Two Hundred Tons Per Hectare of Processing Tomatoes—Can We Reach It?

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Additional index words. productivity, subsurface drip irrigation, high-frequency irrigation, evapotranspiration, fertigation, water-use efficiency

Summary. Processing tomato is an important crop in California, where ≈ 100,000 ha is grown annually. In the past, processing tomatoes have been irrigated mostly by sprinkler and furrow irrigation, although several tests have been conducted with drip irrigation, and a few growers are using subsurface drip irrigation. Yields of tomato have been shown to be sensitive to water management when the amount of irrigation water closely matches plant water use. Tomatoes have been identified as susceptible to drought stress and waterlogging at both ends of the furrow irrigation cycle. Subsurface drip irrigation is a relatively new method in which drip irrigation laterals are buried permanently 20 to 60 cm below the soil surface. This method has provided the control and uniformity of water and fertilizer distribution necessary to maximize the yield of processing tomatoes. A computerized control system maintains nearly constant soil water and nutrient concentration in the root zone by irrigating and fertilizing frequently, thus avoiding small water and nutrient stresses, especially during the critical period between first and peak bloom. During the maturation and ripening stage, irrigation and nutrient concentrations can be adjusted to increase soluble solids and to adjust the maturation rate to coincide with the harvest schedule. Maximum yield levels can be obtained when nearly all the fertilizers (N, P, and K) are injected precisely in time and space through the drip irrigation system to meet the crop nutrient requirement. Water-use efficiency (WUE), defined as the ratio of yield : unit of water used by the plant, can be maximized by using this precise irrigation and fertilization technique. Yields >200 $t\cdot ha^{-1}$ of red tomatoes were achieved in large field plot research, and commercial yields of 150 $t\cdot ha^{-1}$ were achieved in large-scale field applications with a lesser degree of control. Therefore, we predict that with further fine-tuning, commercial yields of 200 tons of processing tomatoes/ha could be achieved using a subsurface drip irrigation system with accurate water and fertility management.

“. . .commercial yields of 200 tons of processing tomatoes/ha could be achieved. . . ”

Processing tomato *(Lycopersicon esculentum* Mill.) is an important crop in California, where it ranks 13th in commodity value. About 100,000 ha of processing tomatoes are grown annually in California, representing a production value of $327 million. Processing tomato production in California depends on irrigation to supply most of the crop’s water requirement. Traditionally processing tomatoes have been irrigated by sprinkler (Vittum et al., 1958) and furrow irrigation (Aljibury and May, 1970); however, several tests have been conducted with drip irrigation (Davis et al., 1985; Pruitt et al., 1984; Rudich et al., 1977; van Ootegem et al., 1982) and subsurface drip irrigation (Phene et al., 1982b, 1987). Surface and subsurface drip irrigation have improved the water management of tomatoes with corresponding increases in productivity and

[1]Convenient metric to British measurement conversions:
1 t (metric ton) = 1000 kg = 2200 lb = 1.1 tons
1 $t\cdot ha^{-1}$ (metric ton/hectare) = 0.44 ton/acre
1 ha = 2.47 acres
25.4 mm = 2.54 cm = 1 inch
1 m = 39.4 inches

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water-use efficiency (WUE) (Davis et al., 1985; Phene et al., 1985a, 1985b, 1987). The im-portance of precise irrigation scheduling to avoid water stress and produce high yield and improved quality of tomatoes has been dem-onstrated by Cannel1 and Asbell (1974), Rudich et al. (1977), Phene et al. (1982a, 1985a), and Hutmacher et al. (1985). In contrast, excess water applications have caused deficiencies in soil aeration, nutrient leaching, and subsequent yield reductions (Feddes et al., 1978; Wacquant et al., 1975).

Under semi-arid and arid irrigated agricultural conditions, Phene et al. (1990) showed that the two major management factors affecting yield and quality of tomatoes are water management and fertility management. Furthermore, accurate water-nutrient management of tomatoes with subsurface drip irrigation can provide maximum economic yield (MEY). Maximum economic yield is defined as the point closest to maximum yield (MY) where the highest possible net return is achieved (Thompson, 1984). Maximum yield differs from MEY in that the input costs are considered in MEY but not in MY. Economically, efficient use of inputs implies that the farmer increases inputs as long as the additional revenue generated exceeds the additional cost of the inputs.

Another often-used approach increases the precision of the management of the inputs (in this case, water and nutrients) in time and quantity to match the crop requirements more precisely, without increasing the amounts of the inputs. In this case, as MY increases, MEY tends to converge to MY, since the increase in yield results from more precise management rather than added inputs, provided that the increase in management does not increase the cost (Phene, 1987). Smith et al. (1991) showed that cotton grown with subsurface drip irrigation produced the highest net return when compared with furrow and low-energy precision application linear-move irrigation systems. Compared with tomatoes, cotton has a much lower profit margin; therefore, if an increase in net return is possible with cotton, it also should be possible with tomatoes.

Some crops achieve maximum crop yield when expansive growth (cell growth and division) is allowed to occur unimpeded by water stress (Hsiao et al., 1976). Expansive growth is extremely sensitive to small water deficits and must be sustained through early to mid-season to develop a plant framework for intercepting light and carrying out transpiration and photosynthesis (Hsiao et al., 1976). To avoid water stress, the water supply in the crop root zone should be maintained at optimum levels with minimal fluctuation in soil water potential.

Expansive growth and gas exchange processes of tomatoes have been found to be particularly sensitive to water deficits between first and peak blooms (Hutmacher et al., 1985; Phene et al., 1990). Hsiao et al. (1976) defined two levels of plant stress severity. The first is when stress is too low to influence stomatal conductance and inhibit photosynthesis but great enough to affect expansive growth. This level of stress reduces leaf area expansion and permanently reduces total field CO_2 assimilation and transpiration, although on a per-leaf basis CO_2 assimilation and transpiration will not be affected. The second level of stress severity occurs when stress is so high that leafwater potential drops below the threshold level for stomatal response, leading to reduced CO_2 assimilation and transpiration per unit leaf area and for the whole plant canopy. However, when the stress ceases, photosynthesis and transpiration recover. Even mild soil-induced water deficits can be avoided when irrigation fully replaces crop evapotranspiration (E_{tc}) at a high frequency, preferably several times each day (Phene, 1987).

Applying plant nutrients through drip irrigation systems is necessary, convenient, safe, and efficient (Phene et al., 1979; Rolston et al., 1979). Drip irrigation without injection of fertilizers is usually inefficient, resulting in little or no yield improvement, and often limits crop response to high-frequency irrigation (Phene et al., 1986). Because dry-matter production increases linearly with transpiration, the nutrient requirement increases in uptake rate and total amount.

A root system developed with subsurface drip irrigation maximizes root density near the buried lateral (Phene et al., 1991). This root system, combined with sustained or even higher nutrient requirements, is not a good match with conventional fertilizer distribution patterns and, in fact, may be contrary to plant nutrient needs under this type of irrigation. The fertilizer distribution and nutrient availability problem is further magnified by P and some minor elements that may be relatively immobile, particularly in fine-textured soils with high pH, and are mostly present in the top 15 to 20 cm of soil (Bar-Yosef et al., 1980; Phene et al., 1986).

Bar-Yosef et al. (1980) showed that the soil-root volume with drip irrigation is typically smaller than with sprinkler irrigation and that large water and nutrient gradients can develop rapidly (as in a greenhouse pot) unless irrigation and nutrient applications are frequent. This is especially true of P, which is adsorbed quickly by the soil. Phene et al. (1986, 1990) and Phene (1987) demonstrated that daily injection of P through the drip system in addition to conventionally

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banded P under the seeds at planting significantly increased the yield of tomatoes. Scheduling frequent irrigations and fertilizations to precisely meet evapotranspiration and fertilizer demands have been demonstrated to affect yield of tomato (Davis et al., 1985; Hutmacher et al., 1985; Phene et al., 1983, 1985a). With proper consideration of soil infiltration and water-holding characteristics, crop water and nutrient requirements can be precisely supplied, not only producing high yields but also maximizing WUE.

Water-use efficiency

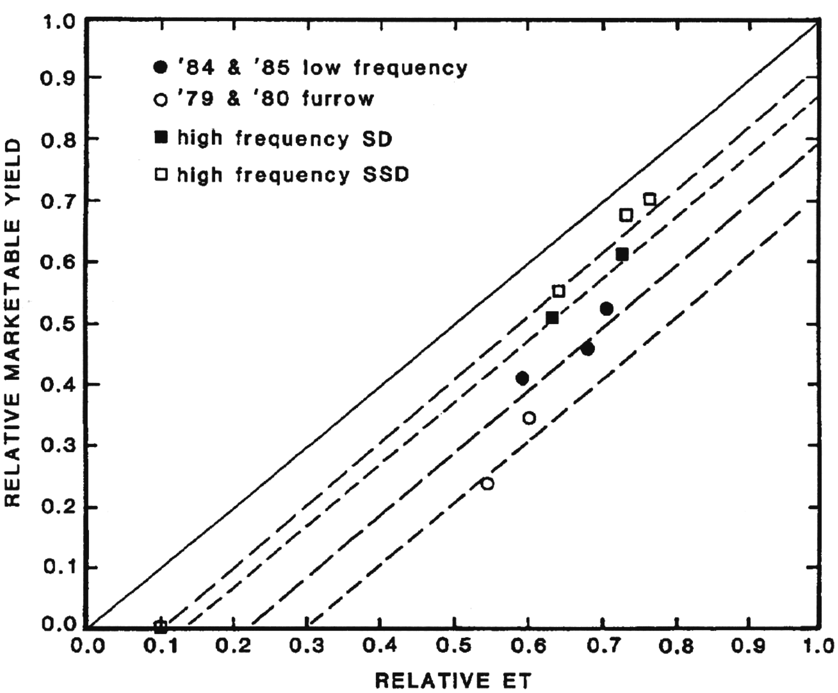
Although there are several definitions for WUE, it is usually defined as the ratio of yield (Y) per unit of water evapotranspired (E + T), where E is the evaporation and T is the transpiration from the plant:

$$WUE = \frac{Y}{(E + T)} \qquad [1]$$

Hanks (1974) showed that, for dry matter, if ($E_p + T_p$) is constant, where the subscript p implies potential values, the linear relationship between relative yield (Y_r) and ($E_p + T_p$) would move to the right as E increased, and to the left as E decreased, but the slope would remain constant. This concept was applied to vegetables using tomato data to demonstrate some of the implications of WUE and the importance of reducing E_p effect on yield and WUE.

Figure 1 shows the relative yield Y_r vs. the relative E_{tc} ($E + T/E_p = T_p$) for high- (HFSD) and low- (LFSD) frequency surface and subsurface (SSD) drip-irrigated tomatoes grown at the Univ. of California West Side Field Station (WSFS), Five Points (Phene et al., 1985a, 1986), and for furrow and low-frequency drip-irrigated tomatoes grown at the Univ. of California, Davis (Pruitt et al., 1984). Several of these values were obtained from lysimetric measurements at the Univ. of California, Davis, and at the WSFS. Evaporation and transpiration were separated in the WSFS lysimeter by using a subsurface drip irrigation system and measuring the bare soil evaporation from a steady soil water profile (Phene, 1991; Phene et al., 1985a). The regression line for the SSD treatment was forced through the evaporation component of E_{tc}, assuming zero yield since T = 0.

Fig. 1. Effects of irrigation systems and irrigation frequencies on relative marketable yield (¡ ,) of tomatoes (after Phene, 1987). The solid line (1:1) represents the relative potential yield (¡ ,) curve (assumed 250 t·ha^{-1}) for potential transpiration (t_p) when evaporation is 0. The dashed line with 0 data points is the regression of (¡ ,) for the subsurface drip-irrigated tomatoes forced through ¡ ,= 0 when T_p = 0 and relative E_p = 0.1 (as measured with the weighing lysimeter). Other dashed lines are for tomatoes irrigated with high-frequency surface drip (■), low-frequency surface drip (•), and furrow irrigation (O). These lines are maintained parallel as suggested by Hanks (1974).



Using a potential tomato yield of 250 t·ha^{-1} (as obtained in greenhouses in Holland under precisely controlled conditions with E = 0), we fitted a line with a slope parallel to the one obtained at the WSFS and passing through the origin, and we concluded that $E_p + T_p$ for tomatoes could reach a maximum of ≈ 1020 mm. From these data it can be seen that increasing the ratio $T : E_p + T_p$ can potentially increase Y_r. This increase in Y_r could result from an increase in photosynthesis associated with an increase in measured leaf area.

This would also explain the increase in $T/E_p + T_p$ for the SSD treatment, because soil E is reduced in two ways: 1) the lack of surface moisture reduces the flux of vapor to the soil surface, and 2) the greater light interception by the crop canopy reduces the soil surface area available for evaporation (Phene, 1991). Since the same amount of incoming energy has to be dissipated, the surrounding temperature would rise and the crop would transpire more. The phenomenon also has been observed with plastic mulching, which limits or eliminates E and increases yields (although this usually is not given as the reason for higher yields). Hence, to maximize yield, select irrigation systems and management schemes that increase the ratio $T/E_p + T_p$. This is particularly important early in the season, when temperature increase is beneficial.

WUE as a function of Y_r is shown in Fig. 2 for the systems defined in Fig. 1. WUE values were calculated using Eq. [1] and the lines relating Y_r to $E + T/E_p + T_p$. The straight diagonal line represents the maximum Y_r and WUE when $E + T/E_p + T_p = 1$, i.e., the maximum achievable for each system and management. The curvilinear relations represent the four systems SSD, HFSD, LFSD, and Furrow (from top to bottom). The horizontal line at the top represents the case when E = 0 and $T = E_p + T_p$, and it is the absolute potential case for all systems under present cultivars and climatic and atmospheric conditions.

It could be possible, however, to raise the potential yield and transpiration of tomatoes to >250 t·ha^{-1} and 1020 mm, respectively, if, for instance, the CO_2 in the atmosphere around the plant could be increased significantly or if a new variety could be introduced. However, it is not the objective of this paper to cover this subject. It can be implied from these data that increasing yield past a certain level (within a system) does not greatly increase WUE because more water may be used by the crop in the transpiration process. On the other hand, one can maximize Y_r and WUE simultaneously by using improved irrigation management and irrigation systems, which increase $T/E_p + T_p$.

In practice, the use of drip irrigation is increasing due to increases in crop productivity and irrigation efficiency, water shortages, higher energy costs associated with pumping, and environmental constraints such as concern about excessive drainage outflow that may occur with inefficient irrigation (Phene, 1991). In California, production of processing tomatoes using SSD has increased recently, because with proper fertilization, growers can expect at least an increase in yield of 10 to 20 t·ha^{-1} over furrow-irrigated tomatoes with water applications of 600 to 750 mm (Phene et al., 1986b).

However, initial capital cost, labor requirements, and sometimes disappointing performance resulting from inadequate system design and management are significant factors impeding rapid widespread use of drip-irrigation systems. Many systems are permanently or semi-permanently installed for irrigation of tree and vine crops, but field andvegetable crops are being irrigated mostly with drip systems that are installed at the soil surface and retrieved at the end of each crop season. Many growers also use disposable drip tapes that are discarded after one or several seasons of use. But discarding large quantities of polyethylene tape can be difficult in certain areas. The annual handling of drip irrigation laterals is labor-intensive and detrimental to the life expectancy of the systems; even under the best handling conditions, retrieval and storage of the drip laterals pose extreme logistical problems. The use of permanently installed subsurface drip irrigation seems to provide all the needed characteristics for maximizing productivity.

Since 1978 the U.S. Dept. of Agriculture, Agricultural Research Service, Water Management Research Laboratory (USDA-ARS-WMRL) and the Univ. of California Cooperative Extension have been involved in research to improve crop productivity in semi-arid regions through the development of irrigation systems and management methods to maximize the efficiency of irrigation and through an improved understanding of precise crop water and fertilizer management.

The objectives of this paper are to demonstrate that 200 t·ha^{-1} of tomato can be produced efficiently and to report the results of drip irrigation experiments where daily injections of N, N + P, and N + P + K were used to fertilize tomatoes.

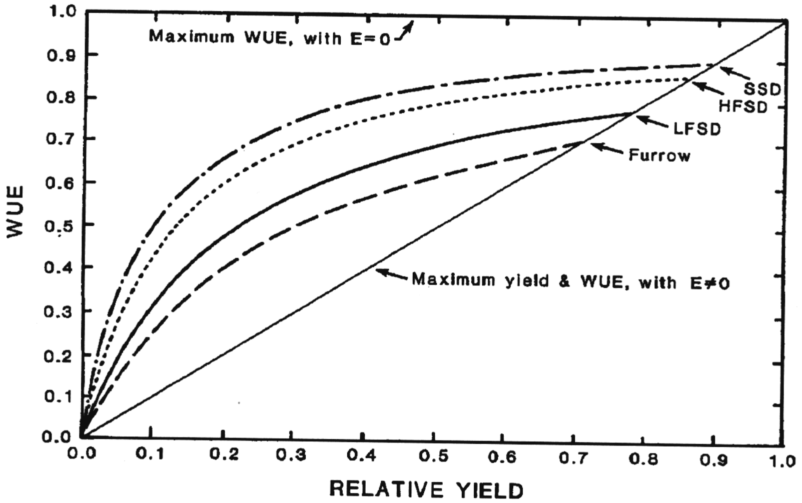


Fig. 2. Effect of irrigation systems and frequencies on water-use efficiency (WUE) of tomatoes (after Phene, 1987). The straight diagonal line represents the maximum relative yields (¡) and WUE when the ratio $(E + T)/(E_p + T_p) = 1$. The curvilinear functions represent the relationships for the four irrigation systems shown in Fig. 1. The horizontal line at the top represents the case where E = 0 and the absolute potential case for all systems under present cultivars and climatic and atmospheric conditions.

Procedures

Processing tomatoes (cv. UC-82B) were grown in large experimental plots [Panoche clay loam soil (Typic Torriorthents)] in 1984, 1985, and 1987 to compare surface and subsurface drip irrigation and to determine the effects of daily fertilizer injection on crop evapotranspiration (E_{tc}), yield, and WUE. The main treatments (randomized block design, replicated four times) were: high-frequency subsurface drip (SSD); high-frequency surface drip (HFSD); and low-frequency surface drip (LFSD) . For the purpose of comparison the LFSD treatment was used to simulate a highly uniform and efficient gravity flow system. To attain similar yields, tomatoes require ≈ 900 mm water to be applied by the gravity flow system and 710 mm applied by the LFSD treatment.

Each plot was 91 m long and contained 10 beds spaced 163 cm from center to center. Installation ofirrigation supply line, centrifugal pump, fertilizer injector (flow-sensing, proportioning pump), manifold, mainlines, and plot manifolds was completed in Feb. and Mar. 1984. Filtration consisted of nested screens, 180-mesh screen being the finest. The headworks of the irrigation system consisted of three sections, each with computer-lysimeter feedback control (backed up by a time clock), electric valve, water meter, pressure regulator, and pressure gauge leading to 7.6-cm-diameter polyvinyl chloride (PVC) mainlines.

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At each plot a 2.5-cm-diameter PVC manifold (submain) was connected by a 5.1-cm-diameter PVC riser assembly to the mainlines. The riser assembly and plot manifold were made portable for the surface-installed drip plots (HFSD and LFSD). The drip irrigation laterals, consisting ofin-line turbulent flow emitters with a flow rate of 4 literšh^{-1} and spaced 0.91 m apart, were connected to the plot manifolds. For the subsurface trickle (SSD) plots, an end-of-line manifold connected the drip laterals to a single riser that was used for flushing. Before planting, we permanently installed SSD laterals in the center of each bed at a depth of 45 cm from the top of the bed. The laterals for the two surface drip irrigation treatments, SD and LFSD, were installed after planting and removed each year at harvest.

A large weighing lysimeter was used in a feedback mode to schedule irrigations automatically in the SD and SSD treatments after 1 mm of crop evapotranspiration (ET_c) had been measured by the lysimeter (Phene et al., 1990). A 25-mm application was applied to the LFSD after 25 mm of ET_c was measured by the lysimeter. The lysimeter was irrigated by SSD and corresponded to the SSD treatment. Details of the lysimeter are available in Howell et al. (1985) and those of the lysimeter control system are in Phene et al. (1990).

Each year, 11N48P-0K fertilizer was applied at the rate of 112 kg·ha^{-1} at planting, directly below the seeds. In 1984, the remaining fertilizer, 150 kg N/ha (urea-sulfuric acid, 28% N), was applied in daily increments through the irrigation system based on nutrient uptake, which was checked against weekly measurements of plant tissue NO_3^--N. In 1985, the remaining N (US-28 urea-sulfuric acid) and P (as H_3PO_4) were applied daily through the drip irrigation system. The total N and P applied through the drip system was 272 and 92 kg·ha^{-1}, respectively.

In 1987, fertilizers injected with each irrigation were KNO_3 and 17N-0P-0K (CAN- 17) calcium-ammonium nitrate. Both fertilizer types had to be used to manage N and K efficiently. Total N and K injected were 301 and 381 kg·ha^{-1}, respectively. Phosphoric acid was injected almost continuously through the drip irrigation system at a rate of 15 mg P/kg of water for a total of 67 kg P/ha. Phosphorous applied as H_3PO_4 served a dual purpose of supplying P to the plant and cleaning the irrigation system. Differences in N application for the 3 years were due to adjustments in injection rates of N based on NO_3^--N threshold levels in petioles.

Yields in 1984 were similar to the best commercial yields obtained in Californiawith gravity irrigation, but with considerably less applied water. In 1985, when N and P were injected, and in 1987, when N, P, and K were injected, all yields and WUE increased significantly, but ET, values were not significantly affected (Table 1). Yield and WUE of the SSD tomato plants increased significantly compared with the HFSD- and LFSD- (simulated furrow) treated plants.

In 1987, yields of WUE of SSD plants fertilized with N, P, and K increased 93% compared with that of the LFSD plants fertilized with N only in 1984. This comparison shows the maximum range of marketable tomato productivity that was found over the course of this experiment. However, even the relatively low 1984 yield (114 t·ha^{-1}) is nearly twice the mean processing tomato yield in California. These results indicate that nearly twice as many tomatoes can be grown with the same amount of water when subsurface drip irrigation and fertigation are practiced correctly as compared with conventional irrigation practices or with inadequately fertilized drip systems.

Although it may appear that application of 301 kg N/ha in 1987 was excessive, in terms of mean N application efficiency (yield per N applied), it ranked higher than the N application efficiency for 1985 (Table 1).

Table 1. Water applied (total irrigation and precipitation, I + P), crop evapotranspiration (E_{tc}), yield of large red tomatoes (¡), water-use efficiency (y ¸ E_{tc} = WUE) and ratio of yield of large red tomatoes per unit of applied N (ANE) for tomatoes grown with drip irrigation at Five Points, Calif (after Phene et al., 1990).

Irrigation treatment[z]	1984 I + P (mm)	1984 E_{tc} (mm)	1984 Y (t·ha^{-1})	1984 WUE (g·kg^{-1})	1984 ANE (t·kg^{-1})	1985 I + P (mm)	1985 E_{tc} (mm)	1985 Y (t·ha^{-1})	1985 WUE (g·kg^{-1})	1985 ANE (t·kg^{-1})	1987 I + P (mm)	1987 E_{tc} (mm)	1987 Y (t·ha^{-1})	1987 WUE (g·kg^{-1})	1987 ANE (t·kg^{-1})
SSD	599	659	121 a[y]	18 a	0.75	775	751	168 a	22 a	0.59	664	708	220 a	31 a	0.70
HFSD	595	650	126 a	19 a	0.78	759	744	152 b	20 b	0.53	665	695	201 b	29 b	0.64
LFSD	591	696	114 a	16 b	0.70	753	724	130 c	18 c	0.46	643	709	187 c	26 c	0.60
Lysimeter (SSD)	692	658	152	23	0.94	811	764	175	23	0.62	723	711	255	36	0.82
Means	619	666	128	19	0.79	775	746	156	21	0.55	674	706	216	31	0.69

[z]SSD, subsurface drip irrigation; HFSD, high-frequency surface drip irrigation; LFSD, low-frequency surface drip irrigation.
[y]Column means followed by similar letters are not significantly different at the 95% confidence level, as determined by Duncan's multiple range test on separation of means.

Respectively, the applied N application efficiencies (ANE) were 0.79, 0.55, and 0.69 t marketable tomato/kg N for 1984, 1985, and 1987. Excluding the lysimeter, mean ANE ranged from a low of 0.46 for the tomatoes in the LFSD treatment in 1984 to a high of 0.78 for the tomatoes in the HFSD treatment in 1984.

As shown by Phene (1991), NO_3^--N leaching losses are not occurring under this management system, even when 301 kg N/ha is applied. The deeper rooting pattern generated by SSD and the daily injection of fertilizer to satisfy uptake rates by the plant combine to increase N-application efficiency and minimize N losses. Similar results were obtained for potatoes in the southeastern United States by Phene et al. (1979).

Southeastern United States yields of 220 and 255 $t \cdot ha^{-1}$ of large red tomatoes were hand-harvested for the SSD treatment and for the lysimeter, respectively, when N-P-K fertilizers were injected based on plant uptake averaged weekly. Mean machine harvest efficiency of 80% was measured in these plots using conventional mechanical harvesting equipment not designed to handle these higher yields of tomato. Harvest efficiency could be increased by modifying the equipment to handle high yields. Similar yields were obtained in Israel (Bar-Yosef et al., 1991). Under similar research conditions in Australia and California, yields of 140 to 150 $t \cdot ha^{-1}$ have been machine-harvested by growers who used subsurface drip irrigation over several hundred hectares, and in 1991 by the USDA-ARS-WMRL in a large-scale field demonstration near Mendota, Calif.

In conclusion, a processing tomato yield of 200 $t \cdot ha^{-1}$ is possible in the San Joaquin Valley of California, where the climate is essentially free of precipitation during the majority of the growing season and the soils and temperatures are often well-suited for tomato production. The technology for achieving extremely high yields is available and in some cases already used. Drip irrigation, preferably subsurface drip, precise water and nutrient management, and computerized control of irrigation and fertility need to be implemented to achieve this level of productivity. However, in areas such as the San Joaquin Valley, where water availability and drainage water disposal are always a problem, the achievable increase in WUE alone justifies adoption of the practice for ensuring long-term sustainability of irrigated processing tomatoes.

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