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 nitrate degradation of groundwater.

Drip irrigation now the standard practice in processing tomato production, so this guide focuses on drip management. The practices outlined here are also relevant to fresh market tomatoes grown 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 4-5 weeks earlier than processing tomato harvest.

Pattern of tomato growth and nitrogen uptake

Virtually all processing tomatoes grown in California are transplanted. In the initial 3-4 weeks after transplanting (WAT) the rate of growth is slow as the plants become established. From about 4 WAT until the early fruits begin to ripen (approximately 11-12 WAT) the rate of growth, and N uptake, is rapid (Fig. 1; data from Hartz and Bottoms, 2009). During this period N uptake in a vigorous, high-yield field will average approximately 4 pounds per acre per day. As fruit ripen and plants senesce, the rate of growth and N uptake declines. At harvest a crop yielding 50-60 tons of fruit per acre has typically developed a biomass of 13,000-15,000 lb of dry matter per acre (vine plus fruit) containing approximately 240-280 lb N/acre.

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 2.0-3.5 lb N/ton and averaging approximately 2.6 lb N/ton (Hartz and Bottoms, 2009; Lazcano et al., 2015). Harvested fruit typically contains between 50-65% of total crop N uptake.

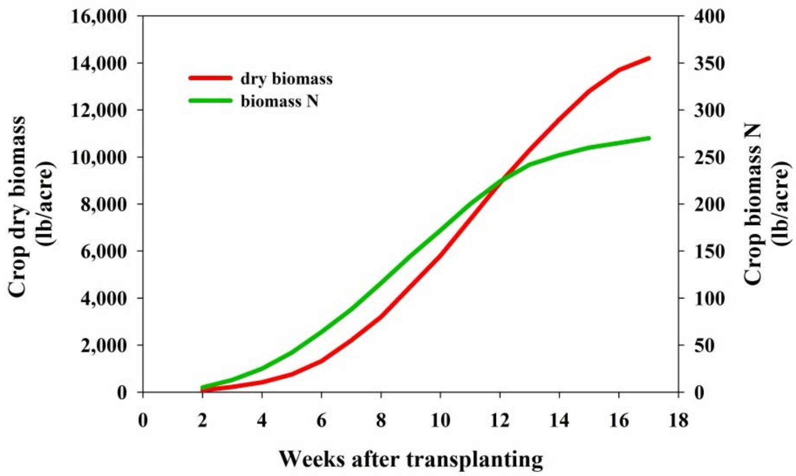

Fig. 1. Pattern of processing tomato growth and N uptake over the production season.

Root development is strongly influenced by irrigation management and soil factors. Although tomato roots may extend > 3 feet deep in the soil profile, the vast majority of roots are found in the top 18 inches of soil. In drip-irrigated production root development is concentrated around the buried drip tape; by mid-season, 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 required less than 150 lb of fertilizer N/acre, and sometimes <100 lb N/acre, to achieve maximum yield (Krusekopf 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 post-harvest soil NO_3-N in 12 fields from that study. These fields represented 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 tons/acre, ranging from 41-63 tons/acre. The seasonal N fertilization rate ranged from 115-220 lb/acre, averaging 185 lb/acre; there was no apparent relationship between N application and residual soil NO_3-N. Crop N uptake (vine plus fruit) averaged approximately 260 lb/acre, with a median crop N uptake of 4.6 pounds of N per ton of fruit harvested; the median N content of harvested fruit was 2.6 lb/ton. Post-harvest soil NO_3-N exceeded 100 lb/acre in the majority of fields, suggesting that N fertilization rates could have been reduced without stressing the crop.

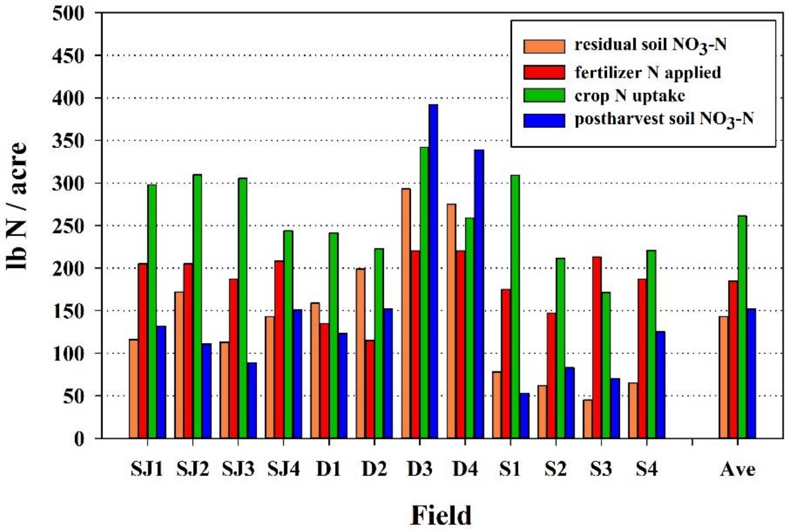

Fig. 2. Comparison of residual soil NO_3-N at planting, seasonal N fertilizer applied, crop N uptake and post-harvest soil NO_3-N in processing tomato fields; data from Lazcano et al. (2015). Field designations: San Joaquin Valley (SJ), Delta region (D) and Sacramento Valley (S).

Estimating fertilizer N requirements

This study 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 N/ton of 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 N/acre would be adequate for a 50 ton/acre crop, while 280 lb N/acre would be adequate for a 60 ton/acre crop. These crop N uptake calculations are somewhat higher than the minimum uptake requirement because the fields on which the 4.6 lb N/ton of fruit estimate was based undoubtedly had some amount of luxury N uptake.

Not all crop N uptake comes from applied fertilizer. In the fields represented in Fig. 2, crop N uptake exceeded the N fertilization rate by an average of >75 lb/acre, and by >100 lb/acre in some fields. This non-fertilizer 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 Fig. 2 averaged 143 lb NO_3-N/acre in the top 20 inches of soil, but they ranged from 42-293 lb/acre. 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 inch depth, within 12 inches of a drip tape, will cover the soil zone most accessible to the crop.

Laboratory results are typically reported as parts per million (PPM) of NO_3-N on a soil dry weight basis. Each 6 inch slice of a typical field soil weights about 1.8 million pounds per acre, so an 18 inch deep sample would represent about 5.4 million pounds 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 the relatively low organic matter soils that dominate the Central Valley (typically less than 3% OM), at least 20 lb N/acre is likely to be mineralized in a summer growing season for every percent soil organic matter. For higher organic matter soil (such as those in the Delta region, which can exceed 10% OM) the N contribution from each percent of soil organic matter may be lower, but the overall soil organic matter contribution to in-season N mineralization will still be higher than in low organic matter soil.

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

PPM NO_3-N x 0.23 = pounds of NO_3-N per acre inch

Therefore, an irrigation water source containing 10 PPM NO_3-N contains 2.3 lb N per acre inch. Seasonal crop water requirements for processing tomatoes range from approximately 22-30 acre inches, meaning that a 10 PPM NO_3-N water source would add 50-70 lb N/acre 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 demonstrated by the Lazcano study, a seasonal application of 185 lb N/acre was adequate to produce >50 ton/acre yields under typical field conditions, and in fields with high residual soil NO_3-N substantially lower seasonal N rates may have been appropriate. A seasonal application rate > 200 lb N/acre would be required only under extremely high yield potential, or where non-fertilizer N contributions (residual soil NO_3-N, soil N mineralization, and irrigation water NO_3-N) are abnormally small.

Once the seasonal fertilizer N requirement has been estimated, the timing of fertigation (the application of fertilizer in irrigation water) can be based on the crop N uptake pattern described in Fig. 1. Fertigation should be concentrated during the period of most rapid growth, approximately 4-11 WAT. Once fruit ripening begins (typically around 11-12 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. Petiole NO_3-N concentration can be highly variable over the course of just a few days, and that variability may have little relationship 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 a crop with an adequate supply of soil N may 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 lists 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 reflects N deficiency or excess. Leaf analysis should be viewed as a technique to document current N sufficiency; results provide little insight into what the fertilization requirement 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.

Table 1. Whole leaf total N nutrient sufficiency ranges.

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

Drip irrigation management

Calculating 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 which estimates the potential loss of water (through both plant transpiration and soil evaporation) from a well-watered grass crop that completely covers the soil surface. Daily ET_o estimates for locations throughout the state can be found on the Department of Water Resources 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.

Table 2. Historical CIMIS reference evapotranspiration (ET_o) averages, in inches per 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

To estimate the crop irrigation requirement the ET_o must be adjusted for the growth stage of the crop by the use of 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, multiplying this estimate by 1.1 accounts for the slightly higher water loss characteristic of tomato compared to the grass crop on which ET_o is based. Therefore, calculation of the K_c is:

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

For this system to work well you need to update the crop canopy coverage estimate at least weekly, particularly during the rapid growth phase during which canopy expansion is rapid. 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.

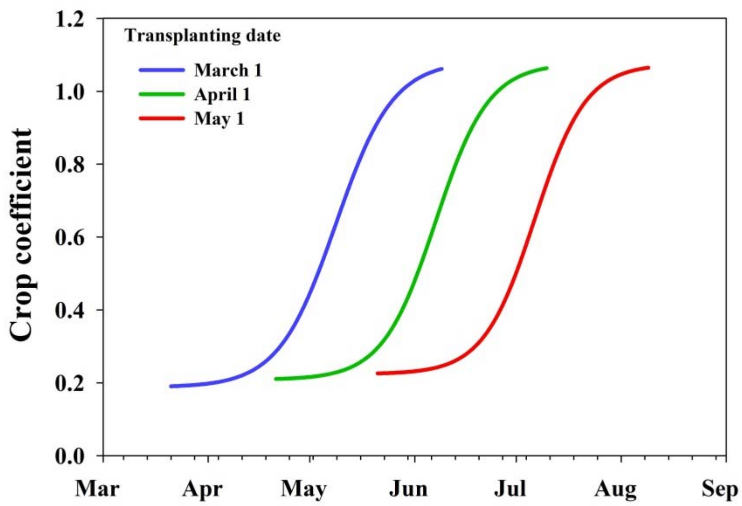

Fig. 3. Generalized crop coefficients (K_c) for processing tomato based on San Joaquin Valley conditions; from Hanson and May (2006). K_c curves were developed using 66-inch bed width.

Multiplying ET_o by the K_c estimates the *crop evapotranspiration* (ET_c). Monitoring in California tomato fields has shown that seasonal ET_c averages approximately 24 inches in drip-irrigated fields, and may be as high as 29 inches 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, the estimated ET_c needs to be adjusted for the degree of non-uniformity of water delivery. Field-scale drip systems should be designed to have a distribution uniformity (D.U.) of 85-90%, meaning that the driest quarter of the field receives 85-90% of the field average. Dividing the ET_c by the D.U. 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:

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

$K_c = (48 / 66)*1.1 = 0.80$

$(ET_o \times K_c) = ET_c$; therefore, 0.50 inches x 0.80 = 0.40 inches

$ET_c \div$ D.U. = irrigation requirement; therefore, 0.40 inches ÷ 0.85 = 0.47 inches

Salinity control can be important in drip-irrigated fields, particularly in areas of low rainfall or 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 as uniform a soil moisture regime as possible. Tomato can tolerate a depletion of 20-30% 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 both the San Joaquin and Sacramento Valleys have shown that, in medium- to heavy-textured soils, it is seldom necessary to irrigate more often than every other day, even during the peak water demand portion of the season. In sandy soils 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 irrigation requirement allowable between irrigations (inches)
sand	0.2 – 0.3
sandy loam	0.3 – 0.5
silt loam	0.5 – 0.7
clay loam	0.5 – 0.7
clay	0.4 – 0.6

Soil moisture monitoring:

There can be several significant sources of error in the method of irrigation management just described. 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 soils placing sensors approximately 6 inches to the side of the drip tape is appropriate. Sensor depth is important as well. A sensor at approximately 12 inch depth will monitor soil moisture in the most active root zone; a second sensor installed at 24-30 inch depth 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 lists 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 20-30% 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 20-30% depletion as much as possible. Immediately after an irrigation, cb readings may go to zero, but they should increase to near or above field capacity before the next irrigation. Until fruit begin to ripen, allowing soil tension to rise above the 20-30% depletion level, even for a day or two, may be enough to induce yield loss or blossom end rot of fruits.

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

	Approximate soil water tension (cb) at	
Soil texture	Field capacity	20-30 % available water depletion
sand	8-12	20-25
loam	12-16	25-30
clay	20-25	25-40

Interpreting soil moisture content data from dielectric sensors is complicated by the fact that the optimum range of soil water content varies considerably by soil texture, requiring a field-specific calibration. Often readings from these sensors are used more to show wetting/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 fruits 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 mid-season. 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 SSC will often be <5.0 ^{o}Brix, and may be <4.5 ^{o}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, SSC of that fruit will slowly decline (typically by about 0.2 ^{o}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 fruits are still green. Since fruit ripening typically begins 5-6 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 2-3 feet of soil must be reduced substantially below field capacity. A root zone soil moisture tension of 40-50 cb should be a sufficient stress to increase SSC of green fruit. This level of stress should not reduce Brix yield (tons of solids/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 40-60% of ET_c over the last 4-5 weeks before harvest is a reasonable compromise between maximizing yield and achieving acceptable SSC. The lower end of that range would be appropriate for soils with high water holding capacity, the higher end of that range would apply to lighter soils 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 (gallons/acre/hour) can help spot the first sign of root intrusion. Chlorine or acid injection can be used as a preventative practice.

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