Yield and Quality of Tomato Fruit under Water-table Management

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ABSTRACT. In a 2-year study (1993–94), tomato (*Lycopersicon esculentum* Mill. ‘New Yorker’) plants grown in a sandy loam soil in field lysimeters were subjected to four water table depth (WTD) treatments (0.3, 0.6, 0.8, and 1.0 m from the soil surface). In 1994, precipitation during the flowering stage was far above average and apparently led to waterlogging in the shallowest WTD treatment, while in the drier year (1993), the deepest WTD treatment suffered from drought stress. In general, over the 2 years, the 0.6-m WTD showed the best yields and largest fruit, while the 1.0-m WTD showed the lowest yields and smallest fruit. However, the incidence of catfacing, cracking, and sunscald was generally higher in the 0.6 m WTD treatment and lower in the 1.0-m WTD treatment. Furthermore, fruit firmness was generally greatest for the two deeper WTD than for the shallower WTD. To strike a balance between yield and quality, a WTD of between 0.6- and 0.8-m is recommended for tomato production on sandy loam soils.

Between 1300 and 1600 ha of land are dedicated to tomato production in the province of Québec, Canada. Mean yields during the 1980s in Québec ranged from ≈ 7 to $14 \text{ t} \cdot \text{ha}^{-1}$ (Bureau de la Statistique du Québec, 1991), well below yields of 45 to $65 \text{ t} \cdot \text{ha}^{-1}$ reported elsewhere (Doorenbos and Kassam, 1979). Furthermore, as of 1989, Québec was only 10% self-sufficient in tomato production (Bureau de la Statistique du Québec, 1991) and imported close to \$15 million worth of tomatoes. To maintain or improve yields, intensive agricultural operations require high fertilizer and pesticide applications, which may lead to surface and groundwater contamination. One cost-effective and -efficient method of reducing nitrate concentrations in subsurface drainage effluent is water table management (Madramootoo et al., 1993). Water table draw-down and drain outflow can be restricted by a water control structure on the subsurface drain outlet. The water table is lowered to allow field machine operations in the spring and fall. It then is raised above the drain pipes in the growing season by pumping water into the control structure. This method also is known as subirrigation.

Compared to sprinkler or furrow irrigation, which are commonly used in Québec, the same levels of water can be supplied by subirrigation using existing subsurface drainage systems. Subirrigation is more water and energy efficient than sprinkler systems and has the added advantages of 1) not causing localized surface runoff that could carry pesticides or fertilizers, 2) having minimal evaporational losses, 3) not wetting the plant, thus reducing the risk of spreading disease, and 4) reducing nitrate losses to surface or groundwater by promoting denitrification.

While subirrigation has been used in this region for corn and soybean (Lalonde et al., 1996; Tait et al., 1995), it has yet to be used for vegetable crops. Soliman et al. (1978) in Egypt and Battilani and Mannini (1992, 1994) in Italy have studied the influence of water table depth on tomato production. However, the length of the growing season, soil type, and other conditions in Québec are different from those encountered in Italy or Egypt. As information is needed to establish appropriate water table levels for local conditions, we undertook this study to determine the effects of water table level on tomato yield and quality on a typical sandy loam soil.

Materials and Methods

SITE AND LAYOUT OF EXPERIMENT. A detailed description of the lysimeters and experimental site is given in Dodds et al. (1996). Tomato plants (‘New Yorker’) were grown outdoors in lysimeters (0.4 m in diameter and 1.0 m deep) containing a Humic Gleysol, a soil type quite common in the St. Lawrence valley (Canada Soil Survey Committee, 1983). This soil, a Courval sandy loam (85% sand, 15% clay) was repacked to a bulk density of $1.1 \text{ t} \cdot \text{m}^{-3}$, identical to that in the field where it was obtained. To determine field capacity, before a rainfall event of $>20 \text{ mm}$, a burlap bag was spread over each of five bare, but otherwise undisturbed, soil sites in the field. After the rainfall, the wet bag served to eliminate evaporation from the soil surface for 12 h, during which excess water was allowed to drain from the field. Volumetric water content of a 0.3-m-deep soil core then was determined for each covered site, and an average of 38% was obtained. For permanent wilting point determination, a dozen uniform, $\approx 1\text{-m}$ -tall maize (*Zea mays* L.) plants growing in different parts of the field were dug up, transferred into 4-L plastic pots and watered to compensate for the transfer stress. The potted plants then were placed in the sun, protected from the rain by a window, and left there until their leaves reached a stage of wilting from which it was deemed they could not recover. Volumetric soil water content then was determined, and an average of 3% was obtained. The lysimeters were cropped to soybeans for 3 years before these experiments.

In 1993 and 1994, water table levels were controlled through attached water tanks, and actual water table depth was monitored

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using a homemade piezometer installed in each lysimeter. The average water table depths (WTD) were 0.3, 0.6, 0.8, and 1.0 m in both years. The four WTD were factorially combined with five potassium–calcium fertilizer treatments, each in four replicate lysimeters, resulting in a total of 80 lysimeters. There was one plant per lysimeter. Potassium was applied as KCl the day before transplanting and calcium as a 1.0% (w/v) CaCl_2 foliar spray. The calcium spray began when the first fruit were 10 mm in diameter until harvest. The fertilizer treatments consisted of K and Ca (in $\text{kg}\cdot\text{ha}^{-1}$), respectively 1) 0 and 0 (LL), 2) 0 and 250 weekly (LH), 3) 133 and 250 every 2 weeks (MM), 4) 332 and 0 (HL), and 5) 332 and 250 weekly (HH).

Seedlings ('New Yorker') were prepared (Dodds et al., 1996) and transplanted to each lysimeter and to guard row sites on 5 June 1993 and 30 May 1994. Any damaged plants were replaced within 1 week after planting. Flowers or flower buds were removed from the plants for 4 weeks after planting.

HARVEST AND QUALITY ASSESSMENT. Fruit that were mature green or riper were harvested 11 Aug. 1993 (harvest 1) and all remaining fruit were harvested 23 Aug. 1993 (harvest 2). In 1994, all fruit were harvested 7 Aug. (harvest 3). In the case of harvests 2 and 3, immature fruit accounted for <3% of fruit.

All fruit were scored subjectively for severity of catfacing, sunscald, cracking, and stage of ripening. Individual fruit size and

mass were measured. Catfacing was rated on a scale from 0 (none) to 4 (severe) based on the diameter of lesions [U.S. Dept. of Agriculture (USDA), 1973]. Sunscald and cracking (vertical and concentric) were rated as 0, 1, or 2, where 0 was none, 1 was mild, and 2 was severe. Ripening stages were assigned numerical values, 0 for mature green, 10 for breaker, 20 for turning, 30 for early pink, 45 for pink, 75 for red, and 100 for full ripe or overripe, corresponding roughly to the cumulative percentage of fruit ripened to the successive stages (USDA, 1973). Blossom end rot occurred on <0.2% of fruit in 1993 and was not found on any fruit in 1994. Measurements of fruit size included height (stem scar to blossom scar) and maximum and minimum equatorial diameters. Fruit were considered marketable if they showed no sunscald or cracking, a catfacing rating of ≤ 1 , and a minimum equatorial diameter of ≥ 47.6 mm (USDA, 1973).

MECHANICAL PROPERTIES OF FRUIT. Fruit firmness was tested by a compression and puncture tests. For firmness testing of the pericarp under constant area compression, two mature green fruit from each plant were harvested and ripened at room temperature to the early breaker stage (USDA, 1973). Firmness of each tomato taken around the equator and over the locules using a 12-mm core borer (Jackman et al., 1990). The thickness of specimens was measured using vernier calipers. Each specimen, with intact epidermal tissue, was put on a flat metal plate and compressed at a speed of $10\text{ mm}\cdot\text{min}^{-1}$ with a 57-mm flat-ended cylindrical mandrel mounted on an Instron universal testing machine (series 4502; Instron Canada, Burlington, Ont., Canada) equipped with a 500-N load cell. Force-displacement data acquisition was at 10 points per second. The raw data were used as input for the Instron Series IX software, which produced a force vs. displacement curve for the sample (Fig. 1a) and other output, including stress and toughness at failure. Stress was calculated as the ratio of force to the cross-sectional area of the specimen. Toughness was calculated by dividing energy, the area under the force-displacement curve up to failure, by specimen volume. Of all the mechanical properties that were studied, stress and toughness provide the best measurement of firmness, as both are normalized measurements.

For measurement of firmness by the puncture test, two fruit from each plant were picked and tested at the red ripe stage. Each tomato was placed on a flat plate and punched around the equator in three places using a cylindrical probe (1 mm in diameter) (Holt, 1970). Crosshead speed and rate of data acquisition were the same as for the compression tests. To prevent a tomato from turning during the puncture it was restricted by modelling clay. Force at failure and energy were computed based on the force-displacement curve (Fig. 1b). However, unlike the compression of a cylinder of known dimensions, one cannot determine the exact area–volume involved in resisting penetration, hence normalized values of stress and toughness cannot be calculated.

Puncture tests were done for all fertilizer treatments in 1993 and 1994. However, in 1993, all WTD were compared, whereas in 1994 only the 0.8-m WTD fruit were tested, which was due to the limited number of fruit available in 1994 and that the normalized values of stress and toughness from the compression test had already been obtained with the available fruit in 1994.

FIELD MEASUREMENTS. Rainfall, class A pan evaporation, wind speed, and minimum and maximum air and water temperatures were measured daily at the site. Daily crop evapotranspiration (ET_c) was calculated by multiplying the pan evaporation by a pan constant (k_p) and a crop consumptive use coefficient (k_c). Values for k_p were computed daily according to American Society of Civil Engineers (1990) and ranged from 0.67 to 0.82. The k_c values were

Fig. 1. Typical force displacement curves for (a) compression and (b) puncture tests.

taken from Doorenbos and Kassam (1979). Rainfall and ET_c are shown in Fig. 2. Mean soil moisture in the top 0.6 m of the soil was measured weekly by time domain reflectometry (Topp and Davis, 1985) for all lysimeters. For each WTD the mean soil moisture was the average of 20 lysimeters.

STATISTICAL ANALYSIS. Fruit height; maximum and minimum equatorial diameter; severity of catfacing, cracking, and sunscald; mean ripening stage at harvest (earliness); fruit per plant; and percent marketable fruit were averaged or computed per plant before statistical analysis. Averages for all measured characteristics were analyzed using PROC GLM (SAS, 1985; DOS version 6.08). For all characteristics measured, fertilizer $\times$ WTD interactions were not significant ($P < 0.05$) for all harvests and whether all or only marketable fruit were analyzed. For catfacing, sunscald, cracking, and earliness, fertilizer effects were not significant ($P < 0.05$). For these measurements, data were pooled across fertilizer treatments and compared by WTD alone using Duncan's multiple range test with an $\alpha = 0.01$. For the physical properties of the fruit, the data were analyzed as a WTD $\times$ K $\times$ Ca fractional factorial, there being only five of nine K $\times$ Ca combinations tested. Each factor was compared using Duncan's multiple range test, $\alpha = 0.01$ for WTD and $\alpha = 0.05$ for K and Ca. Subjecting the rating scale and ripening data to an arcsin transformation did not alter the results of the analysis.

Results and Discussions

WEATHER PATTERNS AND WATER RELATIONS.

The precipitation of June 1993 and 1994 was above average. June precipitation was $\approx 70\%$ (1993, 133.5 mm) and 130% (1994, 174.6 mm) higher than the local 30-year average (78.0 mm) and 30% higher in 1994 than 1993 (Dodds et al., 1996). July precipitation was 3% (1993) and 35% (1994) lower than the local 30-year average. August precipitation before harvest was 65% lower in 1993 (harvest 2) and 50% higher in 1994 than the local 30-year average. Soil moisture in the top 0.6 m of the soil was 6% to 30% higher in 1994 than 1993 and near field capacity for the two shallower WTD treatments (Table 1). While roughly two thirds of the June 1993 precipitation occurred during vegetative growth, the same proportion of June 1994 rain occurred during flowering, including two high-intensity storms of >35 mm (Fig. 2).

SIZE AND YIELD. In 1993, the height of all fruit from harvests 1 and 2 was highest for the 0.6-m WTD and lower for the 1.0-m WTD than for any other WTD (Fig. 3). Fruit height decreased in the order 0.6-, 0.3-, 0.8-, 1.0-m WTD. These trends and differences also were apparent for marketable fruit and for harvests 1 and 2

Fig. 2. Precipitation and crop evapotranspiration (ET_c) for both growing seasons.

combined (not shown). For harvest 3 in 1994, height remained constant across WTD. Height was lower in 1994 than in 1993 (harvests 1 and 2 combined; $P < 0.01$).

Maximum and minimum equatorial diameters of all fruit of harvests 1 and 2 in 1993 were highest for the 0.3- and 0.6-m WTD treatments and decreased successively in the 0.8- and 1.0-m WTD treatments (Fig. 3). For harvest 3 in 1994, equatorial diameter remained highest for the 0.6-m WTD and tended to decrease at deeper water table depths, but the smallest diameters were obtained with the 0.3-m WTD. In 1993, diameters were larger than in 1994 ($P < 0.01$). These differences also were observed for marketable fruit and for harvests 1 and 2 combined (not shown). Cereti et al. (1988) measured increasing fruit size in subirrigated greenhouse-grown tomatoes grown at increasing soil water contents. Others also have measured increased mean tomato fruit mass with increased irrigation (Giardini et al., 1988; Moore et al., 1958; Rubino and Tarantino, 1988).

Yield based on the number of fruit per plant showed no

differences by WTD for harvest 1 (Fig. 3). When based on mass, yield for harvest 1 showed a trend of decreasing yield with increasing WTD—the yield at the 1.0-m WTD being significantly lower than at the shallower WTDs. For harvest 2 and for all 1993, differences in yield between WTD treatments were similar to those for size characteristics: the 0.6-m WTD showed the greatest yield, the 0.3-m WTD less, and the 0.8- and 1.0-m WTD treatments still less. Comparatively, in 1994, harvest 3 showed the highest yield by number and mass at 0.8- and 1.0-m WTD and progressively lower

Table 1. Seasonal mean soil moisture and plant stem mass at harvest for 1993 and 1994.

Water table depth (m)	Volumetric soil moisture (%) to 0.6-m depth		Stem mass at harvest (g)	
	1993	1994	1993	1994
0.3	33.6 a ^z	36.0 a	480 b	69 c
0.6	24.5 b	30.8 a	827 a	341 a
0.8	11.1 c	16.2 b	424 b	230 b
1.0	7.1 d	10.3 c	190 c	206 b

^zFor each year, values sharing a letter are not significantly different ($\alpha = 0.01$) based on Duncan's multiple range test.

yields at 0.6- and 0.3-m WTD. Moore et al. (1958) showed that tomatoes grown in a soil where moisture was maintained at a level of $\geq 50\%$ of field capacity, compared to a minimum slightly above the wilting point, had fewer fruit per plant. However, for this study, when the same comparisons are made for soil moisture contents of 50% of field capacity vs. just above the permanent wilting point (Table 1) in 1993 (0.6 vs. 1.0 m WTD) and 1994 (0.8 vs. 1.0 m WTD), the results show the opposite effect of increased soil moisture.

Thus, in general, differences in height, as well as maximum and minimum equatorial diameter, for 1993 were consistent with increasing water stress with increasing WTD. However, in 1994, the 0.3-m WTD showed reduced dimensions compared to the other WTD treatments, consistent with waterlogging being the primary cause of reduction in size. While the mean seasonal soil moisture content at the 0.3-m WTD was 2% below field capacity, the intense and prolonged rains of late June 1994 would have quickly saturated the soil, creating waterlogged conditions. Thus, the smaller fruit dimensions in 1994 are likely due to the physical damage and short-term waterlogging from the intense late June rains. Also, these factors likely contributed to the greatly reduced seasonal yields (harvest 1 + 2 vs. harvest 3; Fig. 3) and stem mass (Table 1)

Fig. 3. Effect of water table depth on mean fruit size and yield for harvests 1 and 2 (1993) and harvest 3 (1994). For each harvest and each characteristic, values sharing a letter are not significantly different ($\alpha = 0.01$) based on Duncan's multiple range test.

at harvest in 1994. Ten days of flooding at flowering reduced pot-grown tomato fruit set, yield (fruit per plant or mass), and seeds per locule more than flooding during either the seedling or fruit development stages (Lopez and del Rosario, 1983). Similar effects of waterlogging have occurred at equivalent phenological stages of sunflower and sorghum (Orchard and Jessup, 1984). Hubbell et al. (1979) imposed waterlogging on field-grown tomatoes at the second flower cluster stage, resulting in anaerobic soil conditions to a depth of 0.2 m for 24 h, which led to 15% of tomato plants wilting (vs. 4% for nonwaterlogged) and 40% yield reductions.

The 1.0-m WTD showed roughly the same stem mass in 1993 and 1994, while shallower WTD showed reductions ranging from 45% to 880% (Table 1). Again, for the 1.0-m WTD, seasonal yield (by mass or by number) was $\approx 50\%$ less in 1994 than in 1993, while shallower WTD showed reductions ranging from 74% to 93% (Fig. 3). Again, This result strongly suggests that waterlogging in 1994 was a contributing factor to these differences. In 1993, yield and stem mass were highest at the 0.6-m WTD, slightly lower at the 0.3-m WTD, and increasingly lower at the 0.8- and 1.0-m WTD (Fig. 3 and Table 1). Thus, while plant water stress was not measured and a soil moisture

characteristic curve is not available for this soil, it may be inferred that, in 1993, water table effects were predominantly related to moisture deficits at deeper WTD. However, in 1994, yield increased with increasing WTD, suggesting that water table effects were predominantly related to moisture excesses at shallower WTD (Fig. 3).

Our results are similar to those of Battilani and Mannini (1992,1994) in that, in a wet year (1994), yield increased with deeper WTD, while in a dry year (1993, harvest 2), yield increased from the shallowest WTD to the next deepest WTD then steadily declined (Fig. 4). Under dry Egyptian conditions, Soliman et al. (1978) showed the lowest yield for the shallowest WTD they tested (0.4 m; Fig. 4). With deeper WTD (0.7 to 1.6 m), yields increased and then leveled off. The fact that yields did not drop off at deeper WTD in the Egyptian study is likely attributable to the higher clay content of their soils, which would afford a higher water-holding capacity and greater capillary rise of water from the water table.

QUALITY OF FRUIT. In 1994, catfacing was significantly greater at the 0.6-m WTD than at any other WTD (Fig. 5). In 1993, while catfacing tended to be more severe, WTD had no effect on catfacing. In both years, those WTD treatments with the lowest yield showed the lowest catfacing and those with the highest yield were among the most affected by catfacing.

Cracking in 1993 was highest in the 0.3-m WTD and lowest in the 1.0-m WTD (Fig. 5). Again, in 1994, cracking tended to be lowest in the 1.0-m WTD but highest at the 0.6- and 0.8-m WTD. Frazier (1934) and Moore et al. (1958) also found increased incidence of cracking at higher irrigation rates.

Sunscald was significantly higher at the 0.6-m WTD in 1994, but WTD had no effect on the severity of sunscald in 1993 (Fig. 5). Thus, for all three disorders, the 0.6-m WTD was among the worst and the 1.0-m WTD among the best. This result is particularly reflected in the significantly lower percent marketable yield for the 0.6-m WTD in 1994. In 1993, the

Fig. 4. Effect of water table depth on tomato fruit yield under different soils and climatic conditions compared to this study.

Fig. 5. Effect of water table depth on mean severity of catfacing ($\times 10$), cracking ($\times 100$), and sunscald ($\times 10$); mean percent marketable fruit; and mean ripening stage at harvest (MG = mature green, BR = breaker). For each harvest and each characteristic, values sharing a letter are not significantly different ($\alpha = 0.01$) based on Duncan's multiple range test.

Stress (MPa)

Toughness (MPa)

Fig. 6. Effect of water table depth (WTD) and K and Ca levels on stress and toughness of excized cylinders of breaker fruit pericarp. Values sharing a letter are not significantly different ($\alpha = 0.01$ for WTD and $\alpha = 0.05$ for K and Ca) based on Duncan's multiple range test.

^zL = no added Ca, M = Ca at 250 kg·ha⁻¹ every 2 weeks, and H = Ca at 250 kg·ha⁻¹ per week.

^yL = no added K, M = K at 133 kg·ha⁻¹, and H = K at 332 kg·ha⁻¹.

percent marketable yield for the 0.6-m WTD was the highest but was not significantly greater than for the lower (0.8- and 1.0-m WTD). In both years, percent marketable fruit from the 1.0-m WTD was relatively high.

In terms of earliness, the drought stressed 1.0-m WTD in 1993 and the waterlog stressed 0.3-m WTD in 1994 showed much earlier ripening of fruit. In both years, fruit from the 0.6-m WTD were the slowest to mature (Fig. 5). In 1993, this slow maturity was reflected in the larger proportion of the total yield for the 0.6-m WTD, which occurred in harvest 2 than in harvest 1 (Fig. 3).

MECHANICAL PROPERTIES. In 1993 compression tests, stress and toughness, at failure were greatest for the two deeper WTD than the two shallower WTD (Fig. 6). Similarly, puncture tests showed lower force and energy at failure for the two shallower WTD and progressively greater values at the 0.8- and 1.0-m WTD (Fig. 7). However in 1994, while the two deeper WTD again showed higher stress and toughness than the 0.6-m WTD, these characteristics were elevated in the 0.3-m WTD. Thus, under drought and waterlog stress, fruit firmness was heightened. Kaniszewski et al. (1987) showed that irrigated tomato plants produced firmer fruit than non-irrigated plants. In contrast, in apples, over- or under-watering in the weeks before harvest led to lower fruit firmness (J.L. García et al., 1995).

In 1993 and 1994, for compression and puncture tests, firmness values were greatest for the high Ca treatment and lowest for the treatment with no Ca application. Calcium is well known for its effectiveness in maintaining the cell wall, particularly middle lamella structure, through its binding to pectic substances. This property has long been used in maintaining the firmness of canned tomatoes (Kertesz et al., 1940). J.M. García et al. (1995) showed that Ca foliar spray increased firmness of tomato fruit measured with and without the skin present.

Potassium level had no consistently significant effect on firmness characteristics. Shafshak (1961) and Shafshak and Winsor (1964) showed increased tomato fruit firmness with increased potassium fertilization; however, Lanham (1926) showed no effect of potassium on tomato fruit firmness.

Thus, while the 0.6-m WTD generally produced larger fruit and higher yields, the quality, including firmness, of these fruit was generally lower than at deeper WTD. Conversely, the 1.0-m WTD produced smaller fruit and less than maximal yields but had fewer defects and greater firmness.

Madramootoo et al. (1993) recommended a WTD of 0.6 m for subirrigation of soybeans [*Glycine Max* (L.) Merr.] on sandy loam soils of the St. Lawrence lowlands. However, tomato is much less tolerant of waterlogging than soybean. Therefore, we conclude

Force at failure (N)

Energy (mJ)

Fig. 7. Effect of water table depth (WTD) and K and Ca levels on force and energy at failure in a puncture test of red ripe tomato fruit. Values sharing a letter are not significantly different ($\alpha = 0.01$ for WTD and $\alpha = 0.05$ for K and Ca) based on Duncan's multiple range test.

²L = no added Ca, M = Ca at 250 kg·ha⁻¹ every 2 weeks, and H = Ca at 250 kg·ha⁻¹ per week.

³L = no added K, M = K at 133 kg·ha⁻¹, and H = K at 332 kg·ha⁻¹.

⁴In 1994, fruit tested came from only the 0.8 m water table depth; in 1993, all watertable depths were used and compared.

that subirrigation with a WTD between 0.6 and 0.8 m will give the best balance between yield and quality characteristics for tomatoes produced on sandy loam soils.

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