Efficient nitrogen fertility and irrigation management of cool-season vegetables in coastal California

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This publication describes efficient management of nitrogen (N) fertility and irrigation for the production of cool-season vegetables in the coastal valleys of central California. Improving the efficiency of irrigation and N fertility is increasingly important, given the increased regulatory activity designed to protect water resources in this region. In response to widespread N pollution of both surface water and groundwater the Central Coast Region Water Quality Control Board has adopted a regulatory program that requires growers to track and report all N inputs, including those from fertilizer, organic amendments and irrigation water. This information will be used to estimate a *nitrogen balance,* which compares the amount of N applied to fields with the amount of N estimated to be removed from fields in harvested products. The greater the imbalance between applied N and N removed with harvest, 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-nitrogen (NO_3-N) degradation.

Efficient irrigation is also critical to successful production of these crops. Maximizing irrigation efficiency minimizes groundwater pumping; excessive extraction of groundwater is a serious issue in some coastal regions. Excessive irrigation can also lead to NO_3-N loss from fields through surface runoff or leaching to groundwater. Nitrogen in surface runoff can induce algal blooms and associated problems in receiving waters, while NO_3-N leaching can contaminate groundwater; much of the groundwater underlying the coastal vegetable production areas has NO_3-N above the 10 parts per million (PPM) regulatory threshold for drinking water.

Cool-season vegetable production is centered in the Salinas Valley, the Santa Maria Valley and the Oxnard plain. This guide focuses on the production of lettuce, broccoli, cauliflower, celery and spinach, which collectively constitute the majority of vegetable acreage in this region. These crops are also produced in the San Joaquin and Imperial Valleys; the principles outlined here are relevant in all areas, but differences in weather, soils and crop rotations must be considered when formulating management plans in these other production areas.

Nitrogen Management

Pattern of growth and N uptake

Extensive plant sampling in commercial fields has documented the characteristic pattern of growth and N uptake in cool-season vegetables. Growth is slow in the first few weeks following seeding or transplanting while the crop becomes established. From that point forward growth occurs at a reasonably constant rate (Fig. 1A). These crops produce substantially different amounts of biomass by the time of harvest. Those differences are largely due to the length of the growing season; under summer conditions baby lettuce (for salad mixes) is usually harvested less than 35 days after seeding, while celery may take more than 90 days from transplanting to harvest. Planting density is also a factor; the high-density sowing of spinach and baby lettuce results in more rapid biomass production in the initial weeks after crop establishment.

Crop N uptake follows the same pattern as biomass production (Fig. 1B), with little N uptake in the initial weeks after seeding or transplanting, followed by a relatively constant rate of N uptake from then until harvest. Seasonal crop N uptake differs among crops, ranging from about 60 lb N/acre in baby lettuce to more than 300 lb N/acre in broccoli grown under summer conditions. These differences are attributable to several factors: length of the growing season, planting density, and individual crop N uptake characteristics. Broccoli, cauliflower and celery have longer growing seasons, so they accumulate more N by harvest than the other crops. High-density crops like spinach and baby lettuce develop crop biomass quickly, and consequently take up a substantial amount of N earlier in the season. Broccoli and cauliflower typically maintain higher N concentration in their tissues than head lettuce or celery, and consequently their N uptake rate is higher. Iceberg and romaine lettuce have very similar growth and N uptake patterns, so they are collectively referred to as 'head lettuce'.

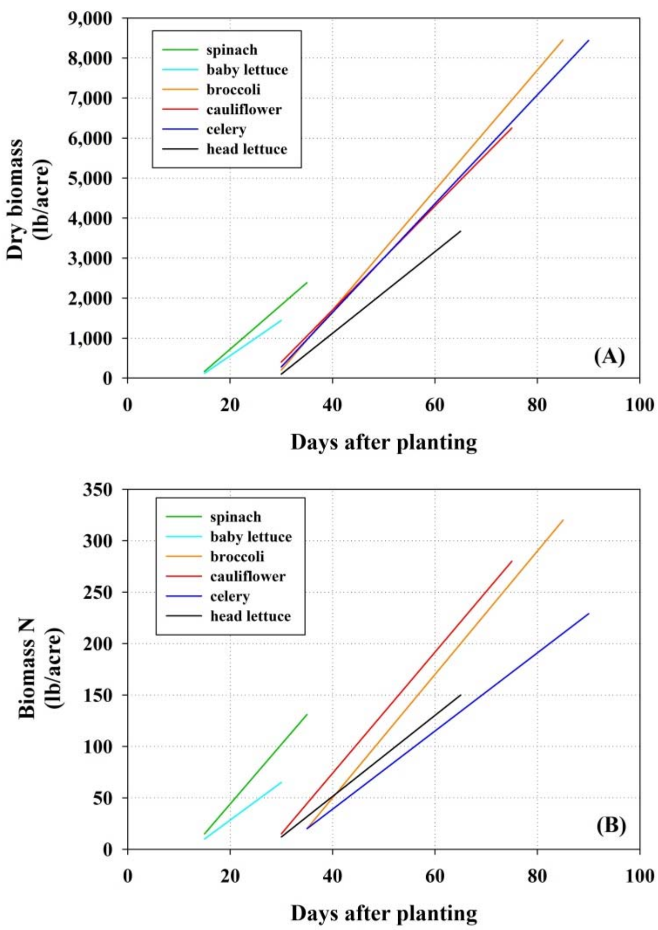

Fig. 1. Pattern of seasonal growth (A) and N uptake (B) by cool-season vegetable crops under summer coastal conditions.

Table 1 summarizes the N uptake and harvest N removal characteristics of these crops. The higher end of the ranges given is typical of crops grown in summer conditions, with the lower end of the ranges representing production during cooler periods. Planting configuration also has an effect; production on 80” beds generally uses a higher plant population, resulting in higher N uptake per acre than production on 40” beds. In addition to differences in seasonal N uptake, these crops differ in the percentage of crop N removed with harvested products. With celery, lettuce and spinach 50-70% of crop biomass N is harvested, while with broccoli and cauliflower only 25-35% is removed with the harvest. The residue of all these crops tends to be high in N concentration (often more than 3% of dry weight), so when that residue is incorporated into the soil much of the N is quickly mineralized.

Table 1. Nitrogen uptake and harvest N removal characteristics of cool-season vegetable crops; data drawn from field monitoring projects conducted by the authors, 2000-2015.

		Pounds per acre		
Crop	Days to harvest	Seasonal crop N uptake	N removed with harvest	Daily N uptake during rapid growth
broccoli	80-100	250-350	90-100	5-7
cauliflower	75-95	250-300	70-80	5-7
celery	85-110	200-250	140-160	3-4
head and romaine lettuce	60-80	120-160	60-90	3-4
baby lettuce	30-35	60-70	40-50	3-4
spinach	30-40	100-130	70-90	5-7

Root development was studied by excavating observation pits in commercial fields at different points in the crop cycle and determining both the depth of rooting and the distribution of roots across that depth. The maximum depth of rooting varied among crops, but that difference was largely a function of length of the growing season (Fig. 2). By harvest, broccoli had roots below 30 inch depth, while the deepest roots of cauliflower, celery and lettuce were generally between 24-30 inches. Spinach roots were confined to the top 18 inches. The pattern of root development was the same for all crops, with depth increasing linearly as the season progressed. Across crops, rooting density diminished quickly with depth; roughly 70% of roots observed were in the top half of the rooting zone.

This consistent pattern of root development has important implications for N management. Although uptake of water and N can occur to the bottom of the rooting zone, efficient crop management should strive to keep these inputs in the top half of the rooting zone. Residual soil NO_3-N, and N fertilizer applied early in the season, are at particular risk of leaching unless irrigation is carefully controlled. Even for crops like broccoli that eventually root to a substantial depth, N uptake in the first half of the growing season takes place mostly from the top foot; it is only later in the cropping cycle that significant N uptake occurs from deeper in the soil profile.

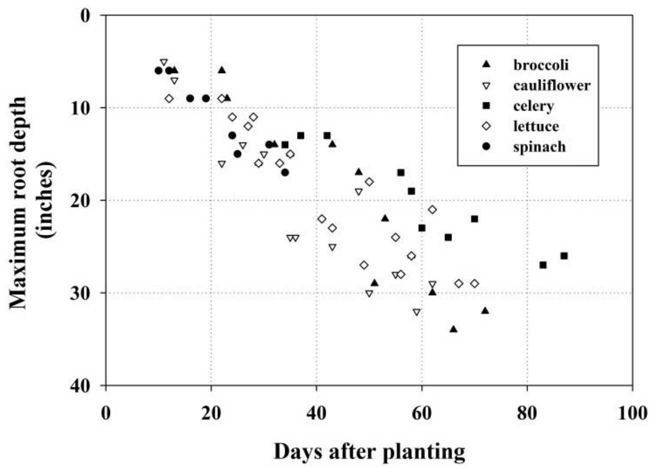

Fig. 2. Pattern of root development in cool-season vegetable crops under summer coastal conditions; data represent the deepest root observed on each evaluation date.

Nitrogen cycling in coastal vegetable rotations

There are unique aspects of coastal vegetable production that present a serious challenge to efficient N management, and to groundwater protection. Fields typically produce 2-3 crops per year, so annual N fertilizer application tends to be high. A significant fraction of the N in crop biomass is returned to the soil in the form of high-N residue; this is particularly important in the case of broccoli and cauliflower, where crop residue can contain in excess of 200 lb N/acre. This residue breaks down quickly, typically releasing >50% of its N content as NO_3-N within 6-8 weeks after incorporation. Lastly, many irrigation wells in this region contain a substantial amount of NO_3-N; wells in the range of 10-30 PPM NO_3-N (representing 2.3-6.9 lb N/acre inch) are common. With annual irrigation often exceeding 18 inches, this can represent a significant N input.

The net result of these factors is that soil NO_3-N concentration is typically high throughout the production season; this presents both a challenge and an opportunity. The challenge is to effectively manage irrigation to limit NO_3-N leaching below the root zone. The opportunity is to take advantage of these non-fertilizer sources of N to supply crop needs, thereby reducing fertilizer N input.

N fertilizer management

A wide range of N fertilizer rates are applied on these crops (Table 2). Seasonal N rates differ among growers, and time of year is also a factor. Crops planted in summer generally receive less N fertilizer, since there is no danger of leaching with rainfall; growers also realize that summer crops can benefit from residual soil NO_3-N carried over from the previous crop. It is important to note that current N fertilizer rates for broccoli and cauliflower are generally lower than the seasonal N uptake of those crops; this suggests that these crops are ‘scavenging’ a substantial amount of N from the soil profile. By contrast, N fertilizer rates for head lettuce and celery are usually equal to or above crop N uptake, while rates used on spinach and baby lettuce are significantly in excess of crop N uptake.

Table 2. Comparison of common seasonal N fertilization rates with crop N uptake and harvest N removal in coastal vegetable fields; data drawn from field monitoring projects conducted by the authors, 2000-2015.

	Pounds per acre		
Crop	N application rate	Crop N uptake	N removed with harvest
broccoli	170-250	250-350	90-100
cauliflower	200-320	250-300	70-80
celery	200-320	200-250	140-170
head and romaine lettuce	100-220	120-160	60-90
baby lettuce	160-190	60-70	40-50
spinach	160-200	100-130	70-90

In a single cropping season the potential for N loading to the environment can be estimated as the difference between N application (from all sources, including fertilizer, NO_3-N in irrigation water and N mineralized from organic amendments) and crop N uptake. However, not all N taken up by the crop is removed from the field; crop residue N is eventually released back into the soil. Thus, in the longer term, it is the difference between N application and N removal in the harvested product that best estimates a cropping system's N loss potential.

Efficient N management begins with a realistic estimate of a crop's N uptake requirement. The seasonal crop N uptake values in Table 2 are a starting point for estimating N uptake requirements. However, it should be noted that in many commercial fields such high soil N availability is maintained that a significant amount of 'luxury consumption' (crop N uptake that neither increases yield nor product quality) takes place; we have repeatedly observed that fields of similar yield and quality can have quite different N uptake. Therefore, the values in Table 2 probably overstate actual crop N uptake requirements.

Residual soil N

Not all of a crop's N requirement must be met with N fertilizer. As previously described, in coastal vegetable production residual soil NO_3-N, N mineralization from crop residue and N supplied in irrigation water can all be significant factors in crop N supply. Therefore, to be efficient one must adjust a crop N fertilizer 'program' for field-specific conditions. Foremost among those conditions is the amount of residual soil NO_3-N present. Soil NO_3-N can change rapidly due to soil N mineralization, leaching losses and crop uptake, so soil sampling just before a planned N application (whether by sidedressing or fertigation) is the only way to accurately assess current soil NO_3-N status. This sampling approach is often referred to as pre-sidedress soil nitrate testing (PSNT). In coastal vegetable production PSNT reflects much of the influence of prior crop residue on soil N availability, since residue N mineralization is rapid, and a pre-sidedress soil sample would typically be collected at least 4 weeks after incorporation of prior crop residue. Also, a soil sample collected after crop establishment measures only the NO_3-N remaining in the root zone after any leaching associated with irrigation for crop establishment has occurred.

Extensive research in commercial lettuce and celery fields documented that sidedress or fertigated N application can be delayed in fields with root zone soil NO_3-N concentration >20 PPM (Hartz et al., 2000). PSNT soil samples are typically taken from the top foot of soil; since field soils usually weight between 3.5-3.8 million pounds per acre foot, multiplying PPM soil NO_3-N by 3.5-3.8 estimates the pounds of plant-available N per acre. A top foot soil sample with 20 PPM NO_3-N represents approximately 70-75 lb N/acre. That amount of N should be adequate to maintain the crop for a period of several weeks, even during peak N uptake. In fields with residual soil NO_3-N below this threshold level fertilizing to bring the soil up to the threshold concentration has proven effective (Breschini and Hartz, 2002).

Broccoli and cauliflower, by virtue of their more rapid N uptake, may require a higher threshold level, perhaps 25 PPM NO_3-N. However, from mid-season onward, broccoli and cauliflower can access soil NO_3-N to a depth of 2-3 feet; sampling just the top foot of soil would underestimate NO_3-N availability for these crops later in the cropping cycle. If soil nitrate sampling is continued beyond mid-season, sampling the top two feet of soil, and applying a 15 PPM NO_3-N threshold, is a reasonable approach.

The greatest benefit of PSNT is reducing early-season N application. Traditionally, N sidedressing was a standard practice after thinning for lettuce and broccoli, or shortly after transplanting for cauliflower and celery. Crop N demand at that stage is still low, and N applied early in the season is more likely to be leached by irrigation before crop uptake than N applied later in the crop cycle. Retesting soil NO_3-N every few weeks can help guide N application throughout the season. When N application is required, the application rate should be based on the crop N uptake rate at that point in the season and on the length of time before the next N application would be contemplated.

It should be noted that a PSNT action threshold of 20-25 NO_3-N does not indicate that continuously maintaining that level until harvest is required; rather, the threshold represents the level of soil NO_3-N adequate to carry the crop for at least several weeks. Vegetable crops can continue to grow at peak rates until soil NO_3-N is depleted to a much lower level. It is important to manage late-season fertilization so that soil NO_3-N is drawn down before harvest, ideally below 10-15 PPM. This is critical to overall N use efficiency because soil NO_3-N remaining at harvest is most at risk of leaching, either with irrigation to establish the following crop, or with winter rainfall.

N contribution from irrigation water

The other important field-specific consideration is the contribution of irrigation water NO_3-N. Recent research conducted in the Salinas Valley on lettuce and broccoli documented that N in irrigation water is just as effective as fertilizer N in supplying crop N requirements; in other words, 100% of irrigation water NO_3-N could be considered a ‘fertilizer credit’. In these studies drip irrigation was used, and only the N efficiency of irrigation applied after crop establishment was evaluated. Therefore, growers may be reluctant to fully credit irrigation water N content because they recognize that irrigation efficiency is not universally high, and a substantial fraction of irrigation water N may lost by leaching, particularly during crop establishment. A conservative approach to evaluating the fertilizer credit of irrigation water N would be to credit only the N contained in the volume of water transpired by the crop, as opposed to the amount of N in the total volume of irrigation applied. An alternative approach would be to credit only the N contained in irrigation water applied after crop establishment, because post-establishment leaching loss is usually limited.

The amount of N in irrigation water can be estimated by the formula:

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

Therefore, a well with 10 PPM NO_3-N would therefore contain 2.3 lb N/acre inch, or about 28 lb N/acre foot. When testing irrigation water it is important to note the units reported. Some laboratories report concentration as PPM NO_3; dividing PPM NO_3 by 4.4 converts the measurement to PPM NO_3-N. Irrigation water N is usually in the form of NO_3-N, but in recycled municipal wastewater (as is used in the Castroville area) a significant amount of other mineral and organic N forms are present; this N is mostly plant-available as well.

It is important to understand that a ‘fertilizer credit’ simply compares the relative availability of irrigation water N to fertilizer N; fertilizer N is also subject to loss by leaching and other mechanisms. Management practices that lead to low crop utilization of irrigation water N will also limit N uptake from applied fertilizer.

Plant tissue testing

Plant tissue testing has been a common practice for decades, but it provides limited guidance regarding efficient N fertilizer management. The common methods of tissue analysis are determination of total N concentration in leaves, or NO_3-N concentration in petioles or midribs. Historically, petiole or midrib NO_3-N analysis has been more common, but recent research has documented that petiole analysis is a flawed technique. The rate at which plants convert NO_3-N into organic compounds can be significantly affected by environmental conditions 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. While maintaining high petiole or midrib NO_3-N concentration throughout the growing season can ensure crop N sufficiency, this practice will often lead to unnecessary N fertilization.

Whole leaf total N concentration provides a more reliable measure of crop N status. Leaf total N is closely correlated with whole plant N concentration (Bottoms et al., 2012). It is much less variable than petiole analysis because it measures all forms of N contained in the tissue. Leaf age affects N concentration, so traditionally a recently mature leaf is used for N analysis. Leaf N concentration tends to decline as a crop matures, so leaf N sufficiency levels are growth stage-specific. California research suggests that leaf N sufficiency for head lettuce (iceberg and romaine) is approximately 4% of dry matter at heading stage, and 3.5% preharvest. Insufficient research has been conducted under California conditions to firmly set leaf N sufficiency standards for broccoli, cauliflower or celery, and unfortunately a wide range of leaf N sufficiency levels for these crops have been suggested by researchers in other production areas. In general, leaf N in broccoli and cauliflower tends to be 0.5-1.0% higher than lettuce, and those in celery tend to be somewhat lower than lettuce.

Across crops, leaf N analysis is better suited to documenting current N status than predicting future N fertilizer requirements. That is because, in fields with adequate soil N availability to maintain maximum crop growth rate (the typical case in commercial production fields), leaf N is poorly correlated with soil NO_3-N; a leaf sample may have the same N concentration in a field with 10 PPM soil NO_3-N as in a field with 40 PPM NO_3-N. Soil NO_3-N is the more useful monitoring technique for predicting N fertilizer requirements.

Winter cover crops

During the winter rainy season fields left fallow are at maximum risk of NO_3-N leaching. The use of winter cover crops can dramatically reduce that risk (Heinrich et al., 2014). Non-legume species like cereal rye can take up in excess of 100 lb N/acre, depending on soil NO_3-N, rainfall pattern, and the termination date. Use of winter cover crops can be challenging in an intensive cropping system because cover crop residue management in the spring can delay cash crop planting. Early termination of a cover crop reduces this problem, but also reduces the nitrogen trapping capability of the cover crop.

Irrigation Management

Irrigation system design and management

Both sprinkler irrigation and drip irrigation are widely used for coastal vegetable production. The goal of irrigation is to maintain sufficient soil moisture for peak crop production in all areas of a field. The less uniformly an irrigation system applies water, the more water must be applied to provide adequate soil moisture in all portions of the field. Leaching and/or run-off may occur in areas that become oversaturated, and crop growth will suffer in areas that do not receive adequate amounts of water.

The application uniformity of an irrigation system, also referred to as the *distribution uniformity* (DU), is assessed by comparing the average depth of water applied in a field with average depth of water applied to the area representing the driest 25% of the field. A DU value of 100% represents perfectly even distribution, while DU values below 60% are considered very uneven. We evaluated the distribution uniformity of 33 irrigation systems operated in coastal vegetable fields between 2006 and 2015 (Table 3). While drip systems were on average more uniform the advantage was not very great. Well designed and operated irrigation systems typically have distribution uniformities greater than 85% for drip and 75% for sprinklers. Small changes in design, operation and maintenance can substantially improve irrigation system distribution uniformity.

Table 3. Distribution uniformity of irrigation systems in 33 coastal vegetable fields.

Irrigation	Number	Distribution Uniformity (%)		
method	of fields	Average	Maximum	Minimum
Drip	20	75	93	38
Sprinkler	13	67	86	48

Sprinklers

Wind is one of the main factors limiting distribution uniformity of impact sprinklers. Operating sprinklers at wind speeds below 5 mph maximizes application uniformity. Unfortunately, it is not practical to always restrict irrigation to periods of calm wind. Several models of plastic sprinkler heads that use a rotator design can improve uniformity in windy conditions compared to standard impact heads. Some of these models also have efficient guards for blocking spray from sprinkler heads located along the edge of roadways, which results in less runoff than from the standard sprinkler guards. Reducing distances between lateral lines to increase overlap among sprinkler heads can also improve uniformity, especially if windy conditions are common.

Increasing nozzle pressure beyond 45 psi does not significantly improve uniformity of most standard impact sprinklers, but it does increase energy required for pumping. Decreasing the distance between lateral lines or increasing nozzle pressure increases the application rate of an irrigation system, which can result in more run-off as the soil becomes saturated. Shorter irrigations are required to meet crop requirements as the application rate of the irrigation system increases. Runoff is less common with hand-move than with solid-set sprinklers. This is because the application rate is usually substantially lower for hand-move than for solid-set sprinklers. Hand-move sprinklers have become less common in areas with a limited supply of labor, but are still often used when a pump has an insufficient flow rate to pressurize a solid-set system.

Poor maintenance of sprinklers can also reduce uniformity and increase run-off. Worn nozzles or using a mixture of different nozzle sizes reduces distribution uniformity, resulting in non-uniform application of water. Nozzles often plug if the lateral lines are not sufficiently flushed before the first irrigation. Sprinkler heads that rotate improperly will not provide a uniform application of water and should be fixed or replaced. Runoff most commonly occurs from furrows that have lateral pipes; leaks are common on lateral lines as gaskets wear and become less effective at sealing joints between pipes. Also, corrosion of aluminum pipes can cause holes that leak significant amounts of water, adding to runoff.

Drip

Poor water pressure management is a problem that often limits the distribution uniformity of drip systems used for vegetable production. The water output of drip irrigation tape is approximately proportional to the pressure at which it is operated. Because drip tapes are operated at relatively low pressures (typically between 8 and 12 psi) a variation in pressure within the system of as little as 2 psi will reduce the distribution uniformity dramatically. Irrigators should be trained to evaluate pressure in drip systems using an accurate pressure gauge. The gauge should be periodically calibrated to assure that readings are accurate. Because most new oil-filled pressure gauges are only accurate to ±1 to 2 psi, using the same gauge to read pressures at Schrader valves installed on the drip system will reduce errors in readings. Schrader valves should be installed on the submains and at the ends of the drip lines to assure that the drip system is operating at the correct pressure and that pressures are uniform throughout the field. Pressure reducing valves (PRV) can be used at the submain to maintain a consistent pressure during all irrigations. However, irrigators are often unfamiliar with how to operate and maintain PRVs, and consequently may leave them in a manual mode and use another valve to control pressure.

Management and maintenance of drip systems is complicated by the fact that, in coastal vegetable production, systems are installed, removed and reused for many crops before the drip tape is replaced. This results in the need to splice tapes repeatedly; spliced tapes may leak, and one common response to minimize leakage is to reduce operating pressure. Also, this system of reuse may result in drip tapes of different flow rates being installed in the same field, making efficient management impossible. Lastly, emitter clogging from soil particles, chemical precipitates or biological growths increases with the number of times the tape is reused.

Irrigation scheduling

The irrigation requirement of vegetable crops is primary related to weather conditions and stage of crop development. Evapotranspiration (ET) data and crop coefficients can be used to estimate irrigation requirements. Daily reference ET (ET_o) data are available for most vegetable production regions through the California Irrigation Management and Information System (CIMIS) from the Department of Water Resources website (www.cimis.water.ca.gov). Historical ET_o values are also available for many locations. Table 4 lists average daily ET_o values by month for representative coastal locations.

Table 4. Historical CIMIS reference evapotranspiration (ET_o) averages, in inches per day.

Location	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Salinas	.05	.07	.09	.13	.15	.16	.16	.15	.13	.09	.06	.04
Santa Maria	.06	.08	.10	.13	.16	.17	.17	.17	.15	.11	.08	.06
Ventura	.07	.09	.10	.13	.15	.16	.18	.16	.14	.11	.08	.06

Several free online tools are available to assist with estimating irrigation requirements using ET_o data, including CropManage (UCANR, https://cropmanage.ucanr.edu), Wateright (Fresno State University, http://www.wateright.org), Irrigation Scheduler (Washington State University, http://weather.wsu.edu/is) and Irrigation Management Online (Oregon State University, http://oiso.bioe.orst.edu). Alternatively, crop ET (ET_c) can be estimated by multiplying the ET_o value by a crop coefficient (K_c) that reflects the site-specific conditions of the crop. Because crop water use is primary related to the portion of solar radiation intercepted by the crop, K_c can be estimated from the fraction of the ground surface covered by the crop canopy. Canopy cover can be estimated visually or by the use of a free cell phone application (www.canopeoapp.com). Figure 3 shows the generic relationship between canopy cover and K_c for cool-season vegetable crops such as lettuce, spinach, and cole crops. For a more complete explanation of irrigation scheduling see Hanson et al. (2004).

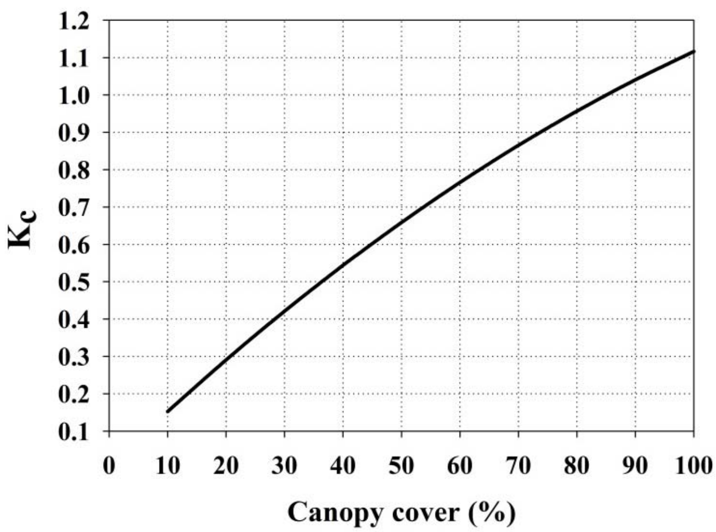

Fig. 3. Relationship between canopy cover (%) and the crop coefficient (K_c); calculation is $K_c = (0.63+1.5C - 0.0039C^2)/100$, where C is the percent canopy cover.

The appropriate irrigation frequency is influenced by the water holding capacity of the soil, rooting depth, and water demand of the crop. A crop grown on a sandy textured soils with a low water holding capacity will need more frequent irrigation than a crop grown on clay loam textured soil with a high water holding capacity. In the early stages of crop development water demand will be low and therefore irrigation can be less frequent than during the main production period.

Monitoring soil moisture can help verify that irrigation is keeping up with the water demand of the crop, and identify areas of the field that may be exceptionally dry or wet. Both soil moisture sensors as well as probing the soil with a hand tool can be helpful. Tension-based soil moisture sensors such as tensiometers and resistance blocks are most often used for scheduling irrigations in vegetables. Soil moisture tension significantly greater than 30 centibars (cb, equivalent to kPa) are considered high for most cool-season vegetables and may lead to reduced growth and yield.

Pre-irrigation

Applying irrigation before planting is often necessary to create optimal conditions for soil tillage and bed shaping. Applying only the required amount of pre-irrigation can minimize NO_3-N leaching risk. Less irrigation is needed if rains have recently saturated the soil profile. Checking soil moisture before pre-irrigation can help determine the amount of water needed.

Crop establishment

Establishing a uniform plant stand is critical for maximizing yield and quality. The first irrigation after seeding or transplanting is usually sufficient to wet the soil to a significant depth; subsequent irrigations during crop establishment need only keep the surface soil moist to prevent soil crusting or drying of seeds before germination. Since the soil is usually saturated by the first watering, irrigating too long during subsequent irrigations may cause runoff, or deep percolation and associated NO_3-N loss. During crop establishment most water loss is due to evaporation from the soil surface; consequently, the amount of water needed to maintain moist surface soil will be closely related to the ET_o. During the establishment phase irrigating more frequently, but for short periods, is more efficient than applying more water less frequently. Monitoring soil moisture at the depth of transplant roots or seed can provide guidance on the volume and timing of irrigation.

Post establishment

Most vegetable crops have low crop ET requirements after establishment because the plant canopy is still small. Irrigations do not usually need to be very long to re-saturate the soil profile at this early stage, and may be spaced more than a week apart depending on weather conditions. Careful monitoring of soil moisture in the root zone of the crop can determine the appropriate irrigation interval.

Nitrate leaching loss potential can be high after the first N side-dressing or fertigation. This is because soil NO_3-N concentration may be at its seasonal peak, crop ET requirement is still low, and crop roots are concentrated mostly in the top foot of soil. Over-irrigating at this stage can result in significant nitrate leaching.

Mid to late season

Crop water requirements quickly increase in the second half of the season as the canopy rapidly expands and reaches maximum coverage. Estimating crop ET using ET_o and K_c values can determine how much water must be applied to prevent crop stress. Soil moisture monitoring as described earlier can be used to determine the adequacy of irrigation.

Leaching requirements

Most cool season vegetables are sensitive to salts that accumulate in soil. Yields will decline when soil salinity exceeds the crop tolerance threshold. Table 3 shows soil salinity thresholds for a range of cool-season vegetables. Irrigation in excess of ET_c may be needed to prevent salts from accumulating in the root zone. However, leaching of salts also leaches NO_3-N from the root zone. Using a leaching fraction appropriate for the salinity of the irrigation water and for the salt sensitivity of the crop can minimize NO_3-N leaching. The online publication "Managing Salts by Leaching" (Cahn and Bali, 2015; http://anrcatalog.ucanr.edu/pdf/8550.pdf) discusses how to calculate leaching requirements. If the salinity of the irrigation water is relatively low (< 1 dS/m) leaching requirements can be quite small. Because the accumulation of salt in the root zone occurs slowly over the season, leaching fractions do not need to be applied with every irrigation. Monitoring soil salinity during the season can identify when leaching is needed. Avoiding leaching when soil NO_3-N is high, such as after a fertilizer application, can minimize NO_3-N leaching losses.

Table 3. Soil salinity threshold for yield loss of vegetable crops; from Maas, 1984.

Crop	EC_e (dS/m)	Salt Tolerance
Broccoli	2.8	Moderately sensitive
Cabbage	1.8	Moderately sensitive
Carrot	1.0	Sensitive
Celery	1.8	Moderately sensitive
Lettuce	1.3	Moderately sensitive
Onion	1.2	Sensitive
Spinach	2.0	Moderately sensitive

Fertigation

Vegetable growers frequently inject a portion of the N fertilizer applied to their crops through the irrigation system. Fertigation uniformity is limited by the distribution uniformity of the irrigation system and the procedures used for injecting fertilizer. Evaluation of the fertilizer distribution uniformity in 11 drip-irrigated lettuce fields demonstrated that systems with low DU values also had uneven distribution of fertilizer. Since fertilizer can react with salts in irrigation water to form insoluble compounds, fertilizers should be injected upstream of a filter to prevent clogging of the drip emitters. Periodic treatment of the drip tape with injected acid and/or chlorine may help reduce emitter clogging.

Assuring that injected fertilizer thoroughly mixes with irrigation water is also critical to distributing fertilizer uniformly through a drip system. If fertilizer injection occurs at the field (as opposed to at the pump), measures should be taken to assure that fertilizer is well mixed before the irrigation system branches; if fertilizer is not adequately mixed before the water flows into the drip lines, some beds may receive more fertilizer than others. Providing extra distance in the submain for mixing before the first branch in the irrigation system and/or using injection quills or static mixers can assure uniform fertilizer distribution.

Equally important to achieving uniform fertilizer distribution is allowing sufficient time for all of the injected fertilizer to flush from the drip tape before ending the irrigation set. Irrigators may believe that injecting fertilizer at the end of the irrigation set is the best practice to reduce leaching of fertilizer; however, because the time required for fertilizer to travel to the furthest point in an irrigation block can be greater than 1 hour in many commercial vegetable fields, waiting too close to the end of an irrigation set to inject fertilizer can lead to a poor distribution. The travel time of fertilizer in a drip system can be evaluated by injecting food dye and determining the time required for the dye to arrive at the furthest point in the irrigation system. Injecting fertilizer during the middle third of the irrigation set is a good rule of thumb for longer irrigations (> 4 hours).

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