16.6K foliar fertilizer (Plant Products Inc., Brampton, Ontario, Canada) at 2 weeks of age, and were watered as necessary. Three-week-old plants were transplanted on 13, 6, and 5 May 1997, 1998, and 1999, respectively. The spacings were 0.7 m between plants and 2.0 m between rows. There were 11 plants per plot with the end plants serving as guards. Immediately after transplanting, all plants received 300 mL of a starter solution (300 mg·L⁻¹ of a 10N-22P-16.6K water soluble fertilizer, Plant Products Inc.). Throughout the experiment, drip irrigation was applied for 5 h after 3 to 4 d without precipitation.

Carbon dioxide concentrations were measured with an infrared gas analyzer (LI-6250; LI-COR, Inc., Lincoln, Nebr.) on 26 May 1997; 12, 16, 20, and 26 May 1998; and 13 and 20 May and 1 or 2 d before anthesis of each treatment in 1999. A liter of air was sampled, 15 cm above the mulch surface, between plants in the

Table 1. Effect of minitunnel and thermal water tube combinations on diurnal carbon dioxide concentration on 26 May 1997 (13 d after transplanting).

Minitunnel and thermal water tube combinations	CO_2 ($\mu\text{mol}\cdot\text{mol}^{-1}$)			
	Time of the day (HR)			
	0000	0600	1200	1800
No tunnel, no tube	414	416	374	380
No tunnel, tube	496	431	377	390
Clear perforated tunnel, no tube	426	431	375	376
Clear perforated tunnel, tube	414	411	379	377
Clear nonperforated tunnel, no tube	1392	1370	1332	1259
Clear nonperforated tunnel, tube	1388	1369	1258	1243
Infrared-blocked tunnel, no tube	1388	1367	1419	1413
Infrared-blocked tunnel, tube	1386	1373	1105	1141
Analysis of variance				
Model	***	***	***	***
Treatments	***	***	***	***
Contrasts				
Tunnel vs. no tunnel	***	***	***	***
Perforated vs. nonperforated	***	***	***	***
Tube vs. no tube	NS	NS	NS	NS

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

middle of each minitunnel using the accessory chamber of the instrument. To maintain the microclimate while sampling, a 30-cm resealable slit in the middle of the tunnels was opened briefly to insert the monitoring equipment and then resealed (Fig. 1). The equipment was manipulated via plastic gloves sealed to the minitunnel walls. After a period of equilibrium (1 to 2 min), measurements were taken.

Replicated soil temperature data were obtained using copper-constantan thermocouples connected to AM-32 multiplexers and a data logger (CR-10; Campbell Scientific, Edmonton, Alberta, Canada) installed in Stevenson screens. Temperatures, 7.5 cm below the mulch surface, were recorded at 10-min intervals and averaged on an hourly basis from transplanting until anthesis.

Data were subjected to analysis of variance procedures using SAS software (Version 6.12; SAS Institute, Inc., 1997). Orthogonal contrasts were used to compare means of groups of treatments.

SOIL RESPIRATION EXPERIMENT. Soil samples (0 to 20 cm deep) were taken from the experimental site to establish the relationship between soil temperature and rate of soil respiration. Samples were kept at 5 °C from the time of collection until incubation. Soil respiration measurements were based on the evolution of CO₂ (Anderson, 1982). A 100-g soil sample with enough water to be equivalent of 80% field capacity was put into a 500-mL screw-top container. A wire-mesh stand was placed on top of the soil in the

container. To trap the CO₂, an open top 50-mL beaker containing 25 mL 1 mol·L⁻¹ NaOH solution was placed on the wire stand. The lid of the 500-mL container was then tightly sealed, and incubated at 10, 20, 30, or 40 °C, respectively, for 48 h. After adding the NaOH solution with 4 mol·L⁻¹ BaCl₂ to precipitate carbonates, the absorbed CO₂ was measured by titrating the NaOH solution with 1 mol·L⁻¹ HCl, using phenolphthalein as an indicator. There were three replicates for each incubation treatment. The procedure was repeated to obtain additional measurements and validate the first measurement. The relationship between soil temperature and soil respiration rate was determined using Proc Reg of SAS Software, Version 6.12 (SAS, Institute, Inc., 1997).

Results and Discussion

Diurnal CO₂ concentrations under nonperforated tunnels (CO, CT, IO, and IT) on 26 May 1997 were significantly greater than those under perforated tunnels (PO and PT) and those without tunnels (OO and OT) (Table 1). Similar results were found 12, 16, 20, and 26 May 1998 (Table 2), and 13 and 20, and 1 or 2 d before anthesis in 1999 (Table 3). No significant differences were found between CO₂ concentrations in ambient (OO and OT), and PO and PT treatments. When CO and CT treatments were ventilated, CO₂ levels decreased from an average of 1254 µmol·mol⁻¹ to 393

Table 2. Effects of minitunnel and thermal water tube combinations on diurnal carbon dioxide concentrations on 12, 16, 20, and 26 May 1998.

Minitunnel and thermal water tube combinations	CO ₂ (µmol·mol ⁻¹)							
	Time of the day (HR)							
	0000	0300	0600	0900	1200	1500	1800	2100
12 May 1998								
No tunnel, no tube	356	356	356	347	343	346	346	345
No tunnel, tube	363	361	350	348	348	341	342	356
Clear perforated tunnel, no tube	371	369	362	365	370	366	365	359
Clear perforated tunnel, tube	369	369	362	369	370	361	362	359
Clear nonperforated tunnel, no tube	1472	1497	1527	1477	1503	1497	1502	1501
Clear nonperforated tunnel, tube	1478	1485	1531	1485	1502	1492	1496	1504
Infrared-blocked tunnel, no tube	1478	1520	1534	1532	1538	1549	1553	1560
Infrared-blocked tunnel, tube	1481	1522	1536	1525	1529	1549	1552	1532
Analysis of variance								
Model	***	***	***	***	***	***	***	***
Treatments	***	***	***	***	***	***	***	***
Contrasts								
Tunnel vs. no tunnel	***	***	***	***	***	***	***	***
Perforated vs. nonperforated	***	***	***	***	***	***	***	***
Tube vs. no tube	NS	NS	NS	NS	NS	NS	NS	NS
16 May 1998								
No tunnel, no tube	350	349	351	344	343	341	346	347
No tunnel, tube	348	349	349	348	347	339	342	341
Clear perforated tunnel, no tube	360	348	358	356	368	363	365	354
Clear perforated tunnel, tube	363	352	356	353	368	358	362	357
Clear nonperforated tunnel, no tube	1497	1498	1499	1498	1506	1511	1502	1500
Clear nonperforated tunnel, tube	1497	1509	1509	1498	1504	1491	1496	1493
Infrared-blocked tunnel, no tube	1535	1538	1538	1533	1541	1549	1553	1536
Infrared-blocked tunnel, tube	1535	1538	1538	1533	1537	1536	1552	1534
Analysis of variance								
Model	***	***	***	***	***	***	***	***
Treatments	***	***	***	***	***	***	***	***
Contrasts								
Tunnel vs. no tunnel	***	***	***	***	***	***	***	***
Perforated vs. nonperforated	***	***	***	***	***	***	***	***
Tube vs. no tube	NS	NS	NS	NS	NS	NS	NS	NS

(Continued next page)

Table 2. Effects of minitunnel and thermal water tube combinations on diurnal carbon dioxide concentrations on 12, 16, 20, and 26 May 1998 (continued).

Minitunnel and thermal water tube combinations	CO ₂ (μmol·mol ⁻¹)							
	Time of the day (HR)							
	0000	0300	0600	0900	1200	1500	1800	2100
20 May 1998								
No tunnel, no tube	345	352	350	344	339	341	339	348
No tunnel, tube	351	349	346	345	342	337	343	345
Clear perforated tunnel, no tube	359	360	358	357	364	364	356	362
Clear perforated tunnel, tube	360	357	358	357	365	363	360	366
Clear nonperforated tunnel, no tube	361	373	386	395	405	420	400	359
Clear nonperforated tunnel, tube	365	380	398	405	408	428	407	367
Infrared-blocked tunnel, no tube	1481	1495	1493	1477	1472	1425	1447	1465
Infrared-blocked tunnel, tube	1489	1495	1496	1455	1371	1353	1413	1458
Clear nonperforated tunnel, no tube, vented	1521	1529	1529	1499	1491	1423	1437	1485
Infrared-blocked tunnel, no tube, vented	1533	1548	1529	1510	1363	1321	1359	1463
Analysis of variance								
Model	***	***	***	***	***	***	***	***
Treatments	***	***	***	***	***	***	***	***
Contrasts								
Tunnel vs. no tunnel	***	***	***	***	***	***	***	***
Perforated vs. nonperforated	***	***	***	***	***	***	***	***
Tube vs. no tube	NS	NS	NS	NS	***	***	*	NS
Ventilated vs. nonventilated tunnels	***	***	***	***	***	***	***	***
Ventilated vs. perforated tunnels	***	***	***	***	***	***	***	***
26 May 1998								
No tunnel, no tube	345	350	345	344	346	349	344	344
No tunnel, tube	347	352	345	348	349	349	346	344
Clear perforated tunnel, no tube	365	367	365	366	365	366	365	362
Clear perforated tunnel, tube	365	366	364	364	369	366	365	361
Clear nonperforated tunnel, no tube	386	385	385	390	390	401	390	396
Clear nonperforated tunnel, tube	389	382	384	403	394	404	390	384
Infrared-blocked tunnel, no tube	1345	1336	1333	1324	1303	1273	1314	1342
Infrared-blocked tunnel, tube	1338	1349	1340	1298	1248	1284	1223	1315
Clear nonperforated tunnel, no tube, vented	1340	1337	1339	1322	1327	1287	1325	1330
Infrared-blocked tunnel, no tube, vented	1348	1365	1358	1310	1310	1267	1230	1325
Analysis of variance								
Model	***	***	***	***	***	***	***	***
Treatments	***	***	***	***	***	***	***	***
Contrasts								
Tunnel vs. no tunnel	***	***	***	***	***	***	***	***
Perforated vs. nonperforated	***	***	***	***	***	***	***	***
Tube vs. no tube	NS	NS	NS	NS	***	NS	***	NS
Ventilated vs. nonventilated tunnels	***	***	***	***	***	***	***	***
Ventilated vs. perforated tunnels	***	***	***	***	***	***	***	***

NS, ***, **** Nonsignificant or significant at $P = 0.05$, 0.01 , or 0.001 , respectively.

μmol·mol⁻¹ (Tables 2 and 3). These values were significantly greater than those of the PO and PT treatments (Tables 2 and 3), probably due to the ventilation cuts made on the leeward side of the tunnels, making air mixing minimal. At 6 (12 May) and 10 (18 May) d after transplanting in 1998, CO₂ concentration in CO, CT, IO, and IT treatments appeared stable during the entire day (Table 2). In 1999, at eight (13 May) days after transplanting, CO₂ levels increased slightly at 1800 HR and reached a minimum at 0900 HR (Table 3). This pattern of CO₂ levels suggests that soil respiration, rather than muskmelon respiration, dominated CO₂ supply in the tunnel during these periods.

The CO₂ evolution rate from the experimental soil ranged from 3 to 10 mmol·m⁻²·s⁻¹. A quadratic equation best described the relationship between soil temperature and soil respiration (Fig. 2). These results are in accordance with those of Pomazkina et al.

(1996) who found that the rate of CO₂ evolution from soil varied from 0.5 to 7.4 mmol·m⁻²·s⁻¹. Mulched minitunnels increased soil temperatures (Table 4). High soil temperature enhances microorganism activities in decomposing organic matter (Milkin and Bowden, 1996). Carbon dioxide concentration under polyethylene mulches has reached 670 μmol·mol⁻¹ (Hopen and Oekber, 1975). However, it has been reported that increased soil CO₂ concentration decreased root respiration (Bassirirad et al., 1996; Burton et al., 1997). This implies that the increased CO₂ concentration found under plastic mulches is a reflection of soil rather than root respiration. By using the equation in Fig. 2, the rate of CO₂ evolution from the mulched soil into the tunnel environment at 25 °C would be 5.8 mmol·m⁻²·s⁻¹. If we assume a completely closed environment in a 0.025 mm thick nonperforated clear tunnel, and a permeability of CO₂ of 0.6 nmol·m⁻²·s⁻¹ for every

Table 3. Effects of minitunnel and thermal water tube combinations on diurnal carbon dioxide concentrations on 13 and 20 May and 1 or 2 d before anthesis in 1999.

Minitunnel and thermal water tube combinations	CO ₂ (μmol·mol ⁻¹)							
	Time of the day (HR)							
	0000	0300	0600	0900	1200	1500	1800	2100
13 May 1999								
No tunnel, no tube	383	370	368	360	356	353	358	364
No tunnel, tube	382	362	368	360	357	357	360	360
Clear perforated tunnel, no tube	428	375	397	370	376	368	376	391
Clear perforated tunnel, tube	447	375	392	369	368	368	374	395
Clear nonperforated tunnel, no tube	1265	1269	1265	1247	1276	1327	1327	1299
Clear nonperforated tunnel, tube	1269	1278	1265	1244	1276	1328	1328	1299
Infrared-blocked tunnel, no tube	1288	1288	1270	1250	1277	1302	1325	1302
Infrared-blocked tunnel, tube	1293	1286	1267	1243	1283	1298	1325	1306
Analysis of variance								
Model	***	***	***	***	***	***	***	***
Treatments	***	***	***	***	***	***	***	***
Contrasts								
Tunnel vs. no tunnel	***	***	***	***	***	***	***	***
Perforated vs. nonperforated	***	***	***	***	***	***	***	***
Tube vs. no tube	NS	NS	NS	NS	NS	NS	NS	NS
20 May 1999								
No tunnel, no tube	380	369	358	359	352	350	352	358
No tunnel, tube	378	368	357	356	355	353	353	359
Clear perforated tunnel, no tube	383	375	360	358	372	362	355	363
Clear perforated tunnel, tube	386	375	365	357	376	364	356	363
Clear nonperforated tunnel, no tube	430	439	386	370	454	442	365	407
Clear nonperforated tunnel, tube	412	436	389	392	433	425	368	408
Infrared-blocked tunnel, no tube	1365	1323	1281	1333	1198	1045	1345	1387
Infrared-blocked tunnel, tube	1499	1402	1305	1378	1020	795	888	1085
Clear nonperforated tunnel, no tube, vented	1263	1268	1272	1235	1244	1101	1394	1417
Infrared-blocked tunnel, no tube, vented	1447	1351	1254	1386	819	1014	860	1107
Analysis of variance								
Model	***	***	***	***	***	***	***	***
Treatments	***	***	***	***	***	***	***	***
Contrasts								
Tunnel vs. no tunnel	***	***	***	***	***	***	***	***
Perforated vs. nonperforated	***	***	***	***	***	***	***	***
Tube vs. no tube	---	**	NS	NS	NS	*	***	***
Ventilated vs. nonventilated tunnels	***	***	***	***	***	***	***	***
Ventilated vs. perforated tunnels	***	***	***	***	***	***	***	***
One or 2 d before anthesis (dates varied)								
No tunnel, no tube	357	360	351	356	352	348	354	353
No tunnel, tube	356	363	352	355	353	349	355	352
Clear perforated tunnel, no tube	357	360	356	361	351	355	359	356
Clear perforated tunnel, tube	356	361	356	359	354	358	358	357
Clear nonperforated tunnel, no tube	391	395	392	361	368	364	364	377
Clear nonperforated tunnel, tube	390	395	380	360	378	365	367	383
Infrared-blocked tunnel, no tube	1241	1231	1297	1214	1081	976	1011	1124
Infrared-blocked tunnel, tube	1301	1208	1360	1197	982	789	928	1108
Clear nonperforated tunnel, no tube, vented	1216	1213	1210	1155	1103	1219	1130	1142
Infrared-blocked tunnel, no tube vented	1247	1241	1323	1202	980	872	965	1038
Analysis of variance								
Model	***	***	***	***	***	***	***	***
Treatments	***	***	***	***	***	***	***	***
Contrasts								
Tunnel vs. no tunnel	***	***	***	***	***	***	***	***
Perforated vs. nonperforated	***	***	***	***	***	***	***	***
Tube vs. no tube	NS	NS	NS	NS	NS	***	***	NS
Ventilated vs. nonventilated tunnels	***	***	***	***	***	***	***	***
Ventilated vs. perforated tunnels	***	***	***	***	***	***	***	***

NS, *, **, *** Nonsignificant or significant at $P = 0.05$, 0.01 , or 0.001 , respectively.

mended for production of many greenhouse crops (Mortensen, 1987). The water tubes reduced air temperature fluctuation in the nonperforated tunnels (Jenni et al., 1998), and provided more favorable temperatures for both photosynthesis and respiration. Since CO₂ serves as an output and input for photosynthesis and respiration, respectively, any changes of these processes due to temperature changes will ultimately alter the CO₂ concentration in the minitunnel.

In conclusion, nonperforated tunnels (CO, CT, IO, and IT) had significantly higher levels of CO₂ than perforated (PO and PT) and no tunnel treatments (OO and OT). The higher soil temperatures under the tunnel treatments likely contributed to greater evolution of CO₂ from the soil under the tunnels. Diurnal CO₂ fluctuation in the tunnel increased as muskmelon developed.

Literature Cited

millimeter thickness at 1 Pa pressure (Long and Hallgreen, 1985), then a loss of 0.0236 mmol.m⁻².s⁻¹ is very small as compared to the potential evolution from the soil. This indicates that soil respiration was mainly responsible for the increased CO₂ concentration in the tunnels. Observations in the nonperforated tunnels containing neither plants nor a thermal water tube (CO) indicates daily CO₂ concentrations were as high as 1295 μmol.mol⁻¹ (1997) and 1266 μmol.mol⁻¹ (1998), confirming that most of the CO₂ in the tunnels was derived from soil respiration.

Daily fluctuations of CO₂ in the tunnel increased as muskmelons developed (Tables 2 and 3). This was evident by 13 d after transplanting, when CO₂ levels peaked at night, decreased during the day, and increased again in late afternoon at 1800 HR. The fluctuation patterns followed CO₂ removal for photosynthesis (Nederhoff and Vegter, 1994), and replacement due to crop respiration (Amthor, 1991). Crops grown in enriched CO₂ during the daytime might increase nighttime respiration (Nijs et al., 1989), but decrease photorespiration (Amthor, 1991). In 1998 and 1999, daily CO₂ fluctuation in all treatments ranged from 3% to 11% and from 6% to 40%, respectively. Fluctuations were especially noticeable in nonperforated tunnels with a water tube, but levels remained higher than levels (800 μmol.mol⁻¹) recom-

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Table 4. Effects of mulch/minitunnel and thermal water tube combinations on maximum and average soil temperatures from transplanting to anthesis during 1997, 1998, and 1999.

Minitunnel and thermal water tube combinations	Soil temperature (°C)					
	1997		1998		1999	
	Max	Avg	Max	Avg	Max	Avg
No tunnel, no tube	23.4	19.5	22.2	19.1	23.9	20.0
No tunnel, tube	23.5	19.3	22.9	19.8	22.6	19.2
Clear perforated tunnel, no tube	24.1	20.1	23.6	20.5	23.9	19.2
Clear perforated tunnel, tube	23.8	19.7	24.8	21.8	24.4	20.0
Clear nonperforated tunnel, no tube	26.9	22.1	25.4	21.7	27.4	22.7
Clear nonperforated tunnel, tube	25.2	21.0	26.0	23.1	28.9	22.6
Infrared-blocked tunnel, no tube	28.2	23.8	31.1	26.1	31.9	24.5
Infrared-blocked tunnel, tube	28.3	23.2	30.7	26.4	34.3	25.3
Clear nonperforated tunnel, no tube, vented	---	---	27.3	23.0	25.1	20.8
Infrared-blocked tunnel, no tube, vented	---	---	29.5	25.2	27.2	22.1

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