Effects of Soil Moisture, Cultivar, and Postharvest Handling on Pillowy Fruit Disorder in Cucumber

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Abstract. Two experiments (1989 and 1990) were designed to characterize the response of cucumber (*Cucumis sativus* L.) plants with different leaf types [normal leaf (*LL*) vs. little leaf (*ll*)] to high soil moisture tension (SMT) and to determine whether hydrocooling would reduce the severity of pillowy fruit disorder (PFD). Comparisons were made among nine cultivars (7 *LL* and 2 *ll*) for aboveground vegetative and fruit response, and between two irrigation regimes. High SMT generally caused increased wilt ratings and stomatal conductance and decreased plant dry weight. PFD severity of fruit from watered plots was less [61% (Expt. 1, 1989) and 26% (Expt. 1, 1990)] than of fruit harvested from plots in which water was withheld. The response of the two *ll* cultivars to moisture stress differed depending on environmental conditions. Increased PFD severity was associated with increased temperature, lower relative humidity (RH), and excluding hydrocooling during postharvest handling. Of the four storage treatments examined, hydrocooling to $\approx 8.5^{\circ}\text{C}$ then storage at 15°C and 85% RH for 4 days produced fruit with the least PFD symptoms. Fruit of 'Carolina' (*LL*) exhibited the highest PFD ratings, while those of 'Calypso' (*LL*) were consistently low compared to other cultivars. Processors can lower PFD incidence and severity by ensuring that adequate moisture is available to plants during fruit enlargement and that harvested fruit are hydrocooled before shipping and storage.

Cucumber vine growth, lateral branching, leaf area, fruit set, and growth rate are adversely affected when plants are subjected to soil moisture deficits (Cummins and Kretchman, 1975). Likewise, leaf water potential decreases with increases in soil moisture tension (SMT), resulting in reduced transpiration (Kramer, 1983; Krizek, 1985).

Fruit yield and quality are also affected by plant water stress. For example, pillowy fruit disorder (PFD) in cucumber is a water- and Ca-related anomaly (Staub et al., 1988; Thomas and Staub, 1992). PFD can be recognized when fruit are radially cut during grading before fresh-pack processing. PFD is typified by styrofoam-like, opaque-white, porous-textured mesocarp tissue in freshly harvested fruit. Affected regions become water-soaked and grayish-brown lesions appear in the overnight-refrigerated product, reducing its textural quality.

Staub et al. (1988) noted that the severity of PFD symptoms increases as mesocarp Ca levels decrease. When plant transpiration is restricted by high relative humidity (RH) (89%), lower fruit Ca levels and a higher PFD incidence were observed compared to fruit that developed at lower (74%) relative humidity (RH). Likewise, Thomas and Staub (1992) observed that PFD was more frequent and more severe (more mesocarp affected) in fruit harvested from treatments in which water was withheld compared to fruit from well-watered treatments.

Walters et al. (1990) conducted a series of experiments that compared the relative water content, osmotic potential, membrane leakage, cell wall composition, and PFD severity of fruit stored at high (93%) and low (62%) RH. Results indicate that fruit stored at 62% RH lost weight more rapidly, showed a more rapid decline in relative water content and osmotic potential, and exhibited higher

levels of membrane leakage compared to fruit stored at 93% RH. Although fruit from both treatments developed PFD, it was more severe in fruit stored at 62% RH. Likewise, Thomas and Staub (1992) showed that PFD was more severe in fruit stored at 26.5°C in either 60% or 75% RH than in those stored at 10.5°C or 15.5°C and 85% RH. Results indicated that, of the postharvest handling regimes evaluated, 15.5°C and 85% RH minimized postharvest losses and 26.5°C and 60% RH produced the highest PFD level. Since only one genotype was evaluated by Thomas and Staub (1992) and the effect of hydrocooling on PFD symptomology has not been investigated, studies were undertaken to: 1) characterize plant response to water stress; 2) test whether genotypes possessing normal leaf size (*LL*) and reduced leaf size (*ll*) differ in response to soil moisture deficits; and 3) determine whether hydrocooling reduces PFD severity.

Materials and Methods

Water stress induction. Experiments were conducted at the Univ. of Wisconsin Research Station, Hancock, on a Plainfield loamy sand (Typic Updisamment; mixed mesic) in 1989 and 1990. In 1989 four and in 1990 eight cultivars were arranged in adjacent randomly assigned treatment plots (control and water withheld) 4.0 m apart. Each plot was divided into four 6.0-m rows with end (0.6-m) and side (7.6-m) plot borders. Cucumbers were planted on 1.5-m row centers and spaced ≈ 7.5 cm apart in the row (89,000 plants/ha). Standard fertilization, spraying, and hand cultivation was practiced in all experiments.

Each treatment (control and water withheld) row was portioned into four equal 1.2-m segments, and cultivars were randomized in each of four replications within each treatment in a split-split-plot arrangement. In 1989, a replication consisted of a single row, while in 1990 two rows comprised a replication. Water stress treatment was the main plot and cultivar was the subplot in all analyses. For measurements taken once (plant harvest variables), an analysis of variance (ANOVA) was conducted using a split-plot design (spatial separation of watered and water-withheld plots). For measurements taken over time [daily stomatal conductance (g_s)], ANOVAs were performed using a split-split-plot model with time (day) as

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the sub-subplot factor nested within cultivar. Measurements were taken on plants of similar physiological maturity, and no plant was measured on 2 consecutive days. Mean separations were performed with Fisher's protected LSD at $P = 0.05$ (Steel and Torrie, 1980).

Cucumber cultivars used in both experiments in 1989 were 'Flurry' (Asgrow Seed Co., Kalamazoo, Mich.), 'Calypso' (North Carolina Agricultural Experiment Station, Raleigh, N.C.), 'Carolina' (Clemson Agricultural Experiment Station, Clemson, S.C.), and the inbred line WI 1983 little leaf (*ll*) [U.S. Dept. of Agriculture, Agricultural Research Service (USDA-ARS), Madison, Wis.]. In 1990, the three normal leaf (*ll*) (area of first fully expanded leaf 80 to 100 cm²; Staub et al., 1992) cultivars used in 1989 ('Flurry', 'Calypso', and 'Carolina') were evaluated along with 'Discover' (Asgrow Seed Co.), 'Endeavor' (USDA-ARS), 'Fancipak' (Asgrow Seed Co.), and the *ll* cultivar H-19 (Univ. of Arkansas, Fayetteville, Ark.). The little leaf character (area of first fully expanded leaf 30 to 40 cm²; Staub et al., 1992) of H-19 and WI 1983 is derived from the same Univ. of Arkansas donor parent, AR 75-79 (*ll*).

SMT was monitored daily during stress periods using tensiometers (model 112; Irrometer Co., Riverside, Calif.) randomly placed in two rows of each treatment plot 23 cm deep. Control treatments received a minimum of 2.5 cm of water per week such that SMT did not exceed 28 kPa. To supplement natural precipitation, water was supplied through a zoned, drip irrigation system. Drip lines were placed ≈ 6.5 cm from the base of plants to provide similar amounts of water until water stress was initiated. Moveable rainout shelters were used during stress periods to protect treatments from precipitation. Treatment differences were examined by comparing linear (b_1) and quadratic (b_2) slope estimates for their equality (SMT and days taken as dependent and independent variables, respectively).

To compare physiological response to water stress, all fruit must be at the same developmental stage. Anthesis occurred in all cultivars within 3 to 4 days of each other, except for H-19, which flowered ≈ 10 to 15 days later than the earliest flowering cultivar. To ensure synchronized fruiting among cultivars and across treatments, H-19 seeds were sown 12 days earlier than those of all other cultivars. Thus, plants in all treatment plots flowered simultaneously. At first harvest, fruit greater than ≈ 4 cm long were removed and the stress episode was initiated.

Daily visual ratings were taken between 13:00 and 15:00 HR during the stress episode based on a five-point scale: 1) loss of turgor resulting in recurved margins of leaves (i.e., downward cupping) between the base of the plant and the midvein; 2) leaves between the base of the plant and the midvein undulating and recurved; 3) $\approx 50\%$ wilting of leaves from the base of the plant to the midvein; 4) $\approx 75\%$ of the plant wilted from the base to the terminal whorl, and 5) complete wilting of leaves (100%) from the base of the plant to the terminal whorl. The average degree of wilt for the entire stress period was calculated based on the daily degree of wilt and number of days that each cultivar remained wilted. During the stress period, stomatal resistance (r_s), photosynthetic photon flux density (PPD), and ambient RH were measured daily between 10:00 and 14:00 HR when PPD was relatively high (1417 ± 498 and 1318 ± 399 mmol·m⁻²·s⁻¹ in 1989 and 1990, respectively).

Measurements of r_s were taken on the fourth leaf from the terminal whorl of five randomly selected plants of each cultivar within a replication with a steady-state porometer (LI-1600; LI-COR, Lincoln, Neb.). These measurements were transformed to g_s (mass to molar units) as $g_s = 0.4/r_s$ (Cowan, 1977), and control

and water-withheld treatments were compared by modeling daily cultivar g_s means as first- or second-order polynomials of time (days of water withheld) using regression. Treatment differences were examined by comparing linear (b_1) and quadratic (b_2) slope estimates for their equality. Readings of g_s taken at the beginning and end of the stress episode divided by the number of days that water was withheld $\times 100\%$ yielded a g_s percent change value to compare cultivars.

Experiments ended when 30% to 40% of the fruit within a treatment were ≈ 3.2 cm in diameter (2B size). Fruit were harvested, average fruit number (FN) and fruit weight (FW) per plant were calculated, and aboveground plant organs (without the fruit) were harvested and dried at 60C for 72 h to determine average plant dry weight (DW). All mean values represent calculations made on a per-plot (replication) basis. Relative plant maturity was standardized with respect to flowering date and harvest time by staggering plantings (H-19 vs. other cultivars) and collecting data at the second harvest (synchronized for fruit development). To examine water stress and genotypic effects, these response variables were examined by ANOVA using a split-plot model. Water stress treatment was the whole-plot factor and was analyzed as a completely randomized design. Genotype effects were subplots nested within water stress and were analyzed as a randomized complete-block design.

Postharvest storage experiments. Harvested fruit were subjected to four postharvest regimes to simulate various conditions that might occur during commercial handling. Eighty fruit of each cultivar within each treatment were randomly selected (≈ 1.9 to 3.8 cm in diameter), partitioned into four groups, and held at ≈ 26 C and 60% RH. Within 3 h of harvest, fruit from each treatment were placed in differing temperatures, RHs, and storage durations (2 to 4 days) in controlled environments. Fruit were subjected to: 1) 4 days storage at 15C, 85% RH [vapor pressure deficit (VPD) = 0.249 kPa] (cool temperature and high humidity); 2) hydrocooling to ≈ 8.5 C within 60 min and storage at 15C, 85% RH (VPD = 0.249 kPa) for 4 days (hydrocooling, cool temperature, and high humidity); 3) storage at 26C, 60% RH (VPD = 1.298 kPa) for 1 day, then hydrocooling to ≈ 8.5 C within 60 min and storage at 15C, 85% RH (VPD = 0.249 kPa) for 2 days (ambient conditions for 24 h, then treatment 2), or; 4) 2 days storage at 26C, 60% RH (VPD = 1.298 kPa) (ambient conditions).

Fruit temperature was measured using thermocouples (0.003

Table 1. Amount of wilting in four cucumber cultigens subjected to water stress in two experiments, Hancock, Wis., 1989.

	Treatment duration	No. of days plants	Average wilt for stress period	
Cultigen	(days) ^z	were wilted	X ^y	SE
<i>Expt. 1</i>				
Flurry	6	4 of 6	1.38	0.22
Calypso	6	4 of 6	1.33	0.19
Carolina	6	4 of 6	1.13	0.18
WI 1983 ^x	6	0 of 6	---	---
<i>Expt. 2</i>				
Flurry	5	3 of 5	2.17	0.48
Calypso	5	2 of 5	1.50	0.29
Carolina	5	3 of 5	1.67	0.49
WI 1983	5	1 of 5	1.00	0.00

^zStress treatment consisted of withholding soil moisture to cause wilting during second-harvest fruit enlargement.

^yAt least four replications of each cultigen.

^xU.S. Dept. of Agriculture little leaf breeding line.

mm in diameter) inserted into the midsection of the fruit 1.5 to 2 cm below the epidermis. Fruit were hydrocooled for ≈ 60 min with $7.7 \pm 1.0^\circ\text{C}$ water until the internal fruit temperature was $8.5 \pm 1.1^\circ\text{C}$. Cooling trends were modeled with Newton's law of cooling: $\ln(\text{fruit temperature} - \text{water temperature}) = a + b \times \text{time}$ (Thayer, 1953) using linear regression (a and b are constants estimated from each data set). Cooling response (y) was calculated as $y = 7.95 - 0.17 \times \text{time}$ ($R^2 = 0.69$) and $y = 10.6 - 0.20 \times \text{time}$ ($R^2 = 0.76$) for hydrocooling in 1989 and 1990, respectively. After postharvest storage, all fruit were halved in longitudinal sections and fresh-pack processed in brine solution supplied by Claussen Pickle Co., Woodstock, Ill.

Table 2. Amount of wilting in eight cucumber cultigens subjected to water stress in two experiments, Hancock, Wis., 1990.

	Treatment duration	No. of days plants	Average wilt for stress period	
Cultigen	(days) ^z	were wilted	X ^y	SE
<i>Expt..1</i>				
Flurry	9	4 of 9	1.75	0.37
Calypso	9	3 of 9	2.50	0.50
Carolina	9	4 of 9	2.25	0.37
H-19 ^x	9	2 of 9	1.25	0.25
Endeavor	9	4 of 9	2.25	0.45
Fancipak	9	3 of 9	1.50	0.43
Discover	9	3 of 9	2.17	0.48
Regal	9	4 of 9	1.57	0.43
<i>Expt. 2</i>				
Flurry	8	2 of 8	0.50	0.22
Calypso	8	2 of 8	1.00	0.58
Carolina	8	2 of 8	1.80	0.66
H-19	8	1 of 8	0.50	0.29
Endeavor	8	2 of 8	0.60	0.40
Fancipak	8	1 of 8	0.67	0.33
Discover	8	2 of 8	1.38	0.26
Regal	8	2 of 8	1.00	0.37

^zStress treatment consisted of withholding soil moisture to cause wilting during second-harvest fruit enlargement.

^yAt least four replications of each cultigen.

^xUniv. of Arkansas little leaf breeding line.

Processed cucumbers were held for 12 to 14 weeks at 8°C before evaluation. Samples were evaluated for PFD severity by two groups of five industry representatives (judges) in each of 2 years. Judges were trained to recognize PFD symptoms just before examining processed samples. Fruit were classified as pillowed if opaque-white, porous-textured tissue was observed in the meso-carp region 2 to 6 mm under the epidermis. Fruit were given a percentage PFD value (percent longitudinal area showing pillowed tissue) by visual approximation according to Staub et al. (1988) and Thomas and Staub (1992). PFD symptoms were rated on a four-point scale, where 1 is $\geq 0\% \leq 10\%$ PFD, 2 is $\geq 10\% \leq 20\%$ PFD, 3 is $\geq 20\% \leq 30\%$ PFD, and 4 is $\geq 30\% \leq 40\%$ PFD.

ANOVAs and mean separations of pillowy evaluations were performed separately for each group of judges using a split-split-split-plot analysis. The whole-plot and split-plot factors were water stress and cultivar, respectively, with the sub-subplot factor of postharvest treatment nested within cultivar and the sub-sub-subplot factor of judges nested within postharvest treatment. Mean separations were performed with Fisher's protected LSD at $P = 0.05$ (Steele and Torrie, 1980).

Results

Plants in well-watered treatments did not wilt. Wilting was recorded in all plots in which water was withheld except in one experiment (Tables 1 and 2). All cultivars, except WI 1983 (Expt. 1, 1989) exhibited some degree of wilting when water was withheld. Cultigen differences were recorded for the time to wilt threshold, number of days plants remained in a wilted condition, and average degree of wilt for the stress period. Little leaf cultivars (WI 1983 in 1989 and H-19 in 1990) were generally less susceptible to imposed water stress, as measured by these wilt variables, than normal leaf cultivars.

Water stress indices. Soil (SMT) and plant (g, DW, FN, and FW) measurements supported visual wilt observations. Regression slope estimates of SMT values (linear b_1 values; Table 3) indicated that there were significant differences in soil moisture status between treatments after water was withheld. Although a significant increase in SMT (b_1 value; $P \leq 0.05$) was recorded in the control plot of Expt. 1 in 1989, the daily mean SMT in control plots

Table 3. Daily mean soil moisture tension (kPa) and response estimates (regression) of cucumber subjected to water stress in four experiments, Hancock, Wis.

													Regression estimates ^z		
	Water stress	Treatment days													
Expt.	treatment ^y	1	2	3	4	5	6	7	8	9	X ^x	SE	b ₁	SE	R ²
1989 ^w															
Expt. 1	Control	10.5	10.0	15.0	23.5	19.0	20.0	---	---	---	16.3	2.22	2.37*	0.84	0.67
	Stress	22.0	29.0	33.0	52.0	64.0	65.5	---	---	---	44.3	7.65	9.76**	1.13	0.95
Expt. 2	Control	13.0	22.0	27.5	17.0	21.5	---	---	---	---	20.2	2.45	1.20	1.88	0.12
	Stress	13.5	25.5	44.5	56.0	68.0	---	---	---	---	41.5	9.90	13.95***	0.72	0.99
1990 ^w															
Expt. 1	Control	6.5	9.0	13.6	2.0	3.0	5.0	6.0	8.0	14.8	7.5	1.46	0.30	0.59	0.04
	Stress	9.0	11.3	18.3	36.8	49.8	65.2	73.9	74.5	76.7	46.2	9.38	10.00***	0.90	0.95
Expt. 2	Control	15.2	19.8	1.5	---	1.2	3.2	5.0	6.0	10.8	7.8	2.27	-0.96	0.87	0.17
	Stress	7.7	14.7	22.5	---	31.2	38.7	48.3	59.2	63.5	35.7	6.80	6.98***	0.33	0.98

^zRegression slope inequality estimates between stress and control treatments were significant ($P \leq 0.001$).

^yWater stress treatments, where control equals sufficient soil moisture for growth and development and stress equals soil moisture withheld to cause wilting during second-harvest fruit enlargement.

^xMean of combined treatment days.

^wFour cultigens were used in 1989 ('Flurry', 'Calypso', 'Carolina', and WI 1983) and eight were used in 1990 ('Flurry', 'Calypso', 'Carolina', H-19, 'Endeavor', 'Fancipak', 'Discover', and 'Regal').

*, **, *** Significant at $P = 0.05$, 0.01, or 0.001, respectively.

over both years was held below 28 kPa. In contrast, maximum SMT levels in water-withheld plots for all experiments ranged from 63.5 to 76.7 kPa. While the mean daily SMT in water-withheld plots increased an average of 9.2 kPa·day⁻¹, well-watered plots increased 1.3 kPa·day⁻¹. Slope inequality between control and water-withheld treatments for each experiment indicated significant differences in soil moisture depletion rates.

Plant response variables (g_s , DW, FN, and FW) indicated water

stress (Tables 4 and 5). In most cases, significant ($P \leq 0.05$) stress and cultivar main effects were observed for these plant measurement criteria. However, main effects of the stress treatment were not detected in Expt. 2 (1989) for g_s , FN, and FW and in Expt. 2 (1990) for DW, FN, and FW. Likewise, significant cultivar main effects were not detected in Expt. 1 (1989) for DW and in Expt. 2 (1989) for g_s . Day main effects for g_s were significant ($P \leq 0.001$) in three of the four experiments (except Expt. 2, 1989). Two-way

Table 4. Cucumber plant response to soil water deficits in two experiments at Hancock, Wis., 1989.

Cultigen	Expt. 1				Expt. 2			
	Stomatal conductance (mol·m ⁻² ·s ⁻¹) ²	Dry wt/plant (kg) ^y	Fruit no./plant	Wt/fruit (kg)	Stomatal conductance (mol·m ⁻² ·s ⁻¹)	Dry wt/plant (kg)	Fruit no./plant	Wt/fruit (kg)
<i>Control</i>								
Flurry	0.232	41.9	1.29	142.3	0.282	31.3	1.69	69.2
Calypso	0.219	38.9	1.40	133.9	0.304	37.5	1.77	78.9
Carolina	0.207	57.4	1.59	147.0	0.286	37.5	1.67	76.6
WI 1983	0.281	42.2	2.00	78.3	0.330	33.9	1.96	50.3
<i>Stress^x</i>								
Flurry	0.226	30.0	1.17	116.0	0.336	26.8	1.43	76.2
Calypso	0.187	36.0	1.10	104.6	0.361	33.8	1.62	72.4
Carolina	0.196	33.8	1.13	107.0	0.339	28.6	1.41	84.9
WI 1983	0.256	32.8	1.63	68.7	0.324	26.8	1.96	39.8
LSD (0.05)	0.032	12.1	0.33	24.6	0.089	5.4	0.42	24.2
CV (%)	20.01	19.5	15.90	14.7	24.34	11.4	16.86	23.8

²Measurements taken ≈24 h before harvest (Table 1) between 10:00 and 14:00 HR.

^yVegetative growth excluding fruit.

^xWater stress treatments, where control equals sufficient soil moisture for growth and development and stress equals soil moisture withheld to cause wilting during second-harvest fruit enlargement.

Table 5. Cucumber plant response to soil water deficits in two experiments at Hancock, Wis., 1990.

Cultigen	Expt. 1				Expt. 2			
	Stomatal conductance (mol·m ⁻² ·s ⁻¹) ²	Dry wt/plant (kg) ^y	Fruit no./plant	Wt/fruit (kg)	Stomatal conductance (mol·m ⁻² ·s ⁻¹)	Dry wt/plant (kg)	Fruit no./plant	Wt/fruit (kg)
<i>Control</i>								
Flurry	0.233	21.0	1.43	61.3	0.177	24.2	1.24	36.1
Calypso	0.235	25.0	1.60	61.8	0.193	28.9	1.68	34.4
Carolina	0.217	23.9	1.57	69.1	0.211	25.5	1.56	31.5
H-19	0.274	26.5	1.51	37.2	0.214	26.3	1.36	36.4
Endeavor	0.233	26.6	1.55	68.2	0.218	31.1	1.65	35.2
Fancipak	0.234	31.7	1.71	56.1	0.227	37.7	1.75	34.8
Discover	0.231	21.8	1.43	57.8	0.190	24.8	1.34	27.1
Regal	0.212	22.2	1.53	65.1	0.183	25.9	1.60	28.3
<i>Stress^x</i>								
Flurry	0.195	20.0	1.23	53.4	0.151	24.7	1.24	31.3
Calypso	0.179	20.9	1.24	57.2	0.141	27.4	1.46	32.5
Carolina	0.170	20.2	1.38	49.6	0.134	23.4	1.51	28.0
H-19	0.199	25.7	1.76	39.9	0.175	24.5	1.23	35.0
Endeavor	0.183	22.1	1.46	55.2	0.155	29.0	1.64	35.8
Fancipak	0.193	28.6	1.63	48.5	0.158	36.7	1.69	32.6
Discover	0.180	19.3	1.36	58.1	0.138	24.0	1.23	26.7
Regal	0.202	21.2	1.35	61.0	0.148	25.2	1.44	34.8
LSD (0.05)	0.027	3.9	0.25	13.2	0.021	3.3	0.38	9.3
CV (%)	18.76	12.1	11.22	16.9	16.48	8.0	17.34	16.6

²Measurements taken ≈24 h before harvest (Table 2) between 10:00 and 14:00 HR.

^yVegetative growth excluding fruit.

^xWater stress treatments, where control equals sufficient soil moisture for growth and development and stress equals soil moisture withheld to cause wilting during second-harvest fruit enlargement.

day $\times$ stress interactions were recorded in all four experiments.

Treatment differences ($P \leq 0.10$) in g_s rates as measured by daily mean g_s slope inequality [b_1 inequality (1989) and b_2 inequality (1990)] were observed for all cultivars except 'Discover' and H-19 at least once over the course of the four experiments. No treatment differences (well-watered vs. water-withheld) for daily mean g_s among cultivars were observed in Expt. 1 in 1990 (Fig. 1). In Expt. 1 (1989), the greatest difference in g_s daily means between well-watered and water-withheld plots was recorded in 'Calypso' plots ($P = 0.095$) (data not presented). A difference in g_s between treatments was observed in WI 1983 by day 3 of the stress episode.

Greater differences between well-watered and water-withheld treatments were recorded in Expt. 2 (1989) compared to Expt. 1 (data not presented). 'Calypso' showed the greatest difference between treatments ($P = 0.003$) in mean daily g_s followed by 'Carolina' (b_1 inequality; $P = 0.034$). Treatment differences among WI 1983 and 'Flurry' were also detected ($P = 0.067$ and $P = 0.081$, respectively). Differences between treatment means were largest in WI 1983 plots on the last day of the stress period (day 4). Although no differences in daily mean g_s slope inequality were observed in Expt. 1, 1990 (Fig. 1), significant differences occurred between treatments for four of the eight cultivars tested in Expt. 2,

Fig. 1. Daily mean stomatal conductance ($\text{mol m}^{-2} \text{s}^{-1}$) for eight cucumber cultivars subjected to water stress, Expt. 1, Hancock, Wis., 1990; $\blacktriangle$ watered, $\triangle$ water withheld). Vertical bars represent LSD ($P = 0.05$).

1990 (Fig. 2). 'Carolina' exhibited the largest daily mean g_s treatment differences (b_2 inequality; $P = 0.003$). The next largest treatment differences in g_s (slope inequality) were recorded for 'Endeavor' ($P = 0.012$), 'Fancipak' ($P = 0.059$), and 'Regal' ($P = 0.099$).

DW in plants from water-withheld plots was always lower compared to plants harvested from well-watered plots, but not always significantly so (Tables 4 and 5). In 1989, DW reductions of 'Calypso' were less than those of 'Flurry' and 'Carolina', which were similar. In 1990 (Expt. 1), DW of 'Calypso' and 'Endeavor' in water-withheld plots was significantly less than in well-watered plots. DW differences of other cultivars were not significant. In

Expt. 2 (1990) there were no significant differences in DW between stress treatments.

While reductions in FN between stress treatments were recorded in Expt. 1, 1989 and 1990, no such differences were observed in Expt. 2 of either year (Tables 4 and 5). In 1989, the FN of 'Carolina' and WI 1983 in water withheld plots was significantly less than that of comparative plants in well-watered plots (Table 4). In 1990 (Expt. 1), FN harvested from 'Calypso' plants in water-withheld plots was significantly less than that harvested from 'Calypso' plants in well-watered plots. In Expt. 2 (1990) there were no FN differences between treatments (Table 5).

FW from plants in well-watered plots in Expt. 1 (1989) was

Fig. 2. Daily mean stomatal conductance ($\text{mol m}^{-2} \text{s}^{-1}$) for eight cucumber cultivars subjected to water stress, Expt. 2, Hancock, Wis., 1990; $\blacktriangle$ watered, $\triangle$ water withheld). Vertical bars represent LSD ($P = 0.05$).

significantly higher than in water-withheld plots for all cultivars, except WI 1983 (Table 4). In Expt. 2 (1989) FW differences between stress treatments were not significant for any cultivar tested. In 1990, cultivar differences in FW between stress treatments were detected in only one comparison ('Carolina') for Expts. 1 and 2 (Table 5).

Postharvest experiments. The main effects of stress on processed fruit quality as measured by PFD were significant in Expt. 1, 1989 ($P \leq 0.001$) and 1990 ($P \leq 0.05$) (Table 6). Cultigen main effects were significant for Expts. 1 and 2 ($P \leq 0.05$) in 1989 and for Expts. 1 ($P \leq 0.001$) and 2 ($P \leq 0.05$) in 1990. No second-order cultivar interactions were detected in either year (data not presented). Postharvest treatment main effects were highly significant

Table 6. Mean pillowy fruit disorder² (PFD) ratings of processed fruit by five judges after preharvest water stress and postharvest storage treatments in controlled environments.

Source of variation	PFD rating			
	1989		1990	
	1 ^y	2 ^x	1	2
Judge				
1	2.56	0.86	2.48	3.42
2	2.98	1.72	1.90	2.41
3	2.52	0.97	2.35	2.62
4	2.97	0.56	1.00	2.29
5	2.17	1.19	2.98	1.95
LSD	0.46	0.25	0.20	0.17
Water stress treatment ^w				
Control	1.47	0.65	1.82	2.44
Stress	3.77	1.47	2.46	2.63
LSD	0.36	0.16	0.38	0.31
Postharvest treatment ^v				
1	2.30	1.18	1.90	2.98
2	2.22	0.66	1.75	2.21
3	2.31	0.75	1.92	2.58
4	3.71	1.65	3.00	2.37
LSD	0.41	0.23	0.18	0.16
Cultigen				
Flurry	2.85	1.34	1.58	2.43
Calypso	2.68	0.98	1.80	2.40
Carolina	2.78	1.10	2.51	2.76
WI 1983/H-19 ^u	2.23	0.91	3.23	2.45
Endeavor	---	---	2.16	2.72
Fancipak	---	---	1.83	2.54
Discover	---	---	1.85	2.40
Regal	---	---	2.18	2.61
LSD	0.41	0.23	0.26	0.22
CV	49.31	68.79	54.53	39.61

²PFD was rated on a 10-point scale to represent the portion of fruit affected, where 0 = 0% to 9%, 1 = 10% to 19%...9 = 90% to 100%.

^yExperiment 1 (1989 and 1990) was conducted 1 to 15 Aug. each year.

^xExperiment 2 (1989 and 1990) was conducted 15 to 25 Aug. each year.

^wWater stress treatments, where control equals sufficient soil moisture for growth and development and stress equals soil moisture withheld to cause wilting during second-harvest fruit enlargement.

^vPostharvest storage treatments before processing: 1 (cool temperature, high humidity) = 4 days at 15C, 85% relative humidity (RH); 2 (hydrocooling, then cool temperature, high humidity) = hydrocooling to ≈ 10 C, 4 days at 15C, 85% RH; 3 (ambient conditions for 24 h, then treatment 2) = 1 day at 26C, 60% RH, hydrocooling to ≈ 10 C, 2 days at 15C, 85% RH; 4 (ambient conditions, control) = 2 days at 26C, 60% RH.

^uLittle leaf cultigen used in 1989 and 1990 was WI 1983 and H-19, respectively.

($P \leq 0.001$) across all experiments (1989 and 1990) for PFD (data not presented). Main effects for judge were highly significant in all experiments. Several two-way judge interactions were detected in 1989 and 1990, including judge $\times$ stress, judge $\times$ cultivar, and judge $\times$ treatment. These second order interactions, however, were few and inconsistent. A three-way judge $\times$ stress $\times$ treatment interaction occurred in all four experiments.

Increased PFD severity was associated with increased temperature, lower RH, and absence of hydrocooling in postharvest storage. PFD ratings for control fruit (treatment 4, Table 6) after postharvest treatment were significantly higher than those for other postharvest treatments in three of the four experiments (except Expt. 2, 1990). Fruit stored in treatment 2 exhibited fewer PFD symptoms in all experiments (Table 6).

Individual cultivar differences with regard to PFD susceptibility varied between year. WI 1983 fruit exhibited the lowest PFD ratings in 1989, while 'Flurry' fruit displayed the highest PFD ratings (Table 6). In Expt. 1, 1990, H-19 fruit exhibited the highest PFD scores, while 'Flurry' fruit were given the lowest PFD ratings of the eight cultivars tested. 'Flurry', 'Discover', 'Calypso', and H-19 exhibited low PFD ratings. In contrast, 'Carolina' fruit were most affected by the various treatments across years, exhibiting relatively high PFD in three of the four experiments (Expt. 1, 1989; Expts. 1 and 2, 1990; Table 6).

Discussion

Thomas and Staub (1992) evaluated the effect of water stress and postharvest management without hydrocooling on the development of PFD in 'Calypso'. In this study, postharvest comparisons (four treatments) were made between fruit harvested from nine processing cucumber cultivars that had been subjected to water stress. These comparisons were made to determine if cultivars differ in susceptibility to PFD and if hydrocooling can decrease the severity of PFD below the optimal postharvest treatment used by Thomas and Staub (1992) (4 days storage at 15C, 85% RH).

Response to stress. Plants were adversely affected by the soil moisture deficits imposed in these experiments. The effects of increased SMT were in turn associated with increased PFD severity. These observations paralleled those of Thomas and Staub (1992), in which PFD frequency and severity were higher in fruit harvested from water-stressed plants (i.e., reduced photosynthesis and increased stomatal resistance and crop water stress index values) compared to well-watered controls. The fact that the plant parameters measured in this study were not always associated with PFD indicates that other factors are involved in pillowy development. It is known that temperature and RH also contribute to PFD development (Staub and Navazio, 1993).

The effects of imposed soil moisture deficits in all experiments were documented by at least three of the seven variables measured. In Expts. 1, 1989 and 1990, all seven plant variables documented the effects of soil moisture deficits in water-withheld plots (Tables 1, 2, 4, 5, and 6). In all experiments, g_s values decreased in well-watered and water-withheld plots. The observed change in g_s values among well-watered cucumber plants is a function of the aging process and fruit development (Nagoaka et al., 1984). Decreases in stomatal conductance in well-watered plots during stress episodes are consistent with those observed in greenhouse-grown cucumbers (Janoudi et al., 1993) and other crops (Davis et al., 1977) in which fruit enlargement occurred in nonstress environments.

SMT was relatively high by the last day of imposed stress in

Expt. 2, 1989 and 1990 (day 5 = 68 kPa in 1989 and day 8 = 63.5 kPa in 1990). However, no differences in PFD were detected between fruit harvested from well-watered and water-withheld plots in either year. Irradiance and temperature could have affected PFD expression in these experiments, since these variables were lower than normal during the stress episodes. For example, during Expt. 2, 1990, the percent daily insolation ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$) was below average for this time of year. The mean percent daily insolation during the stress period was $14.1 \text{ MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ compared to the potential insolation mean of $23.6 \text{ MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ for those days (estimates by the Univ. of Wisconsin Agricultural Weather Observation Network, Madison). The mean daily air temperature for the last 4 days of stress in Expt. 2, 1990, was relatively low compared to the 20-year mean for 1 to 15 Aug. (17.1 and 20.4C, respectively). When irradiance and temperature were relatively high (e.g. Expt. 1, 1990), dramatic decreases in overall daily g_s mean values and increases in 8-day percent change values of plants were recorded in water-withheld plots compared to experiments during which temperature and irradiance were lower than normal (Expt. 2, 1990). Such deviations (irradiance and temperature) from normalcy may partially explain why differences were not detected among water stress and postharvest treatments in Expt. 2, 1989 (g_s , FN, FW, and PFD) and in Expt. 2, 1990 (DW, FN, FW, and PFD). Such evidence documents the necessity of conditions optimal for plant growth and fruit development when studying PFD development.

Cultivar differences. Genotypic differences in susceptibility to Ca-related disorders has been reported in several crops (Johnson, 1991; Li and Gabelman, 1990). PFD is associated with low fruit Ca levels and is exacerbated by environmental stresses (Staub et al., 1988; Thomas and Staub, 1992). The cultivar differences (e.g., *ll* vs. *LL*) in PFD observed in these experiments (Tables 4–6) concurs with previously observed variability in cultivar response to water stress and its concomitant influence on PFD (Staub et al., 1988). The current study extended the variables measured in the studies of Staub et al. (1988) and Thomas and Staub (1993) to include wilting ratings, g_s , DW, and fruit yield. The relative cultivar ranking with regard to stress tolerance varied within and across experiments (e.g. 'Flurry' in Expt. 2, 1989, and Expt. 1, 1990), indicating that large genotype $\times$ environment interactions can affect the interpretation of PFD expression. Nevertheless, the reaction of certain cultivars to soil moisture deficits was consistent. For example, PFD severity in 'Calypso' fruit was consistently low compared to the other *LL* cultivars tested. In contrast, the severity (intensity of visual symptoms) of PFD in fruit harvested from 'Carolina' plants subjected to water stress was greater than the other cultivars evaluated (Table 6; Expt. 1, 1989; Expts. 1 and 2, 1990).

Although WI 1983 and H-19 (*ll*) are derived from AR 75-79, their response to soil water deficits differed depending on stress environment. WI 1983, had lower average wilt scores (Table 1) and higher average g_s readings (Table 4) than *LL* cultivars in the 1989 experiments, a result indicating a relatively high plant tolerance to the imposed stress. WI 1983 fruit also possessed significantly less PFD than *LL* cultivars in Expt. 1 (Table 6). Likewise, H-19 exhibited a relatively high tolerance to high SMT levels in 1990 (Table 3). However, in Expt. 1 (1990), during which the plant variables measured indicated that stress levels were high, 'Flurry' and 'Fancipak' performed as well as 'Calypso' for fruit quality, while H-19's PFD symptoms were significantly higher than those of any *LL* cultivar tested. When daily insolation levels and temperatures were low (Expt. 2, 1990), PFD differences between H-19 and *LL* cultivars were not detected. Thus, although

a plant may not exhibit symptoms of stress during periods of soil water deficits (e.g., H-19, Expt. 1, 1990), it is possible that physiological responses may occur during incipient stress and cause poor fruit quality (i.e., cause and effect). Moreover, the inconsistent response of *ll* cultivars to water stress over environments suggests that miniature leaf size may not be directly related to water-stress tolerance in cucumber (i.e., genetic background). The hypotheses as to cause and effect, and genetic background could be tested using nearly isogenic inbred lines differing in leaf size (*ll* vs. *LL*).

Postharvest treatments. It is well known that removing field heat immediately after harvest enhances postharvest fruit quality (Kays, 1991). The optimum postharvest treatment of Thomas and Staub (1992; postharvest 1) approximates the industry practice of loading cucumbers directly into refrigerated trucks having a humidity saturating device for extended transport. A postharvest regime similar to treatment 4 is likely to occur in isolated production areas where hydrocooling is not available or refrigerated transport is unpredictable. This treatment equates to leaving fruit in ambient conditions for 2 days at a receiving station. Under what are often considered optimal conditions for freshly harvested cucumbers, fruit are hydrocooled for 60 min before being placed into refrigerated storage [similar to the optimum of Thomas and Staub (1992) but with hydrocooling; treatment 2] (Miller and Wehner, 1989). In our experiments, hydrocooling was added to the postharvest treatment that simulated the conditions under which fruit are left at ambient conditions in a packing shed (treatment 3; 1 day at 26C, 60% RH; then hydrocooling to $\approx 8.5\text{C}$, then 2 days at 15C, 85% RH). It is not uncommon at the peak harvest periods for fruit to be stored in a packing shed for 18 to 24 h before hydrocooling before shipping to a processing facility (R. Thomas, personal communication, 1993).

Our results confirm those of Thomas and Staub (1992), who found marked increases in PFD severity in fruit held at 26C and 60% RH (treatment 4) compared to those stored at 15C and 85% RH (treatment 1). In all experiments, the superior postharvest treatment (treatment 2) involved hydrocooling immediately upon harvest, followed by the optimum storage conditions characterized by Thomas and Staub (1992) (15C and 85% RH). Such a postharvest regime rapidly dissipates field heat from fruit (from ≈ 22.5 to $\approx 8.5\text{C}$ in 60 min) and controls transpirational water loss somewhat. PFD development is affected by fruit transpiration rate (Staub et al., 1988; Staub and Navazio, 1993). Treatment 2 undoubtedly slows the postharvest physiological changes that normally occur during fruit ripening and senescence, thus, decreasing the potential PFD severity (Salunkhe and Desai, 1984).

Our results suggest that there are several management practices that can be used to decrease PFD incidence and severity in field-grown cucumbers. Processors can lower PFD incidence and severity if adequate moisture is given to plants during fruit enlargement and harvested fruit are hydrocooled before shipping and storage. PFD severity may also be decreased by growing genotypes that are less susceptible to environmental stresses.

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