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Efficient Nitrogen Fertility and Irrigation Management in California Processing Tomato Production

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This publication describes efficient management of nitrogen (N) fertility and irrigation in California processing tomato production. Improving the efficiency of N and irrigation inputs is increasingly important given the limited availability of irrigation water and increased regulatory activity designed to protect groundwater resources. In response to evidence of widespread nitrate pollution of groundwater, the Central Valley Region Water Quality Control Board has adopted a regulatory program that requires growers to track and report N inputs. This information will be used to estimate a nitrogen balance, which compares the amount of N applied to fields with the amount of N removed from fields in harvested fruit. The greater the imbalance between applied N and N removed in harvested fruit, the greater the potential for N loss to the environment. Growers who consistently show a large imbalance between N application and harvest N removal are likely to come under increased scrutiny for potential contribution to groundwater nitrate degradation.

This publication focuses on managing drip irrigation, which is now the standard practice in processing tomato production. The practices outlined here are also relevant to fresh market tomatoes grown on ground beds for harvest at the mature green fruit stage. This type of fresh market production has similar growth patterns and fertility and irrigation requirements up to the point of harvest, which occurs approximately 4 to 5 weeks earlier than processing tomato harvest.

Nitrogen Management

Pattern of Tomato Growth and Nitrogen Uptake

Virtually all processing tomatoes grown in California are transplanted. In the initial 3 to 4 weeks after transplanting (WAT) the rate of growth is slow as the plants become established. From about 4 WAT until the early fruit begin to ripen (approximately 11 to 12 WAT), the rate of growth and N uptake is rapid (fig. 1). During this period, N uptake in a vigorous, high-yield field will average approximately 4 lb/ac/day. As fruit ripen and the plants senesce, the rate of growth and N uptake declines. At harvest a crop yielding 50 to 60 T/ac of fruit has typically developed a biomass of 13,000 to 15,000 lb/ac of dry matter (vine plus fruit) containing approximately 240 to 280 lb/ac N.

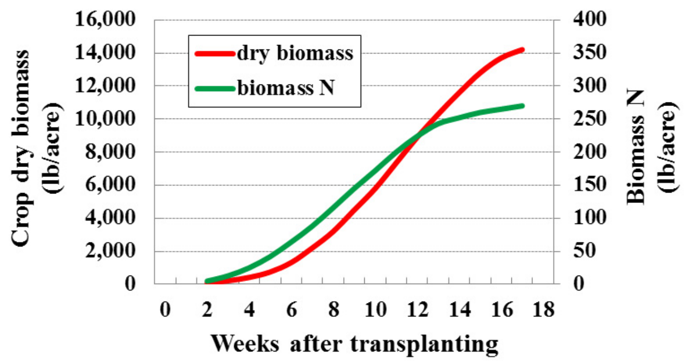

Figure 1. Pattern of processing tomato growth and N uptake over the production season. *Source*: Hartz and Bottoms 2009.

Fields vary considerably in their N uptake based on crop productivity as well as on the amount of soil N available for plant uptake. When soil N availability is maintained at a high level, plants can take up more nitrogen than is necessary for them to reach their maximum yield potential; this is referred to as luxury uptake, which often represents 10% or more of crop N uptake in commercial fields. Similarly, tomato fields vary in the N content of harvested fruit, ranging from about 2.0 to 3.5 lb/T N and averaging approximately 2.6 lb/T N (Hartz and Bottoms 2009; Lazcano et al. 2015). Harvested fruit typically contains from 50 to 65% of total crop N uptake.

Root development is strongly influenced by irrigation management and soil factors. Although tomato roots may extend more than 3 ft deep in the soil profile, the vast majority of roots are concentrated in the top 18 in. of soil. In drip-irrigated production root development is further concentrated around the buried drip tape; by midseason, little water or N uptake is likely to occur beyond the soil zone wetted by the drip tape.

Nitrogen Fertilizer Management

Many field trials in California have shown that furrow-irrigated processing tomatoes generally require less than 150 lb/ac of fertilizer N, and sometimes less than 100 lb/ac N, to achieve maximum yield (see Krueskopf et al. 2002). This is because the crop recovers a substantial amount of N from the soil, primarily residual soil NO_3-N present at the beginning of the cropping season, augmented by in-season soil organic N mineralization. The higher yield potential of drip-irrigated fields increases the crop N uptake requirement, but that potential increase in fertilizer N requirement may be partially offset by lower nitrate leaching due to improved irrigation control.

The most comprehensive study of N relations in drip-irrigated processing tomato fields was conducted by Lazcano et al. (2015). Figure 2 compares at-planting residual soil NO_3-N, seasonal N fertilization rate, crop N uptake, and postharvest soil NO_3-N in 12 fields from that study representing the three major tomato producing regions of the state (the San Joaquin Valley, the Delta region, and the Sacramento Valley). Fruit yield in these fields averaged 54 T/ac (above the mean statewide yield), ranging from 41 to 63 T/ac. The seasonal N fertilization rate ranged from 115 to 220 lb/ac, averaging 185 lb/ac. Crop N uptake (vine plus fruit) averaged approximately 260 lb/ac, with a median crop N uptake of 4.6 lb/T of harvested fruit. Averaged across fields, the postharvest soil NO_3-N was actually higher (151 vs. 143 lb/ac N) than the initial residual soil NO_3-N measured at planting time. This suggested that, in some fields at least, N fertilization rates could have been reduced without stressing the crop.

Estimating Fertilizer N Requirements

Lazcano et al. 2015 provides valuable guidance in the development of efficient, field-specific N management plans. The first step is to realistically estimate the crop yield potential of a field based on variety and prior field history. Multiplying that yield goal by 4.6 lb/T of N in fruit provides a reasonable estimate of the amount of crop N uptake necessary to produce a crop of that size. For example, a crop uptake of about 230 lb/ac N would be adequate for a crop of 50 T/ac, while 280 lb/ac N would be adequate for a crop of 60 T/ac. These crop N uptake calculations are somewhat higher than would actually be required, since the fields on which the estimate of 4.6 lb/T N of fruit was based undoubtedly had some amount of luxury N uptake.

Not all crop N uptake comes from applied fertilizer. In the fields represented in figure 2, crop N uptake exceeded the N fertilization rate by an average of 75 lb/ac, and by more than 100 lb/ac in some fields. This nonfertilizer N comes from three major sources: residual soil NO_3-N, in-season soil N mineralization, and NO_3-N in the irrigation water. The amount of residual soil NO_3-N varies widely among fields. The fields in figure 2 averaged 143 lb/ac NO_3-N in the top 20 in. of soil, but they ranged from 42 to 293 lb/ac. While the level of residual soil NO_3-N was somewhat predictable (the Sacramento Valley, by virtue of higher winter rainfall, tends to have lower residual soil NO_3-N than the San Joaquin Valley, for example), the only way to be certain is to collect and analyze a soil sample. Residual soil NO_3-N is most appropriately measured in a sample collected in the initial weeks after transplanting; at that time any leaching associated with transplant establishment would have already occurred. Sampling to approximately 18 in. deep within 15 in. of a plant row will cover the soil zone most accessible to the crop.

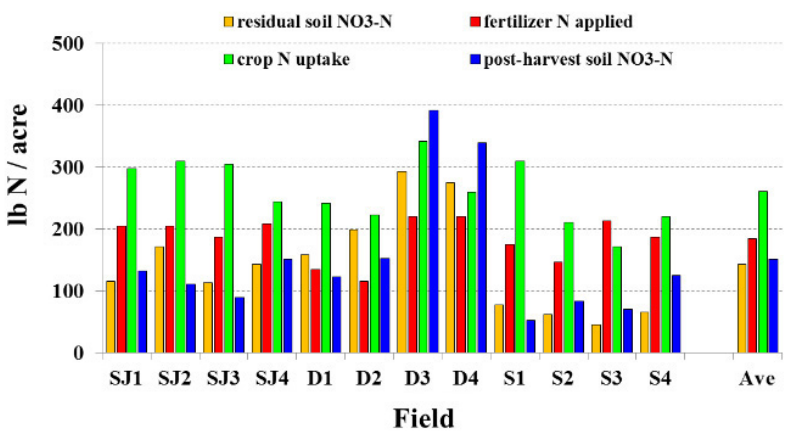

Figure 2. Comparison of residual soil NO_3-N at planting, seasonal N fertilizer applied, crop N uptake, and postharvest soil NO_3-N in processing tomato fields. Field designations: San Joaquin Valley (SJ), Delta region (D) and Sacramento Valley (S). *Source*: Lazcano et al. 2015.

Laboratory results are typically reported as parts per million (PPM) of NO_3-N on a soil dry weight basis. Each 6-in. slice of a typical field soil weighs about 1.8 million lb/ac, so a sample 18 in. deep would represent about 5.4 million lb of soil. Therefore, multiplying the soil NO_3-N concentration (in PPM) by 5.4 would estimate the pounds of residual soil NO_3-N. There is no firm rule on what fraction of residual soil NO_3-N should be credited toward the crop N uptake requirement, but a crop availability of at least 50% is a reasonable expectation.

In-season soil N mineralization is difficult to predict because it can be influenced by many factors. Incubation experiments with California soils suggest that as a general rule, for soil with relatively low organic matter, at least 20 lb/ac N is likely to be mineralized in a summer growing season for every 1% soil organic matter. For soil with higher organic matter content (such as those in the Delta region), the N contribution per percent of soil organic matter may be less, but the overall contribution from soil N mineralization will be significant.

Nitrate contained in irrigation water is as equally available for crop uptake as N fertilizer. Irrigation water from surface sources typically has very low NO_3-N concentration (usually less than 3 PPM), so the amount of N applied by irrigation is minimal. However, some well water has much higher NO_3-N concentration, in some cases greater than 10 PPM; this represents a substantial amount of N over a cropping season. The formula to calculate the NO_3-N content of irrigation is

$$\textbf{PPM } NO_3\textbf{-N} \times 0.23 = \textbf{lb/ac-in } NO_3\textbf{-N.}$$

Therefore, an irrigation water source containing 10 PPM NO_3-N provides 2.3 lb/ac-in. N. Seasonal crop water requirements for processing tomatoes range from approximately 22 to 30 ac-in., meaning that a water source with 10 PPM NO_3-N would add 50 to 70 lb/ac N over a cropping season.

There is no definitive formula for calculating the seasonal N fertilization requirement for processing tomatoes. While it is clear that efficient N fertilization management requires consideration of field-specific factors, some generalizations can be made about fertilizer requirements. As shown by the fields represented in figure 2, a seasonal application of 185 lb/ac N is adequate to produce yields greater than 50 T/ac under typical field conditions; in fields with high residual soil NO_3-N, substantially lower seasonal N rates may be appropriate. A seasonal application rate greater than 200 lb/ac N would be required only under extremely high yield conditions or where nonfertilizer N contributions (residual soil NO_3-N, soil N mineralization, and irrigation water NO_3-N) are small.

Once the seasonal fertilizer N requirement has been estimated, the timing of fertigation can be based on the crop N uptake pattern described in figure 1. Fertigation should be concentrated during the period of most rapid growth, approximately 4 to 11 WAT. Once fruit ripening begins (typically around 11 to 12 WAT) few fields will benefit from additional N fertigation.

Nitrogen Monitoring

Both soil and plant monitoring can be useful in maximizing N efficiency. As previously described, determination of residual soil NO_3-N at or just after transplanting is a key element in formulating a field-specific N fertilization plan. Soil testing later in the season is less useful because it becomes increasingly difficult to collect a representative sample. Soil NO_3-N can become stratified in the zone of soil wetted by the drip tape, and the bed position from which samples are drawn can significantly influence the result.

Tissue analysis has been a common practice for decades. Historically, petiole analysis for NO_3-N determination was the most common technique, but recent research has documented that petiole analysis is of limited value. The rate at which plants convert NO_3-N into organic compounds can be significantly affected by environmental variables unrelated to soil N availability; therefore, petiole NO_3-N concentration can be highly variable over the course of just a few days, and that variability may have little to do with soil N availability. Also, once fruit begins to develop, the plant metabolizes NO_3-N rapidly to supply assimilates to the developing fruit; even crops with an adequate supply of soil N may still show very low petiole NO_3-N concentration after fruit development begins.

Whole-leaf total N concentration provides a more reliable measure of crop N status because it measures all forms of N contained in the tissue. Leaf total N is much less variable than petiole analysis, and leaf N concentration declines more gradually over the growing season. Table 1 gives the ranges of whole-leaf N concentration typical of adequately fertilized, high-yield processing tomatoes (Hartz and Bottoms 2009; Hartz et al. 1998). Leaf N concentration within these ranges can be considered sufficient for the growth stage; the farther outside these ranges a leaf analysis falls, the more likely it is to reflect N deficiency or excess. Leaf analysis should be viewed as a technique to document current N sufficiency; results provide little insight into what fertilization

Table 1. Whole leaf nutrient sufficiency ranges

Growth stage	Leaf N (% of dry matter)
early flower	4.0 to 5.0
full bloom	3.5 to 4.5
early red fruit	2.7 to 3.8

requirements might be later in the season. Once a fertigation plan is developed, leaf analysis can indicate whether N fertigation is falling behind plant demand, but it is less reliable in indicating whether fertigation should be delayed or reduced.

Drip Irrigation Management

Calculating the Irrigation Requirement

Environmental variables such as solar radiation, air temperature, relative humidity, and wind speed interact to influence the rate of water loss from plants and soil. The California Irrigation Management Information System (CIMIS) is a network of computerized weather stations that measure these environmental variables and compute a daily reference evapotranspiration (ET_o) value that estimates the potential loss of water (through both plant transpiration and soil evaporation) from a well-watered grass crop completely covering the soil surface. Daily ET_o estimates can be found on the Department of Water Resources CIMIS website, http://wwwcimis.water.ca.gov/. Historical ET_o values are also available for many locations. Table 2 lists average daily ET_o values by month for representative Central Valley locations.

To estimate the crop irrigation requirement, the ET_o must be adjusted for the growth stage of the crop by using a crop coefficient (K_c). The primary force controlling crop water loss is the heating of the foliage caused by solar radiation. This provides a convenient way to account for crop growth stage: simply estimate the fraction of the field surface covered by the crop canopy. This is easily done by estimating the average width of the crop canopy per bed and dividing by the bed width. Include in the estimate any wet soil surface not covered by foliage because evaporation from exposed, wet soil is nearly as rapid as transpiration from foliage. Once you have estimated the fraction of the ground surface covered by foliage or exposed, wetted soil, multiply this estimate by 1.1 to account for the slightly higher water loss characteristic of tomato compared with the grass crop on which ET_o is based. Therefore, calculation of the K_c is

$$\mathbf{ET_o \times (\% \text{ of ground covered by crop canopy} \times 1.1) = K_c.}$$

For this system to work well you need to update the crop canopy coverage estimate at least weekly, particularly during the rapid growth phase. Alternatively, generic K_c estimates are available for Central Valley conditions (fig. 3). However, the limitation of a generic K_c system is that fields can differ widely in crop vigor based on field management, planting configuration, variety, and seasonal weather conditions.

Multiplying ET_o by the K_c estimates the crop evapotranspiration (ET_c). Monitoring in drip-irrigated California tomato fields has shown that seasonal ET_c averages approximately 24 in. and may be as high as 29 in. where crop vigor and seasonal ET_o are particularly high. Furrow-irrigated fields average slightly higher seasonal ET_c due to higher soil evaporation.

To ensure that even the driest area of a field receives adequate water, adjust the estimated ET_c for the degree of nonuniformity of water delivery. Field-scale drip systems should be designed to have a distribution uniformity (DU) of 85 to 90%, meaning that the driest quarter of the field receives 85 to 90% of the field average. Dividing the ET_c by the DU will estimate the depth of water required to adequately water all portions of the field. The following example illustrates the calculation of the irrigation requirement.

Table 2. Historical CIMIS reference evapotranspiration (ET_0) averages, in in./day

Location	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Five Points	.03	.06	.11	.17	.21	.26	.28	.24	.18	.11	.05	.03
Tracy	.03	.06	.09	.15	.20	.24	.26	.22	.18	.10	.04	.02
Woodland	.03	.06	.10	.16	.20	.26	.26	.23	.18	.12	.06	.03

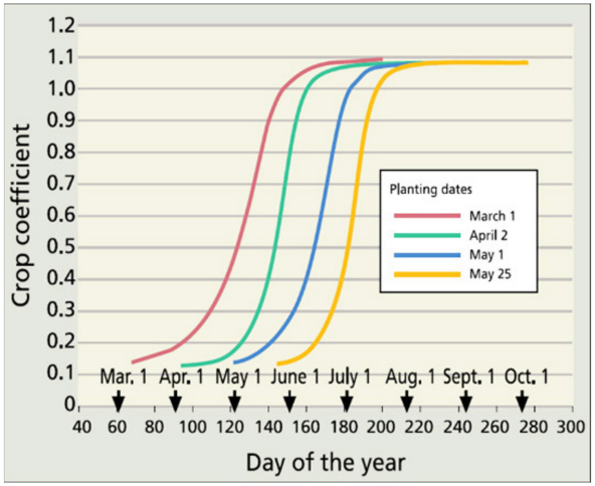

Figure 3. Generalized crop coefficients (K_c) for processing tomato based on San Joaquin Valley. conditions. K_c curves were developed using 66-in. bed width. *Source*: Hanson and May 2006.

Field situation: A tomato crop in full bloom, with a canopy width of 48 in. on a 66-in. bed. Cumulative ET_o is 0.50 in. since the last irrigation. The drip system DU is assumed to be 85%.

$$\mathbf{K_c = 48 \div 66 \times 1.1 = 0.80}$$

$$\mathbf{ET_o \times K_c = ET_c}$$

$$\mathbf{0.50\ in. \times 0.80 = 0.40\ in.}$$

$$\mathbf{ET_c \div DU = irrigation\ requirement}$$

$$\mathbf{0.40\ in. \div 0.85 = 0.47\ in.}$$

Salinity control can be important in drip-irrigated fields, particularly in areas of low rainfall and where low-quality irrigation water is used. However, leaching is most effectively accomplished between crops rather than by applying an in-season leaching fraction. Tomato is a relatively salinity-tolerant crop; if it is established under relatively low salinity conditions it can tolerate high soil EC later in the growth cycle (Mitchell et al. 1991). Also, with a drip irrigation system, simply matching ET_c provides adequate localized leaching to allow high crop productivity (Hanson et al. 2009).

Determining Irrigation Frequency

Although tomato can tolerate a moderate degree of moisture stress, the goal of drip irrigation is to maintain the soil moisture regime as uniform as possible. Tomato can tolerate a depletion of 20 to 30% of available soil moisture in the active root zone with no yield loss. Early in the season, when plants are small, irrigation may not be required more often than once a week. Field trials in the San Joaquin and Sacramento Valleys have shown that, in medium- to heavy-textured soil, it is seldom necessary to irrigate more often than every other day, even during the peak water demand portion of the season. In sandy soil, daily irrigation may be appropriate during peak demand. Table 3 provides guidance on the maximum irrigation requirement that should be allowed to accrue between irrigations.

Table 3. Effect of soil texture on the cumulative irrigation requirement allowable between irrigations without inducing crop water stress

Soil texture	Cumulative irragation requirement allowable between irrigations (in.)
sand	0.2-0.3
sandy loam	0.3-0.5
silt loam	0.5-0.7
clay loam	0.5-0.7

Soil Moisture Monitoring

The method of irrigation management described above can contain several significant sources of error. Direct soil moisture monitoring is an essential safeguard to avoid over- or under-watering. Soil moisture sensors measure either soil moisture tension or soil moisture content. Soil moisture tension is a measure of the strength with which water is held by the soil; soil moisture content is the amount of water contained in a given volume of soil. Soil moisture tension can be monitored by tensiometers or Watermark electrical resistance blocks; soil moisture content is most often monitored by dielectric sensors, of which there are many commercial choices. Sensors can be attached to low-cost electronic recorders to collect and store readings many times a day. Experience has shown that continuous monitoring gives a more complete picture of irrigation management than periodically taking readings manually.

Sensor placement relative to the drip tape is important. Soil moisture varies with lateral distance from the drip line and with depth above or below the drip tape. The readings of sensors placed either too close or too far from the drip line may not be representative of the root zone. In most soil, placing sensors approximately 6 in. to the side of the drip tape is appropriate. Sensor depth is important as well. A sensor approximately 12 in. deep will monitor soil moisture in the most active root zone; a second sensor installed 24 to 30 in. deep can document whether the amount of irrigation applied was sufficient to maintain deep moisture without either drying out or saturating the lower root zone. Installing sets of sensors in several different areas of the field is ideal to ensure that the readings are representative of the whole field.

Table 4 gives approximate soil tension values (in centibars, cb) for field capacity (the amount of water the soil can hold against the force of gravity, commonly thought of as the "ideal" soil water status), and for 20 to 30% available moisture depletion (the maximum "safe" level of depletion between irrigations). The goal of drip irrigation management is to keep soil water tension between field capacity and 20 to 30% depletion as much as possible. Immediately after an irrigation, soil tension readings may go down to zero, but they should rebound to near or above field capacity before the next irrigation. Until fruit begin to ripen, allowing soil tension to rise above the 20 to 30% depletion level, even for a day or two, may be enough to induce yield loss or blossom end rot of fruit.

Table 4. Approximate soil water tension at field capacity, and at 20% to 30% available moisture depletion.

	Approximate soil water tension (cb) at	
Soil texture	**Field capacity**	**20-30% available water depletion**
sand	0.3-0.5	20-25%
loam	0.5-0.7	25-30%
clay	0.5-0.7	25-40%

Interpreting soil moisture content data from dielectric sensors is complicated by the fact that the optimal range of soil water content varies considerably by soil texture, requiring a field-specific calibration. Often, readings from these sensors are used to show wetting or drying trends at various soil depths rather than to directly quantify soil moisture availability.

End-of-Season Irrigation Management

The proceeding discussion describes irrigation management from planting until the early fruit begin to ripen. From that point forward irrigation should be reduced for several reasons. Once fruit begin to ripen, plants begin to senesce and water use declines. By harvest, ET_c can be as much as 25% lower than at midseason. Also, some degree of moisture stress may be necessary to increase fruit soluble solids concentration (SSC) to a level acceptable to the processor. In a fully watered crop, the SSC will often be less than 5.0°brix and may be less than 4.5°brix, depending on variety and field conditions. The goal of end-of-season irrigation management is to induce sufficient moisture stress to achieve acceptable SSC with minimum yield loss.

Recent research has documented that once a tomato fruit reaches the "pink" stage of maturity, its SSC is unaffected by irrigation management: regardless of subsequent soil moisture stress, the SSC of that fruit will slowly decline (typically by about 0.2°brix by harvest). However, the SSC of green fruit is greatly affected by irrigation. Therefore, in order to have a significant influence on overall fruit SSC, some moisture stress must be imposed while the majority of fruit are still green. Since fruit ripening typically begins 5 to 6 weeks before harvest and proceeds at a relatively constant rate, deficit irrigation may need to be initiated at least a month before the projected harvest date, perhaps even earlier in fields with high soil water holding capacity.

To significantly increase fruit SSC, the moisture content of the top 2 to 3 ft of soil must be reduced substantially below field capacity. A root zone soil moisture tension of 40 to 50 cb should be a sufficient stress to increase the SSC of green fruit. This level of stress should not reduce brix yield (tons of solids per acre), but rather simply limit the amount of water in the fruit; this represents the minimum yield sacrifice for increased SSC. A more severe soil moisture deficit will further increase SSC but may also reduce brix yield. As a general guideline, application of 40 to 60% of ET_c over the last 4 to 5 weeks before harvest is a reasonable compromise between maximizing yield and achieving acceptable SSC. The lower end of that range would be appropriate for soil with a high water-holding capacity; the higher end of that range would apply to lighter soil with limited water storage.

Whenever deficit irrigation is practiced, the possibility of root intrusion into the drip emitters exists. Monitoring the water delivery rate of the system (gal/ac/hr) can help spot the first sign of root intrusion. Chlorine or acid injection can be used as a preventative practice.

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