Role of Excess Water in Tomato Fruit Cracking

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Abstract. Excess irrigation water was provided to spring crops of bag-grown greenhouse tomatoes (*Lycopersicon esculentum* Mill.) to test the effect on radial fruit cracking. Varied numbers of emitters were placed in bags filled with soilless medium to provide different amounts of irrigation water. In 1990, all emitters provided water containing nutrient solution, but in 1992, the extra water added in one treatment did not contain nutrient solution. In both years, the percentage of cracked fruit was 20 percentage points higher in the treatments receiving more water. The increase in cracking was similar whether or not nutrient solution was added to the extra water. There also were some effects of the extra water on yield. Fruit count per plant was slightly higher (9.5%) when extra water was provided without nutrient solution, but was the same when nutrient solution was added to the extra water. Fruit weights per plant were 18.6% higher in 1990 when watering was increased. In 1992, fruit weights were similar, except for the treatment where the extra water provided did not contain nutrient solution. Fruit weight in this treatment was 19.7% higher than in the other treatments. In both crops, the percentage of cracking increased as linear and quadratic functions of cluster positions, i.e., there was more cracking in the upper clusters. In greenhouse situations, growers should consider water reduction when experiencing high levels of fruit cracking and as a precautionary measure when harvesting from the upper clusters. Providing excess water to greenhouse-grown tomatoes may be a viable technique for screening cultivars or for conducting research on practices to reduce cracking.

Fruit cracking in tomatoes can cause serious economic losses in the field. Cracks decrease the attractiveness of the fruit and offer an entry point for insects and decay organisms. Although this can cause significant income loss in the fresh market and processing tomato industries (Calbo, 1990; Cotner et al., 1969; Walter, 1967), cracking occurs only sporadically for most commercial tomato growers because they use crack-resistant cultivars. In addition, fruit grown commercially for fresh market is normally harvested at the mature-green or breaker stage when cracking is less likely. Home gardeners, greenhouse growers, and growers for local or specialty markets are much more vulnerable to fruit cracking losses because their cultivars lack crack resistance and because fruit is harvested at the pink stage or later.

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The environmental and physiological causes of cracking of soft fruit, apples, and citrus are not well understood. The literature on radial fruit cracking in tomatoes was recently reviewed (Peet, 1992). Tomato fruit cracking is most likely to occur when the movement of water and solutes into the tomato fruit is rapid or protracted. Fruit are particularly susceptible if physiological changes in the tomato skin during ripening or under certain soil moisture conditions reduce the strength and the ability of the tomato skin to stretch. For field-grown tomatoes, this most likely occurs when low soil-moisture levels are suddenly relieved by rain. Rain has several effects. Kamimura et al. (1972) reported that a sudden increase in soil moisture reduced the tensile strength of the skin and increased root pressure. They also noted rainwater could be directly absorbed into the fruit through any uncalled minute cracks in the skin and through the corky tissue around the stem scar.

Little is known, however, about the causes of fruit cracking in greenhouse-grown tomatoes, where it is a serious problem (Koske et al., 1980). The above explanation for cracking—a rapid increase in soil moisture of water-stressed plants—would explain few examples of fruit cracking. In greenhouses, plants are watered about the same amount every day and seldom water-stressed. In our studies, and in normal greenhouse practice, plants are watered several times daily and watering frequency or quantity increased at the first sign of wilting. Abbott et al. (1986) increased the frequency of daily watering of greenhouse tomatoes from 1 to 4, keeping the total amount

of water and fertilizer added the same. They reported that variations in watering should be minimized, but when the same amount of total water was provided, effects of irrigation frequency on cracking were not particularly large or consistent between cultivars, years, or watering regimes and media.

In the following experiments, we test the hypothesis that cracking can be reduced in the greenhouse by decreasing the amount of water applied. This hypothesis is based on the idea that high root pressure caused by excess water would increase turgor pressure in the fruit. Preliminary data to support this hypothesis was obtained as part of a Fall 1989 experiment on the effect of nighttime cooling (Willits and Peet, 1992). As part of that experiment, the effects of irrigation with one, two, or three emitters on yield and cracking were compared for fruit at clusters 1 to 8. There was a clear trend for plants receiving the least water (the single-emitter treatment) to have less cracking but generally similar yields compared to treatments receiving more irrigation. Fruit harvested from the lower clusters were less likely to be cracked than those harvested from the upper clusters.

We report here the effect on yield and fruit cracking of providing varying amounts of water and nutrient solution to two spring crops of bag-grown greenhouse tomatoes and discuss the implications. We also report on differences in fruit cracking between early and late-developing clusters on the plant. On a practical basis, fruit cracking is difficult to study because, to our knowledge, no experimental protocols are known that reliably induce cracking in attached fruit. Screening for cracking-resistant cultivars must be done either in environments where high levels of cracking have been observed in the past or in the laboratory where vacuum infiltration (e.g., Kamimura, 1977) is used to artificially pull water into detached fruit. Our study assesses the feasibility of using excess watering in greenhouses to study cracking or to screen cultivars for cracking.

Materials and Methods

Varying amounts of nutrient solution (Spring 1990). ‘Caruso’ tomato was seeded 5 Dec. 1989. On 12 Feb. 1990, seedlings were transplanted into individual upright black polyethylene grow-bags (Hydro-Gardens, Colorado Springs, Colo.) containing 19 liters of medium. Bag medium consisted of a mixture of 50% (by volume) of Pro-Mix-BX (Premier Brands, New Rochelle, N.Y.) and 50% aged pine bark. Plastic sheeting was placed under the bags to prevent root penetration through bag bottoms. Bags were placed in a 5.2 × 6.1-m freestanding, gutter-connected-style experimental greenhouse. A detailed description of the experimental greenhouses is given in Willits and Peet (1989).

Day/night heating setpoints were 21C/16C. Setpoints for low-vent, high-vent, and evaporative pad cooling were 25, 27, and 28C, respectively. The date on which each individual flower opened fully was considered to

be the date of anthesis and was recorded to allow comparison of days to maturity for fruit that eventually cracked and those that did not.

A modified Hoagland's solution was injected into the watering lines each time the plants were irrigated. Solution concentration was modified as follows during crop development. After transplanting, initial fertilizer levels were ($\text{mg}\cdot\text{liter}^{-1}$) 90 N, 45 P, 195 K, 155 Ca, and 44 Mg. On 28 Mar., these levels were raised to 125 N and 310 K (Stage II), with other nutrient concentrations maintained. On 6 June, N levels were raised to 165 (Stage III). Plants were irrigated daily at 0900, 1200, 1500, and 1800 HR, with the number of minutes per watering depending on crop water usage. For the two emitter treatments, this averaged between 1.6 and 2.0 liters/plant per day. To ensure uniformity of water delivery, turbulent-flow emitters and pressure regulators were incorporated in the irrigation system. The number of emitters was the same in all lines and the length of the line was <5 m to reduce water delivery differences from the first to last emitter in the line. Amount of water delivered at the end of each line was measured by taping two emitters to an empty bucket at about the same height as the emitters providing water to the plant. The amount of water in the bucket was regularly measured to ensure irrigation scheduled by the computers actually took place and that there were no significant differences in amount of water delivered between lines. Nutrient solution pH and soluble salts were also monitored regularly. Soluble salts levels in representative bags in each greenhouse were measured at the end of the experiment.

Within the greenhouse, irrigation treatments of one vs. two emitters were imposed on 12 blocks of two adjacent plants arranged in two double rows of six plants for a total of 24 plants in the greenhouse (12 replications). Initially, two emitters were placed in each bag. Within each two-plant block, irrigation treatments of one vs. two emitters were assigned randomly to the grow-bags. Irrigation treatments were imposed on 21 Mar., by removing one emitter. The 5-week delay in imposing irrigation treatments was to ensure that plants in all treatments had equivalent vegetative cover and fruit set at the start of ripening, the period in which fruit are most sensitive to cracking. Bright, sunny weather in mid-April wilted plants in the one-emitter bags. At the same time, excess solution was draining out of the two-emitter bags. To reduce the difference between the treatments in amount of water provided, an additional emitter was added to each bag on 18 Apr. 1990. From this time on, only 50% rather than 100% more water was provided to the high soil moisture treatment.

Normal cultural practices for greenhouse tomatoes were employed, including removing all suckers and training one main stem to plastic twine attached to an overhead wire. The growing tip of the plant was removed on 16 Apr. after six clusters had formed. Fruit were harvested at the "turning to red" stage two to three times weekly, beginning 16 Apr. Weight and number of cracked fruit were recorded separately. Any fruit with cracking

detectable to the naked eye was counted as "cracked." The cluster from which fruit were harvested also was recorded.

Tensiometers to monitor soil water potential were installed in two bags in each treatment on 19 Sept. and connected to a datalogger. Tensiometers were removed for repairs several times, but recorded soil water potential for most of the season. Because of the limited number of tensiometers installed, tensiometer data were analyzed by paired *t* tests rather than SAS analysis of variance as was done with the other data (SAS Institute, Cary, N.C.). Regression equations were plotted with JMP statistical software (SAS Institute).

Varying amounts of nutrient solution and amounts of water independently (Spring 1992). Procedures followed in Spring 1992 differed from Spring 1990 as follows. Seeding and transplanting took place on 20 Dec. 1991 and 18 Feb. 1992, respectively. We used larger (6.7×12.2 m) freestanding, gutter-connected greenhouses. Both greenhouses were divided into beds raised 0.3 m above ground level with dimensions 2.4×1.2 m. Each watering treatment was imposed on two beds in each house, each bed containing 12 plants. This resulted in a total of four replications, two in each house.

From the time plants were placed in the beds to the first harvest, each bag received nutrient solution through two emitters. On 13 Mar., the following three irrigation treatments were imposed on two beds in each greenhouse for a total of six experimental beds per greenhouse: 1) two emitters per bag, both delivering nutrient solution (2EN); 2) one emitter per bag, delivering nutrient solution (1EN); 3) two

emitters per bag, one delivering nutrient solution and one delivering water (1EN + 1EW). The line providing only water was set to irrigate 20 min after the end of irrigation with nutrient solution. Irrigation treatments were assigned to beds randomly in the two greenhouses. The design was completely randomized, with two replications in each house and with the two greenhouses providing additional replication. Nutrient solution concentration was raised to Stage II on 17 Mar. and to Stage III on 11 May. Plants were topped on 15 Apr., leaving seven clusters on each plant. Fruit were harvested beginning 13 Apr.

Spring 1992 was cool and humid compared to 1990, and it was possible to avoid wilting in the one-emitter plants, without providing so much water that excess drained from the two-emitter plants. Excess watering was detected by placing catch pans under selected plants in the 2EN bags. When there was any runoff within 5 min after the end of the first watering in the morning, the amount of irrigation was decreased by shortening or deleting the next scheduled irrigation. Wilting in the 1EN plants signaled the need for resuming previous irrigation levels.

Results and Discussion

Numbers of emitters and cracking. In both years, the percentage of cracked fruit increased significantly when irrigation water was increased (Fig. 1). In 1990, fruit cracking was significantly higher on the basis of proportion of fruit cracked (40% vs. 60%) and on the basis of weight of fruit cracked (43% vs. 65%) when

Fig. 1. Effect of emitter treatment on percentage of cracked fruit on the basis of total number and total weight in Spring 1990 and 1992. For treatments of one and two emitters, both emitters delivered nutrient solution. One of the emitters in the 1 + 1 treatment delivered nutrient solution and the other delivered water. Within the same series (year and weight or year and number), columns with the same letter on top were not significantly different (for number: $P \leq 0.10$, $n = 12$ for 1990; $P \leq 0.05$, $n = 28$ for 1992; for weight: $P \leq 0.05$, $n = 12$ for 1990, $n = 28$ for 1992).

we used two rather than one emitter. In 1992, the percentage of cracked fruit grown in 2EN and 1EN + 1EW treatments was significantly higher on the basis of number (13.0% vs. 26.5%) and on the basis of weight (14.5% vs. 28.4%) compared to those from the 1EN treatment. For some of the early harvests in 1992, differences between treatments were almost 5-fold. On 5 May 1992, for example, only 6% of the total number of fruit was cracked with 1EN, while 25% was cracked with 2EN and 29% with 1EN + 1EW.

In 1992, significantly more cracked fruit were harvested from one house than the other. However, the interaction of house and irrigation treatment was not significant for number or weight of cracked fruit and the houses did not differ in yield. The only difference in the percentage cracking data between the two houses was that in the house with more cracking, the 2EN treatment had a higher percentage of cracking than the 1EN + 1EW treatment (39% vs. 34% by number and 39% vs. 35% by weight), while in the house with less cracking overall, the 2EN and the 1EN + 1EW treatments did not differ significantly. For more convenient comparison with 1990, data from the two houses were therefore combined in Fig. 1. For the combined data from both houses in 1992, there were no significant differences between the 2EN and the 1EN + 1EW treatments in percentage of cracked fruit.

The 1992 experiment allowed us to separate the effects of providing extra water from those of providing extra nutrients, effects that were confounded in the 1990 experiment. When treatments receive differing amounts of fertilizer as well as different amounts of water (as in 1990), plants receiving more fertilizer may have grown faster. This more rapid growth might, in and of itself, result in greater cracking. There is, indeed, evidence that rapid fruit growth from any of a number of causes increases fruit cracking. Dutch investigators reported increased incidence of russetting (a disorder related to cracking where minute cracks appear all over the skin) when fruit were developing more rapidly (Bakker and Janse, 1988; Schilstra-van Veelen and Bakker, 1985). Our 1990 data also provide partial support for the hypothesis that rapid fruit growth increases cracking (Peet, 1992). Fruit that were cracked at harvest had matured significantly ($P \leq 0.05$) more rapidly than uncracked fruit (58.4 days vs. 61.8 days). However, once cracking occurred, fruit may have ripened more rapidly and so were harvested sooner.

Based on our 1992 data, however, we suggest that extra water alone can cause cracking, even if no extra fertilizer is provided, and the increase in cracking is not a secondary result of more rapid plant growth. Plants receiving the most water had the most cracking, regardless of the amount of fertilizer provided. Plants in the 1EN treatment received half as much water as those in the other two treatments and had only half as much cracking. Plants in the 1EN treatment received the same amount of fertilizer as 1EN + 1EW plants, but still had much less cracking.

Our data have practical application for greenhouse production of tomatoes. Where fruit cracking is a problem, irrigation should be reduced. Overirrigating is particularly tempting late in the season in the spring crop as the plants become older and days become longer and hotter. By the end of the season, however, few fruit remain on the plant, and leaf area is either the same or may be less if lower leaves have been removed, a normal cultural practice. The remaining leaves are older, leathery, and may transpire less. Thus, it would probably be safer in terms of preventing fruit cracking to reduce irrigation at the end of the crop than to automatically raise it. This concept has several implications for automatic greenhouse watering. If the concept is correct, models that predict watering requirements on the basis of evapotranspiration and leaf area would overpredict water usage unless they take into account changes in plant transpiration. Lysimeter-based control systems, which add water only as it is actually used by the plant, may lead to reduced cracking if properly set.

A Japanese study on the effect of soil moisture content on cracking in field-grown tomatoes offers a partial explanation for increased cracking in the treatments receiving more water. Kamimura et al. (1972) found that fruit of tomato plants grown under high soil moisture differed anatomically from those grown under low-moisture conditions. Under

high soil-moisture growing conditions, fruit enlarged rapidly and minute cuts occurred frequently on the surface. These minute cuts could later act as focal points for stresses that further tear the cuticle (Brown and Considine, 1982). The cuticle was also thinner and the epidermal and subepidermal cells flatter and more markedly stretched compared to those of fruit grown under low soil moisture. Fruit on plants grown under low soil moisture were smaller and had higher tensile strength with few minute cuts.

Presumably because of these anatomical differences, Kamimura et al. (1972) found the most severe cracking under high, compared to low, soil-moisture conditions. This explanation fits our tensiometer data from 1990, as cracking was significantly higher and soil moisture tensions were significantly lower (-3.45 kPa compared to -16.21 kPa) in the treatment given more water over the course of the study. The -12.2 kPa difference in soil moisture tension was significant at $P < 0.0001$ using paired t tests ($SE = 1.99$ kPa).

Position of the cluster and cracking. In both years, the upper clusters were more prone to cracking, regardless of irrigation treatment. For both seasons, linear regressions of cracking percentage (on the basis of number) on cluster were significant ($P \leq 0.01$ with $r^2 = 0.90$ for Spring 1990 and $r^2 = 0.98$ for Spring 1992). Linear regression of cracking percentage on cluster position resulted in the following pre-

Fig. 2. Percentage of cracked fruit on the basis of total number at each cluster for greenhouse-grown tomatoes in (A) Spring 1990 and (B) Spring 1992. Vertical lines show standard error of the mean. Cluster 1 is nearest the base of the plant.

dicted parameters: intercepts were 2.2 and -4.7 and slopes were 13.1 and 7.5 for 1990 and 1992, respectively.

There was evidence of nonlinearity in Spring 1990, when the percentage of cracked fruit was fairly stable from the first to third clusters, then doubled for the fourth through sixth clusters (Fig. 2A). However, regression of cracking percentage vs. cluster count did not support a quadratic relationship in that the second-order term was not significantly different from zero (P that "c" = 0 > 0.2). The increase also appeared to be linear in 1992, when the percentage of cracked fruit increased from 2% in the first cluster to 38%, 41%, and 45% in clusters 5, 6, and 7, respectively (Fig. 2B).

Several factors, including temperature and irradiance, may contribute to greater cracking in the upper clusters. Upper fruit were more exposed to the sun than those on the lower clusters, especially once plants were topped. Verner (1935) found that apples (*Malus domestica* Borkh.) grown on the outside of the tree and exposed to the sun were most likely to crack. Because of their greater exposure to the sun, fruit on upper clusters could also be expected to heat up more during the day than fruit on lower clusters. Frazier (1947) found that higher temperatures in general, and sudden high temperatures in mid-afternoon in particular, caused ripe tomato fruit to crack in the greenhouse, probably because of expansion of the fruit pulp as temperatures increase. Lang and Düring (1990) reported that raising the temperature of grape berries dramatically increased the pressure exerted by the pulp on the skin while simultaneously decreasing the stiffness and strength of the skin.

An additional component of cracking in upper clusters may be the reduced fruit load as fruit is progressively harvested up the main stem. Low fruit load has been associated with increased cracking in greenhouse tomatoes (Bakker and Janse, 1988; Schilstra-van Veelen and Bakker, 1985).

Number of emitters and fruit production. Effects of the various irrigation treatments on total fruit number were not significant in Spring 1990 (Table 1). In Spring 1992 (Table 1), the 1EN and 2EN treatments did not differ significantly in fruit count, but count was significantly higher ($P < 0.10$) in the 1EN + 1EW treatment compared to the other two treatments. Although the differences were not large (9.8%), they suggest that plants in the 1EN + 1EW treatment may have benefited from the daily flushing with water a few minutes after receiving nutrient solution. Further studies need to be done to confirm this hypothesis, since the number of samples of the medium taken at the end of the experiment was insufficient to determine if salt levels differed significantly between treatments. All were in the normal range, however.

Increasing the amount of water provided increased total fruit weight per plant by 18.6% (Table 1) in 1990. In 1992, there were no differences in weight of fruit per plant between the 1EN and 2EN treatments, but as with fruit count, fruit weight per plant was significantly (19.7%) higher in the 1EW +

Table 1. Total number and weight (grams) of fruit per plant (Spring 1990 and Spring 1992) irrigated with different amounts of water.

Treatment ^z	Fruit			
	Count		Wt	
	1990 ^y	1992 ^x	1990 ^y	1992 ^x
1EN	37.3 a	26.2 b	8129 b	4209 b
2EN	38.4 a	26.4 b	9639 a	4647 b
1EN + 1EW		28.8 a		5302 a

^z1EN = one emitter per bag providing nutrient solution; 2EN = two emitters per bag providing nutrient solution; 1EN + 1EW = two emitters per bag, one of which provided only nutrient solution and one of which provided only water.

^yOne-way analysis of variance indicated no treatment effects ($P = 0.66$, $n = 12$) for fruit count, effects significant for fruit weight ($P = 0.003$, $n = 12$).

^xMean separation within columns by Duncan's multiple range test, $P < 0.1$, $n = 12$.

1EN emitter treatment than in the other treatments.

We have demonstrated in two crops of greenhouse tomatoes that increasing the amount of water applied increases cracking. This result suggests that in greenhouse situations where cracking is severe, a reduction in watering should be considered. These results also may apply to field crops (Kamimura et al., 1972; Nassar et al., 1971; Nitzsche and Storlie, unpublished data). Caution should be used in watering reduction, however, because low root pressures will make the plants more susceptible to blossom-end rot. The number of fruit with blossom-end rot was lower than the number of cracked fruit in all crops studied but was inversely proportional to cracking. That is, when the amount of water was increased, cracking increased, but blossom-end rot decreased. Good Ca nutrition is important in preventing blossom-end rot and has also been implicated in controlling fruit cracking (Peet, 1992). The best strategy to protect the younger clusters if cracking appears in the older clusters would be to reduce watering gradually, watching for the appearance of blossom-end rot, severe wilting, or reduced fruit size. At the appearance of any of these signs, watering should be stabilized and gradually increased, again avoiding sudden increases, which will, of themselves, trigger cracking. Where possible, water provided should be tied to water usage, as through the use of lysimeter-based irrigation systems.

Our data suggest that by deliberately overwatering the plants, cracking resistance of cultivars or the efficacy of treatments to prevent cracking could be compared.

We cannot draw any conclusions on the mechanism by which overwatering increased cracking, but we demonstrated in Spring 1990 that soil water potential was less negative in the treatments receiving more water. This likely increased root pressure and seems the most likely explanation for increased fruit cracking. Using the Spring 1992 data, we demonstrated that the effect water supply has on fruit cracking was independent of the effect of providing more nutrient solution.

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