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Differential Cold Stress Duration and Frequency Treatment Effects on Muskmelon Seedling and Field Growth and Yield

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Summary

In attempts to produce the earliest yields of spring melons, muskmelon fields are transplanted in late winter before the last frost date. Seedlings may then be repeatedly exposed to temperatures cycling between almost freezing and optimal temperatures for weeks until the weather stabilizes. To simulate this potential cold stress possible in the field, 'Athena' *Cucumis melo* L. (Reticulatus Group) muskmelon seedlings were subjected to 2±1 °C in a walk-in cooler then to 29±5 °C in a greenhouse before field transplanting. In 1997, the durations of cold exposure were 3, 6, and 9 hours which were repeated (frequency) for 1, 3, 6, and 9 days before transplanting. In 1998, duration levels were the same as in 1997 but frequencies were 3, 6, and 9 days. In both years, cold stress duration interacted with frequency, significantly reducing almost all seedling growth characteristics of muskmelon, indicating that these two stress factors are not acting independently and that they need to be considered together. Muskmelon flowering and vining were delayed significantly by increasing cold stress duration and frequency in both years but fruit set was delayed only in 1998. Muskmelon yields decreased with increasing cold stress frequency in both years but not with cold stress duration indicating that frequency was the driving factor behind the yield reduction. Therefore, muskmelon plants should not be planted early in the season without protective tunnels if there is a chance of repeated low temperature exposure.

Zusammenfassung

Die Wirkung unterschiedlicher Kältestressdauer und –häufigkeit auf Netzmelonensämlinge, ihr Wachstum und die Erntemenge. Um im Frühjahr die ersten Netzmelonen ernten zu können, werden die Sämlinge im Spätwinter vor den letzten Frösten gepflanzt. Die Bedingungen, denen sie dann über Wochen bis zur Wetterstabilisierung ausgesetzt sind, können wiederholt zwischen fast Gefrieren und Optimaltemperatur wechseln. Zur Simulation dieses potentiellen Kältestresses wurden Netzmelonensämlinge *Cucumis melo L. (Reticulatus Group)* der Sorte 'Athena' in Kühlräumen bei 2±1 °C und anschließend im Gewächshaus bei 29±5 °C kultiviert, bevor sie auf dem Feld ausgepflanzt wurden. Im Jahr 1997 betrug die Kältedauer 3, 6 oder 9 Stunden und wurde 1, 3, 6 bzw. 9 Tage lang wiederholt. 1998 waren die Abstufungen der Kältedauer wie 1997, allerdings wurden sie 3, 6 bzw. 9 Tage wiederholt. In beiden Jahren traten Interaktionen zwischen Dauer und Wiederholungshäufigkeit der Kältestressbehandlungen auf, die beinahe alle erfassten Wachstumsparameter negativ beeinflussten. Diese Ergebnisse zeigen, dass die beiden Stressfaktoren nicht unabhängig voneinander wirken und deshalb gemeinsam beurteilt werden müssen. In beiden Jahren führte die Zunahme von Kältestressdauer und -häufigkeit zu einer signifikanten Verzögerung der Blüten- und Rankenbildung, doch zog dies nur 1998 einen verzögerten Fruchtansatz nach sich. Mit zunehmender Kältestresshäufigkeit nahm die Erntemenge in beiden Jahren ab. Die Variation der Kältedauer zeigte keine entsprechende Wirkung. Das weist daraufhin, dass die Kältestresshäufigkeit die Ursache für die Mengenreduktion darstellt. Netzmelonen sollten deshalb früh in der Saison, wenn noch die Möglichkeit des wiederholten Auftretens von niedrigen Temperaturen besteht, nicht ohne schützenden Folientunnel gepflanzt werden.

Key words. Chilling stress – *Cucumis melo* – Cucurbitaceae – yield

Introduction

The optimum air temperature for muskmelon *Cucumis melo L. (Reticulatus Group)* plant growth ranges from 20 to 32 °C, with 18 °C (minimum) and 35 ° (maximum) (BATES and ROBINSON 1995). Exposure of plants of a tropical or subtropical nature, such as cucurbits, to chilling temperatures may stunt plant growth, induce wilting and necrotic lesions on leaves, and increase susceptibility to diseases and pathogens (HÄLLGREN and ÖQUEST

1990). Growth may be reduced as a consequence of impaired photosynthesis, respiration, membrane integrity, and hormonal balance (ALLEN and ORT 2001).

Melons are grown extensively in southwest Turkey and southeast United States. Although climatic conditions in these areas are ideal for growing melons, targeting late June and early July harvests requires field planting in early March before the last killing frost. Once the seedlings have been planted in the field, they may be exposed to temperatures cycling between chilling and optimal for weeks before temperatures finally stabilize.

Previous work has shown that cold temperatures reduced the growth of tomato (SINGER et al. 1993), cucumber (HELMY et al. 1999), muskmelon (RISSER et al. 1978), and watermelon (KORKMAZ and DUFAULT 2001). Little is known about temperatures repeatedly alternating from cold to warm and how these stresses affect muskmelon seedling growth, earliness, and yield. Therefore, the objective of this study was to determine the long-term effects of repeated exposure to short-term cold stress at transplanting on muskmelon seedling growth, earliness, yield, and fruit quality.

Materials and Methods

Greenhouse sudy

'Athena' muskmelon seeds were obtained from Rogers Brothers Seed Co. (Salinas, CA, USA). Seeds were planted with the micropyle pointing down in 5.4 cm deep (57 cm^3) cells (Hummert Int., Earth City, MO, USA) filled with Metro Mix 300 growth medium (Grace Sierra Co., Milpitas, CA, USA) on 1 May 1997 and 4 May 1998. The flats were covered with plastic sheets to retain moisture and placed in a germination room at 32 °C for two days then moved into a greenhouse where they were kept under natural photoperiod and a temperature regime of 25±3 °C (day) and 20±3 °C (night). Seedlings were watered as needed with tap water and fertilized twice with 50 mg L^{-1} of a 20N-8.6P-16.6K water soluble fertilizer.

Table 1. Timing (24-hr system) of 2 °C cold temperature stress treatments imposed on 'Athena' muskmelon seedlings in dark coolers in 1997 and 1998.

		Clock hours						
Duration (hrs)	Frequency (days)	Days before field planting						
		9 to 7	6	5	4	3	2	1
1997								
3	1	G[z]	G	G	G	G	G	21.00–24.00
3	3	G	G	G	G	21.00–24.00	21.00–24.00	21.00–24.00
3	6	G	21.00–24.00	21.00–24.00	21.00–24.00	21.00–24.00	21.00–24.00	21.00–24.00
3	9	21.00–24.00	21.00–24.00	21.00–24.00	21.00–24.00	21.00–24.00	21.00–24.00	21.00–24.00
6	1	G	G	G	G	G	G	24.00–06.00
6	3	G	G	G	G	24.00–06.00	24.00–06.00	24.00–06.00
6	6	G	24.00–06.00	24.00–06.00	24.00–06.00	24.00–06.00	24.00–06.00	24.00–06.00
6	9	24.00–06.00	24.00–06.00	24.00–06.00	24.00–06.00	24.00–06.00	24.00–06.00	24.00–06.00
9	1	G	G	G	G	G	G	21.00–06.00
9	3	G	G	G	G	21.00–06.00	21.00–06.00	21.00–06.00
9	6	G	21.00–06.00	21.00–06.00	21.00–06.00	21.00–06.00	21.00–06.00	21.00–06.00
9	9	21.00–06.00	21.00–06.00	21.00–06.00	21.00–06.00	21.00–06.00	21.00–06.00	21.00–06.00
1998								
3	3	G	G	G	G	21.00–24.00	21.00–24.00	21.00–24.00
3	6	G	21.00–24.00	21.00–24.00	21.00–24.00	21.00–24.00	21.00–24.00	21.00–24.00
3	9	21.00–24.00	21.00–24.00	21.00–24.00	21.00–24.00	21.00–24.00	21.00–24.00	21.00–24.00
6	3	G	G	G	G	24.00–06.00	24.00–06.00	24.00–06.00
6	6	G	24.00–06.00	24.00–06.00	24.00–06.00	24.00–06.00	24.00–06.00	24.00–06.00
6	9	24.00–06.00	24.00–06.00	24.00–06.00	24.00–06.00	24.00–06.00	24.00–06.00	24.00–06.00
9	3	G	G	G	G	21.00–06.00	21.00–06.00	21.00–06.00
9	6	G	21.00–06.00	21.00–06.00	21.00–06.00	21.00–06.00	21.00–06.00	21.00–06.00
9	9	21.00–06.00	21.00–06.00	21.00–06.00	21.00–06.00	21.00–06.00	21.00–06.00	21.00–06.00

[z] Seedlings kept in the greenhouse all day.

Before the onset of the cold stress, cell flats were cut into quarters with each section containing eight transplants for transplant growth analysis and fifteen seedlings for field planting. Each quarter represented one replication. The cold stress treatments consisted of a factorial combination of cold duration and frequency. Imposition of cold stress started on 20 May 1997 and 19 May 1998 and ended on 29 May 1997 and 28 May 1998. Plants were moved into dark walk-in coolers during the night, exposed to cold temperatures for prescribed time, and then returned to a warm greenhouse (25 °C) (Table 1). Duration of cold exposure in 1997 and 1998 was 3, 6, and 9 hours, and repetition of cold exposure (frequency) were 1, 3, 6, and 9 days in 1997 and 3, 6, and 9 days in 1998. The combination of these duration and frequency levels produced 12 and 9 treatment combinations in 1997 and 1998, respectively. The cumulative exposure to 2 °C ranged from 3 hours to 81 hours in 1997 and from 9 hours to 81 hours in 1998. Additionally, a control treatment that had plants never exposed to cold stress and remained in the greenhouse was also included. The treatments were replicated four times in 1997 and six times in 1998 with all trays arranged in a randomized complete block design in the greenhouse.

On 29 May 1997 and 28 May 1998, eight plants from each treatment were harvested for transplant growth and quality determination. The following growth variables were measured: leaf area per seedling (including petioles) as measured with a Model LI-3100 leaf area meter (LI-COR, Lincoln, NE, USA.), shoot and washed root fresh weight (cut at the medium surface) and dry weight (dried at 65 °C for 48 h). Leaf chlorophyll content of the youngest fully expanded leaf on each plant was determined using a SPAD chlorophyll meter (SPAD 502, Minolta Co., Osaka, Japan) and expressed in SPAD units defined by the manufacturer as "1" equivalent to very pale green coloration (chlorotic) and "50" equivalent to very dark green coloration. Sucrose content of dried muskmelon seedlings was determined on ground shoot samples using the Anthrone method as described by MORRIS (1948).

Growth data were tested by analysis of variance (ANOVA), and mean separation was performed by the least significant difference at P=0.05 if the F test was significant. The relative importance of each source of variation in the ANOVA including cold stress duration and frequency was determined by partitioning the total sum of squares for treatments into main and interaction effects and expressing the individual contributions to variation as a percentage of the total sum of squares for the model. Orthogonal contrasts were performed comparing the effect of cold stress (pooled over all cold stress treatments) to the non-stressed control.

Field Study

'Athena' muskmelon seedlings were grown as described above and subjected to 2 °C cold temperature stress (Table 1). Fifteen transplants from each treatment plot were hand-transplanted into the field on 29 May 1997 and 28 May 1998 at Clemson University Coastal Research and Education Center in Charleston, SC, USA after all risk of frosts had passed. Soil tests were conducted for the experimental area each year prior to planting, and then the fields were fertilized with 175N-75P-146K kg ha^{-1}. The fields were limed with 146Ca-88Mg kg ha^{-1} from dolomitic limestone in both years as recommended by soil tests. Beds on 1.8 m centres were fumigated with methyl bromide (75 % methyl bromide and 25 % chloropicrin) at the rate of 450 kg ha^{-1} and mulched with 0.032 mm black plastic. The soil type was Younges loamy fine sand, an Aquic Hapludult. The treatment plots consisted of one row, 4.5 m long, and contained 15 plants. Treatments were replicated four times in 1997 and six times in 1998 in a randomized complete block design. The plots were irrigated as needed using tensiometers (20 cm deep) to detect a 15 % moisture depletion. The plants were sprayed with pesticides based on standard commercial recommendations from transplanting to one week before the first harvest (COOK 1996).

Effects of cold stress on early stand establishment in the field were monitored. Days to vining (date first runner touched the ground), detection of first male and female flowers, and first fruit set (>3 cm in diameter) were recorded daily for the second, third, and fourth plants of each test row. In 1997, muskmelons were harvested 8 times at full slip (23, 25, 28 and 30 July, 1, 4, 7, and 12 Aug). In 1998, seven harvests were made (17, 20, 22, 24, 27, 29, and 31 July). On the last harvest, all fruits were stripped from each plant. Each fruit was weighed and graded as marketable or cull according to USDA standards (U.S. Dept. of Agric. 1978). If fruits were <0.7 kg and misshapen, they were classified as cull.

To determine the effects of cold temperature exposure on fruit quality, a sub-sample of 3 fruits in 1997 (one from first 3 harvests) and 5 fruits in 1998 (one from first 5 harvests) from each treatment plot was randomly selected, fruits were cut open, and length and width were measured. Sugar content was measured with a hand-held refractometer (ATC-1E, Atago Co., Japan) on a sample taken from the center of the each fruit between the blossom and stem ends. Data analysis was performed same as outlined in the greenhouse study.

Results

The effect of cold stress on seedling growth

Increasing the duration and frequency of exposure to 2 °C reduced significantly almost all growth variables in comparison to plants not exposed to cold stress in both years.

In 1997, all of the seedling variables were affected by either cold stress duration or frequency or by both (Table 2). Although the main effects of both duration and frequency affected shoot fresh and dry weights, the main effects of frequency accounted for major portions of total variation in these variables. Frequency was also the major contributor to the variation in sucrose content and as frequency increased from 1 to 9 days, sucrose content decreased but leveled off with 6 days of frequency. The main effects of duration accounted for most of the total variation in root fresh and dry weights, leaf area and chlorophyll content. Cold stress duration interacted with frequency to affect significantly all seedling growth variables except sucrose content (Table 2), indicating differential im-

Table 2. Influence of cold temperature stress duration and frequency on muskmelon seedling growth variables.

	Shoot weight (mg plant^{-1})				Root weight (mg plant^{-1})				Leaf area		Sucrose		Chlorophyll	
	fresh		dry		fresh		dry		(cm^2 plant^{-1})		(mg g^{-1} dry wt)		(SPAD)	
Cold stress	1997	1998	1997	1998	1997	1998	1997	1998	1997	1998	1997	1998	1997	1998
Duration														
3	3846 a[z]	3068 a	485 a	396 a	2657 a	1468 a	131 a	120 a	58.4 a	45.2 a	86.7 a	105.2 a	28.3 a	28.1 a
6	3158 b	2670 b	404 b	336 b	2131 b	1235 b	105 b	107 b	45.7 b	39.8 b	78.9 ab	97.9 a	26.8 b	25.7 b
9	2981 c	2510 c	386 b	328 b	2007 c	1000 c	100 b	94 c	45.2 b	36.6 c	68.5 b	75.4 b	26.6 b	25.9 b
Frequency														
1	3919 a	–[y]	478 a	–	2472 a	–	121 a	–	58.1 a	–	101.3 a	–	27.6	–
3	3204 c	3405 a	427 b	433 a	2367 b	1610 a	116ab	135 a	47.2 c	51.0 a	80.9 b	102.2 a	27.3	28.7 a
6	3459 b	2801 b	441 ab	362 b	2204 c	1155 b	112 b	105 b	51.2 b	41.4 b	66.0 c	94.8 a	26.9	25.8 b
9	2731 d	2043 c	353 c	265 c	2016 d	938 c	100 c	81 c	42.7 d	29.3 c	63.9 c	81.5 b	27.0	25.2 c
Cold $\bar{X}$	3331	2750	425	353	2265	1234	112	107	48.8	40.6	77.8	90.8	27.2	26.2
Control	4249	5076	519	699	2401	1665	114	146	67.9	75.0	142.0	114.0	27.1	29.2
Contrasts														
Control vs. cold $\bar{X}$	*	**	*	**	NS	*	NS	**	**	**	**	*	NS	*
Source of variation[x]														
Rep	5	2	4	1	2	1	3	0	3	3	2	4	3	1
Duration (D)	29**	12**	26**	13**	57**	24**	53**	14**	32**	10**	12*	38**	30**	20**
Frequency (F)	38**	67**	29**	68**	21**	51**	17**	61**	27**	62**	47**	17**	4	37**
D x F	8*	2	19**	5**	10**	14**	14**	14**	12**	5	1	3	20*	19**
Error	20	17	22	13	10	10	13	11	26	20	39	38	43	23
CV	11	12	12	10	6	12	7	11	14	14	21	16	4	5

NS, *, ** Non significant or significant at P=0.05 or 0.01, respectively.
[z] Means within columns and main effects separated by LSD at the 0.05 level.
[y] Treatment not used in 1998.
[x] Sum of squares for each source converted to a percentage of total sum of squares in the ANOVA.

pact of duration at various frequencies (Table 3). Shoot fresh weight increased at the lowest level of both factors compared to control plants; however, as frequency increased from 1 to 9 days at any level of duration, seedling fresh weight decreased, resulting in the smallest seedlings at the higher levels of both factors. Shoot dry weight decreased at 6 and 9 hours of duration as frequency increased from 1 to 9 days, but at 3 hours duration, this variable remained unchanged. As cold stress frequency increased from 1 to 9 days, root fresh weight decreased at all levels of duration where as increasing frequency caused reductions in root dry weight only after 6 and 9 hours duration. Leaf area also decreased with increasing frequency at all duration levels. The interaction between the two cold stress factors on chlorophyll was inconsistent and changes in chlorophyll content of muskmelon seedlings were very minor. Orthogonal contrasts comparing the unstressed control to the pooled mean of all cold stress treatments indicated that cold stress stimulated a decrease in shoot fresh and dry weights, leaf area and sucrose content (Table 2).

Plants responded similarly to the cold stress in 1998 as 1997 although there were a few differences between the years. Cold stress frequency accounted for most of the total variation in all muskmelon seedling growth variables except sucrose content (Table 2). As frequency increased from 3 to 9 days, shoot fresh weight and leaf area decreased. Cold stress duration and experimental error accounted for the same amount of variation in sucrose content, which decreased when duration increased from 6 to 9 hours. Duration also interacted with frequency to significantly affect most of the seedling growth variables (Table 4) in 1998. Shoot dry weight decreased as stress frequency increased from 3 to 9 days at any duration levels and the highest levels of both cold stress factors produced the smallest plants. Although not statistically compared, cold stress seem to increase root fresh and dry weights compared to control plants at the lowest levels of both cold stress factors but increasing frequencies from 3 to 9 days at any levels of duration reduced these variables. Increasing duration from 3 to 9 hours at 6 and 9 days of frequency, however, did not cause any change in root dry weight. Chlorophyll content decreased with increasing frequency from 3 to 9 days at 3 and 6 hours of duration levels and remained unchanged at 9 hours of duration. Converse to 1997, orthogonal contrasts comparing the

Table 3. Interaction of cold temperature stress duration and frequency on muskmelon seedling growth in 1997.

Duration (hrs)	Frequency (days)				
	0	1	3	6	9
			Shoot fresh weight (mg)		
0	4249 [z]	–	–	–	–
3	–	4373 a[y]	3572 c	3975 b	3463 cd
6	–	3937 b	3376 d	3031 e	2288 g
9	–	3447 cd	2665 f	3369 d	2443 g
			Shoot dry weight (mg)		
0	519	–	–	–	–
3	–	494 ab	465 ab	524 a	457 ab
6	–	493 ab	457 ab	365 cd	294 d
9	–	448 b	353 d	436 bc	306 d
			Root fresh weight (mg)		
0	2401	–	–	–	–
3	–	2678 ab	2746 a	2617 bc	2586 c
6	–	2503 d	2344 e	1994 g	1681 i
9	–	2408 e	2010 g	2002 g	1781 h
			Root dry weight (mg)		
0	114	–	–	–	–
3	–	125 bc	136 ab	137 a	127 abc
6	–	120 cd	113 d	102 e	84 g
9	–	117 cd	98 ef	96 efg	89 fg
			Leaf area (cm^2)		
0	67.9	–	–	–	–
3	–	65.8 a	53.2 c	60.5 b	54.1 c
6	–	59.1 b	47.6 e	40.9 f	35.4 g
9	–	49.3 de	40.5 f	52.2 cd	38.6 fg
			Chlorophyll (SPAD)		
0	27.1	–	–	–	–
3	–	29.8 a	28.7b	27.0 def	27.8 c
6	–	26.8 efg	27.4 cd	26.3 gh	26.5 fg
9	–	26.3 gh	25.8 h	27.3 cde	26.8 efg

[z]Mean for control given for comparison purposes only and not included in the statistical analysis.
[y]Mean separation of each variable within rows and columns by LSD at the P=0.05 level.

unstressed control to the pooled mean of all cold stress treatments in 1998 showed a decline in all seedling growth variables (Table 2).

The effect of cold stress on field performance

It was expected that, although in a diminishing fashion, the effect of short-term cold stress at the seedling stage would last by fruit maturity; thus, in order to track this assumption, different events in field were monitored. The events that were used to judge the field growth rate occurred in the following developmental and chronological order: male flowering, vining, female flowering, and fruit set.

Both cold stress duration and frequency affected early plant growth in the field in 1997 (Table 5). As cold stress frequency increased progressively from 1 to 9 days, 3 additional days were needed for the appearance of first male flowers and vining. Cold stress duration affected earliness to female flowering more than frequency. Increasing duration from 3 to 9 hours increased days to first female flower by 3 days. Earliness to the first fruit was the only variable that was unaffected by the main effects of duration and frequency. Experimental error from uncontrolled factors in the field accounted for the most of the variation in all variables. Orthogonal contrasts comparing the unstressed control to the pooled mean of all cold stress treatments revealed a retardation of early muskmelon field growth as indicated by increased time to 1st male flower and vining.

In 1998, the main effects of cold stress duration and frequency affected all events to monitor muskmelon field growth (Table 5). Duration accounted for the major portions of the total variation in earliness to male flowering and increasing cold stress duration from 3 to 9 hours delayed earliness to male flower and vining by 7 and 2 days, respectively. Frequency had a stronger effect on earliness to female flowering and fruit set than dura-

Table 4. Interaction of cold temperature stress duration and frequency on muskmelon seedling growth in 1998.

Duration (hrs)	Frequency (days)			
	0	3	6	9
		Shoot dry weight (mg)		
0	699 [z]	–	–	–
3	–	457 a [y]	391 cd	340 e
6	–	411 bc	365 de	233 f
9	–	431 ab	329 e	222 f
		Root fresh weight (mg)		
0	1665	–	–	–
3	–	2116 a	1249 c	1040 e
6	–	1542 b	1253 c	910 fg
9	–	1173 d	963 f	864 g
		Root dry weight (mg)		
0	146	–	–	–
3	–	169 a	107 cd	83 f
6	–	124 b	111 c	85 ef
9	–	111 c	96 de	76 f
		Chlorophyll (SPAD)		
0	29.2	–	–	–
3	–	30.9 a	27.3 c	26.2 d
6	–	28.5 b	25.6 e	22.9 g
9	–	26.6 d	24.4 f	26.6 d

[z]Mean for control given for comparison purposes only and not included in the statistical analysis.
[y]Mean separation of each variable within rows and columns by LSD at the P=0.05 level.

tion, delaying these variables by 3 and 2 days, respectively. Experimental error from uncontrolled factors was the major source of the variation in all variables except earliness to male flowering. As the growth season progressed, the difference between treatments somewhat disappeared, indicating that a slow recovery from cold stress was in progress. In 1998, duration interacted with frequency to significantly affect earliness to male flowering (Table 6). At all durations, increasing frequency from 3 to 9 days delayed male flowering. Additionally, at all frequencies, increasing duration delayed male flowering.

In both years, neither the main effects of duration nor frequency affected muskmelon fruit number (Table 7). The trends, however, indicated that increasing cold stress duration and frequency reduced fruit number by 10 and 20 % in 1997 and 10 and 11 % in 1998, respectively, but these reductions were not significant since duration and frequency together accounted for only 19 % or less of total variation in all variables during both years. In both years only the main effects of cold stress frequency affected total marketable yield and total yields decreased by 24 % in 1997 and 13 % in 1998 with increasing frequency to 9 days. Orthogonal contrasts comparing the control to the pooled mean of all cold-stressed treatments indicated that fruit number and total yield were higher for control plants than cold-stressed plants in 1998, but not in 1997. Experimental error was the main source of total variation in fruit number and yield in both years. The contribution of experimental error to the total variation remained the same in 1998 and increasing number of replication from 4 to 6 unaffected CV values.

Muskmelon cull yield was unaffected by cold stress in both years. Additionally, cold stress did not affect fruit quality, specifically fruit length, diameter, and soluble solid content in either year (data not presented).

Discussion

Differential cold stress durations and frequencies profoundly retarded muskmelon seedling growth. Exposure of muskmelon seedlings to 2 °C for increasingly longer periods reduced shoot and root growth, and carbohydrate content in both years, with growth reductions becoming more severe as cold stress duration and frequency increased. These results agree with cold damage reported on corn relative growth rate (WOLFE 1991), cucumber leaf area (BULDER et al. 1987), watermelon shoot fresh and dry weights (KORKMAZ and DUFAULT 2001) and cucumber and squash root fresh and dry weights (REYES and JENNINGS 1994). In addition, HASSELL (1979) reported that 'Gold Star' muskmelon seedlings exposed to continuously 1 and 4.4 °C severely yellowed within the 2nd day of exposure and some of them died after 4 days of exposure.

Plant growth reductions may be attributable to several factors, including impaired photosynthesis, respiration, membrane integrity, water relations and hormonal balance (ALLEN and ORT 2001). Reduction in photosynthatetic capacity can be facilitated by reduced CO_2 uptake and/or loss of chlorophyll during and following cold temperature exposure or impaired oxidation-reduction chain linking PSII to PSI (KINGSTON-SMITH et

Table 5. Influence of cold temperature stress duration and frequency on muskmelon early field growth.

	Days to							
	1st male flower		Vining		1st female flower		1st fruit set	
Cold stress	1997	1998	1997	1998	1997	1998	1997	1998
Duration (hrs)								
3	5.6 b[z]	4.4 c	11.0 c	9.1 c	17.9 b	18.1 b	30.5	23.4 b
6	5.3 b	8.9 b	12.8 b	10.0 b	18.7 b	17.4 b	29.7	23.7 b
9	7.1 a	11.4 a	13.5 a	11.0 a	20.7 a	19.7 a	31.7	24.8 a
Frequency (days)								
1	4.6 b	–[y]	10.4 c	–	17.6 c	–	29.3	–
3	5.3 b	5.4 c	12.8 b	9.2 b	18.8 b	16.9 c	30.8	22.8 c
6	6.7 a	8.2 b	12.8 b	10.6 a	19.9 a	18.4 b	30.9	24.2 b
9	7.4 a	11.2 a	13.9 a	10.3 a	20.2 a	20.0 a	31.4	24.9 a
Cold $\bar{X}$	6.0	8.3	12.5	10.1	18.4	18.2	30.3	24.0
Control	4.1	2.8	8.6	7.7	19.3	15.1	30.2	21.3
Contrasts								
Control vs. cold $\bar{X}$	*	**	*	*	NS	NS	NS	NS
Source of variation[x]								
Rep	0	2	3	5	2	8	6	19
Duration (D)	16**	47**	22**	23**	23**	13**	11	14**
Frequency (F)	32**	31**	33**	13**	18*	24**	10	28**
D x F	8	8**	9	8	6	5	8	7
Error	44	11	33	51	51	50	65	42
CV	26	21	12	13	11	12	8	5

NS, *, ** Nonsignificant or significant at P= 0.05 or 0.01, respectively.
[z]Means within columns and main effects separated by LSD at the 0.05 level.
[y]Treatment not used in 1998.
[x]Sum of squares for each source converted to a percentage of total sum of squares in the ANOVA.

Table 6. Interaction of cold temperature stress duration and frequency on male flowering of muskmelon plants in 1998.

Duration (hrs)	Frequency (days)			
	0	3	6	9
	Days to first male flower			
0	2.8[z]	–	–	–
3	–	3.4 g[y]	4.7 f	5.1 f
6	–	5.6 f	8.6 d	12.7 b
9	–	7.2 e	11.3 c	15.7 a

[z]Mean for control given for comparison purposes only and not included in the statistical analysis.
[y]Mean separation within rows and columns by LSD at the P=0.05 level.

al. 1999). Several studies documented that chilling sensitivity of plants is moderated by carbohydrate levels (KING et al. 1988), by light/dark cycles (KING and REID 1987), and by short-term cold acclimation (CHANG et al. 2001). Severe leaf yellowing and lowered chlorophyll and carbohydrate (sucrose) levels reported in our study concur that some chloroplasts may have been indeed killed and that plants' carbohydrate reserves were depleted due to increasing hours of cold stress.

Field growth of muskmelons in both years was significantly delayed with increasing cold stress hours, but the response slightly differed each year. Excessive rainfall and cooler temperatures during flowering in 1997 (Table 8) probably inhibited bee activity to a great extent, which may have delayed pollination or caused extensive abortion of female flowers and fruits, allowing plants exposed to cold stress for longer periods to set fruit at the same time as those exposed to cold stress for shorter periods. In 1998, however, the weather was very conducive to muskmelon growth with timely rainfall and warmer temperatures.

Flower initiation in most plants including cucurbits starts within three weeks after the cotyledon expansion and is highly correlated with daily temperatures

Table 7. Influence of cold temperature stress duration and frequency on total muskmelon yield.

Cold stress	Fruits / plot		Yield (kg/plot) [z]	
	1997	1998	1997	1998
Duration (hrs)				
3	23.7	26.2	63.8	84.5
6	22.9	25.6	63.5	78.3
9	21.4	23.3	57.2	75.5
Frequency (days)				
1	24.8	–[y]	69.8 a[x]	–
3	22.8	26.7	59.6 ab	85.9 a
6	23.2	24.7	63.7 ab	77.7 ab
9	19.8	23.7	53.0 b	74.8 b
Cold $\bar{X}$	22.6	25.1	61.6	79.7
Control	26.0	30.7	69.9	93.7
Contrast				
Control vs. cold $\bar{X}$	NS	*	NS	*
Source of variation[w]				
Rep	1	2	3	4
Duration (D)	4	8	5	8
Frequency (F)	15	8	19*	13*
D x F	16	5	9	2
Error	64	77	64	73
CV	19	18	22	16

[NS, *] Nonsignificant or significant at P= 0.05.
[z]Conversion factor for kg ha^{-1} is 1216.
[y]Treatment not used in 1998
[x]Means within columns separated by LSD at the P=0.05 level.
[w]Sum of squares for each source converted to a percentage of total sum of squares.

Table 8. Summary of weather data for 1997 and 1998 growing season[z] of muskmelon.

	May		June		July		August	
	1997	1998	1997	1998	1997	1998	1997	1998
Rainfall (mm)	0	0	343	76	216	173	17	–
Temperatures (°C)								
Ext. minimum	15.0	20.0	12.7	11.6	17.7	20.5	15.6	–
Mean minimum	15.9	20.8	19.4	22.4	22.2	23.8	20.4	–
Ext. maximum	28.3	31.0	32.7	37.8	35.5	36.6	31.6	–
Mean maximum	27.0	26.1	28.3	34.4	32.0	33.8	30.0	–
Mean	21.7	24.7	23.8	28.3	27.2	28.8	25.3	–

[z]Data represent the time between May 29 and August 12 in 1997 and May 28 and July 31 in 1998

(HURD and COOPER 1970). Warmer temperatures enhance flower development, but both below and above optimum temperatures delay flower initiation (MOE and HEINS 1990). DUNLAP (1986) reported that soil temperatures above 21 °C accelerated female flowering and fruit set of muskmelon cultivar 'Tamuvalde'. Furthermore, HASSELL (1979) reported that exposing 'Gold Star' muskmelon seedlings to 27/1 °C (day/night) for 8 days delayed perfect flowering by 4 days compared to those exposed to 27/18 °C. The results of this study agree with these previous studies, but it is important to note that cold stress affected fruit set minimally, since first fruiting of those exposed to 2 °C for longer periods occurred only 2 days later than those exposed for shorter periods and by fruit set.

Total muskmelon yields decreased significantly by increasing cold stress frequency in both years indicating that the driving factor behind the yield reductions was the cold stress frequency not the duration. This implies that repeated exposure of muskmelon plants early in the season to low temperatures will have much more

profound effect on the long-term yield than the duration of low temperature exposure.

Although very scarce, there are few studies on the effects of low temperatures on muskmelon growth and yield. HASSELL (1979) found that exposing two-week old 'Gold Star' muskmelon seedlings to 1 °C during night time (9 hours) for eight days reduced yield by 19 % compared to plants exposed to 18 °C during nights. KORKMAZ and DUFAULT (2003) reported that growth reductions at transplanting stage of 'Sugar Bowl' muskmelons caused by exposure to 2 °C for just 11 hours persisted until harvest, reducing total yields by 10 %. AZIZ et al. (2001) also found that using nonperforated tunnels along with thermal water tubes significantly increased early yields of 'Earligold' melon plants over mulch alone during the three years of their research due to increased air temperature.

To reduce the risk of early plantings from a production standpoint, protective tunnels or thermal tubes can be used as suggested by JENNI et al. (1998). Although they are costly, non-perforated tunnels protect against chilling/freezing temperatures and may increase early yields, particularly if greater returns are expected for early production.

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