Using Nutrient Uptake Patterns to Develop Efficient Nitrogen Management Strategies for Vegetables

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SUMMARY. Nitrogen (N) in a soil that is not immediately taken up by a crop is subject to leaching, denitrification and other mechanisms of loss. Nitrogen uptake studies identify the total amount of N accumulated by the crop and the period of peak demand. This information can be used to devise management strategies aimed at supplying N preceding anticipated uptake. Split sidedress application, fertigation, and use of controlled release fertilizers (CRN) are all viable options for N management, depending on the crop production scenario and available infrastructure. Soil and plant tissue testing can be useful feedback tools for adjusting N applications for soil contributions of N and unexpected N losses. Efficient irrigation is of paramount importance in achieving efficient N fertilization regardless of management practice.

Nitrogen is the fertilizer element required in the greatest quantities by most crops. The N available to crops might include symbiotically fixed N, residual soil organic and inorganic N, and soil applied organic and inorganic N. Only leguminous vegetable crops, such as peas (*Pisum sativum* L.) and beans (*Phaseolus vulgaris* L.), may derive a significant portion of their N requirement by symbiotic N fixation. While some soils have sizeable organic fractions where soil N mineralization can contribute significantly to a crop's N requirement, only vegetable crops produced on organic soils (Histosols) derive most or all of their N through soil N mineralization. Although some organically grown vegetables rely almost exclusively on N mineralized from soil applied organic N sources, most of the N requirement of commercial vegetables is met by the addition of synthetic fertilizers. Ideally, N from all sources should become available to a crop at a rate about equal to its N uptake requirement. The availability of N in amounts exceeding the immediate requirements of the crop will remain unused in the soil. This nitrogen is subject to leaching, denitrification and other mechanisms of loss. Therefore, N fertilization practices and other management decisions that influence N availability should take into consideration crop N demand and uptake patterns.

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Fig. 1. Seasonal nitrogen (N) accumulation by broccoli fit to nitrogen accumulation (NA) = (a/(1 + exp(b - ct))), where t is time in days and a, b, and c are constants (A) and daily N flux, which is given by taking the first derivative of the above equation with respect to time (t) to become dNA/dt = ac(exp(b - ct))/(1 + exp(b - ct))² (B). Figures generated from unpublished data of C.A. Sanchez, which were obtained from field experiment with furrow irrigated broccoli; 1 kg·ha⁻¹ = 0.89 lb/acre.

Fig. 2. Nitrogen (N) accumulation of lettuce by days after planting (A) and effective degree days (EDD) (B). 1/EDD = 1/DD + α/SR, where DD is degree day accumulation, SR is daily solar radiation, and α is a constant obtained by this preliminary evaluation we used α = 0.5 after Wurr et al., (1988). Figures derived from unpublished data of C.A. Sanchez, which were obtained from field experiments with furrow irrigated lettuce; 1 kg·ha⁻¹ = 0.89 lb/acre.

Nitrogen accumulation and flux

Experiments that generate N uptake data are useful for determining the total N contained in the crop biomass and identifying periods of peak demand. Nitrogen uptake is often approximated by measuring total N accumulation in aboveground whole plants at selected intervals during the growing season. Nitrogen flux density is uptake per unit time and is determined by taking the first derivative of a fitted N accumulation function. There are several possible mathematical functions that can be used to approximate N accumulation patterns.

Nitrogen accumulation and flux for furrow irrigated broccoli (*Brassica oleracea* L. Italica Group) in Arizona are shown in Fig. 1. Daily uptake of N by broccoli is very slow for the first 40 d after planting, but increases to ≈7 kg·ha⁻¹ (6.3 lb/acre) by 90 d. Because this crop is harvested prior to completing its reproductive growth stages, N uptake remains relatively high until harvest. These data for broccoli are generally similar to that for other cool season leafy vegetables (Doerge et al., 1991) and show that ≥80% to 90% of the N is taken up during the last half of the growing period.

In the aforementioned examples, N uptake and flux were expressed using days after planting (DAP) as the expression of time. However, the use of DAP may be less useful in areas where crops are planted over a range of air and soil temperatures. Under these conditions, time in DAP is not a reliable predictor of growth stage and the use of heat units or some sort of solar-thermal unit may be more useful. Heat units are likely to be better suited for most warm season vegetables (Arnold, 1974; Katz, 1952). However, for cool season crops such as lettuce (*Lactuca sativa* L.), where response to temperature is heavily influenced by response to light, a combined heat-solar model is likely required (Madariaga and Knott, 1951; Sanchez et al., 1986). One approach used with success is the effective degree day (EDD) concept, which includes summations of temperature and solar radiation (Wurr et al., 1988). The N uptake patterns for furrow irrigated lettuce planted at two different dates in southwestern Arizona are shown in Fig. 2. Note that while N uptake patterns were offset substantially during the cooler season when plotted

Fig. 3. Nitrogen (N) accumulation by lettuce as influenced by N fertilization rate. Figure generated with unpublished data of C.A. Sanchez, which were obtained from field experiments evaluating N rate and N source for furrow irrigated desert lettuce. The N rates were split into three equal applications; 1 kg-ha⁻¹ = 0.89 lb/acre.

by DAP, they were more similar when plotted using the EDD units. We wish to stress that this is only a preliminary evaluation and we are currently conducting research aimed at identifying the most useful approach for predicting

growth stage and maturity. Nevertheless, these data show that weather based summation models will likely provide the more reliable approach for predicting N uptake patterns. Finally, data for determining N uptake patterns should be collected under conditions where N is not limiting marketable yield. The data in Fig. 3 were collected from an N rate study with furrow irrigated lettuce in Arizona. Nitrogen accumulation by lettuce was low through 60

DAP for all N rates but between 60 DAP and 120 DAP uptake patterns varied by N rate and final N accumulation depended on N rate.

Nitrogen application, timing, and availability

The application of N should be timed to coincide with the characteris-

Fig. 5. Response of cool season vegetable crops to N management: (A) lettuce on silty clay with N at 200 kg-ha⁻¹, (B) broccoli on sandy loam with N at 300 kg-ha⁻¹ (C) lettuce on loamy sand with N at 300 kg-ha⁻¹ (D) cauliflower on loamy sand where N for PP and SD were applied at 320 kg-ha⁻¹ and N with controlled release N (CRN) products were applied at 270 kg-ha⁻¹. Controls did not receive N fertilizer except a small amount applied with preplant phosphorus over the entire experiment area. PP indicated preplant application of soluble N fertilizer and SD indicates split sidedress application of soluble N fertilizer. CRN90 and CRN120 are controlled release N fertilizers with designations of rate of N release of 90 and 120 d based on designated heat unit accumulation. Bars (I) show LSD values for treatment comparisons (C. A. Sanchez, unpublished data); 1 Mg-ha⁻¹ = 892 lb/acre and 1 kg-ha⁻¹ = 0.89 lb/acre.

Fig. 4. Potential nitrogen (N) losses under a single preplant N application (A) or incremental split N application (B). Adapted from Doerge et al. (1991).

Table 1. The minimum number of N applications recommended for varying soil types.^z

Soil texture	Recommended N applications per crop (no.)
Clay, sandy clay, silty clay	1
Clay loam, silty clay loam, silt, silt loam, sandy clay loam	2-4
Sandy loam and loam	3-5
Sand	8-15

^zAdapted from Doerge et al. (1991) but modified with unpublished data from C.A. Sanchez and T.A. Doerge.

Fig. 6. Marketable yield of watermelons to fertigation and two controlled release nitrogen (CRN) sources. MU is methylene urea and MUAS is a blend of methylene urea and ammonium sulfate (adapted from Doerge et al., 1992); 1 Mg·ha⁻¹ = 892 lb/acre.

ticipated N uptake pattern of the crop. We illustrate this point in Fig. 4 where the potential for N loss from the soil is much higher if all required N is made available early during the growing season, compared to becoming incrementally available during the growing season. Nitrogen management must also consider the lag time between application of fertilizer and N availability. At low soil temperatures where urea hydrolysis and nitrification reaction rates slow considerably, plant growth and N uptake rates are also reduced. Hence, there is rarely a difference in N availability and crop response among soluble N sources (Gardner and Pew, 1979; Walworth et al., 1992). However, for controlled release N fertilizers (CRN) and most organic fertilizers, the time of fertilizer release and/or mineralization, respectively, should precede an-

tipated N uptake. The release patterns for CRN products are typically defined by the number of days required for releasing 80% of the N at some base temperature (often 20 °C, 68 °F). However, experimental verification of field performance for individual crops during specific seasons is usually required. Similarly, field evaluation of organic fertilizers is usually required to insure mineralization rates correspond closely to crop demand.

From 1991 to 1998, we conducted several experiments aimed at evaluating N management strategies for furrow irrigated cool season vegetables. Nitrogen management treatments evaluated included the preplant application of conventional soluble N fertilizers (PP), the split sidedress application of soluble N fertilizers (SD), and the preplant application of CRN. The experiments included lettuce, broccoli, and cauliflower (*Brassica oleracea* L. Botrytis Group) and were randomized complete block designs with at least four replications. On fine to medium textured soils, both SD and CRN were often superior to PP (Fig. 5a and b), but differences between SD and CRN were minimal. However, on coarse textured soils

CRN frequently outperformed SD (Fig. 5c and d). These observations are generally consistent with other data that we (Sanchez, unpublished) and others (Wiedenfield, 1986; Cook and Sanders, 1991) have collected and show the benefit of controlled release fertilizers when conditions for N losses are high. The consistent superior performance of CRN compared to SD on sandy soils is likely a logistical limitation of field sidedress N applications rather than an actual failure in the efficacy of split N application. Sidedress N applications are made prior to irrigation and rarely, are more than four or five irrigations needed for furrow irrigated cool season vegetables. Additionally, rows have to be spiked and cultivated before each sidedress application and furrows and beds are reshaped after each sidedress application. Hence, it is rare to make more than three sidedress N applications. Sidedress application on sandy soils often fails to supply N as frequently as needed for optimal N use efficiency. The minimum number of nitrogen applications per crop cycle recommended by the University of Arizona for varying soil types is shown in Table 1.

When irrigation infrastructure permits, fertigation is often an effective means of achieving frequent split applications. The data in Fig. 6 show that watermelons (*Citrullus lanatus* Thunb.) produced on a sandy loam in

Fig. 7. Marketable yield response of lettuce by nitrogen (N) rate to sprinkler applied N where yield (Y) = $-26.8 + 0.388N - 0.0006N^2$; $R^2 = 0.64$ and controlled release nitrogen (CRN) where $Y = 10.3 - 0.070N + 0.0020$; $R^2 = 0.70$. Data generated from unpublished data of Sanchez; 1 Mg·ha⁻¹ = 892 lb/acre.

Fig. 8. Predicted marketable yield of cabbage (A) nitrogen (N) accumulation in the marketable harvest (B), and N that was applied but not recovered in the marketable harvest (C), during an irrigation and N fertilization experiment conducted on a sandy soil. Adapted from Sanchez et al. (1994). CU is consumptive use or estimated evapotranspiration (ET); 1 Mg·ha⁻¹ = 892 lb/acre and 1 kg·ha⁻¹ = 0.89 lb/acre.

central Arizona showed a similar response to CRN and fertigation. The data for lettuce shown in Fig. 7 is from a study conducted on a Superstition sand in southwest Arizona. In this experiment, fertigation through the sprinkler system outperformed preplant application CRN. The midrib nitrate-N data suggest that release of N from the CRN product used did not precede or parallel the crop N demand (data not shown). There is no question that we might have obtained more comparable results between the two methods of N fertilization had we successfully selected a CRN product with a release rate more closely matching N uptake during this particular growing season. Nevertheless, these data bring to light the risks of committing to a strategy early compared to making adjustments throughout the growing season. It is the opinion of the authors, that in the western United States, where virtually the entire water requirement of the crop is applied by irrigation, the best CRN product can only perform as well as properly managed fertigation. However, in the humid regions where the need to irrigate is problematic the use of CRN may be more effective even where infrastructure for fertigation is available.

Soil and plant monitoring

The actual rate of fertilizer N applied should be adjusted based on the

Fig. 9. Seasonal midrib nitrate-N concentrations of cabbage at three irrigation regimes compared to critical concentration; 1 g·kg⁻¹ = 1000 ppm. Adapted from Sanchez et al. (1994).

contributions of soil N (primarily mineralization) and unexpected N losses. Soil and plant tissue tests can be useful tools in making adjustments in N rates during the growing season using a feed back approach. Diagnostic midrib nitrate-N levels have been developed and published for several vegetables produced in the western United States (Doerge et al., 1992). Quick sap tests have also been evaluated and preliminary standards have been published (Hartz et al. 1994; Kubota et al., 1996, 1997). A presidedress nitrate-N test has also been recently calibrated for vegetables (Hartz et al., 1998).

Efficient irrigation

Efficient irrigation is of paramount importance in achieving efficient N management even where split application or controlled release N applications are used. This is depicted in Fig. 8, which shows cabbage (*Brassica oleracea* L. Capitata Group) responses to sprinkler applied water and N rates (Sanchez et al., 1994). Although N was split into weekly applications through the irrigation system, marketable yield and N recoveries decreased and unaccounted for N increased as irrigation rates exceeded 100% consumptive use (CU) or evapotranspiration (ET). Another illustration of this is shown with the midrib NO₃-N data presented in Fig. 9. Note that even with weekly N applications, the midrib nitrate-N values were continually below published critical concentrations when irrigation exceeded ET. These data are consistent with data we collected for other vegetable crops (Pier and Doerge, 1995; Sanchez et al., 1996; Stark et al., 1983; Thompson and Doerge, 1996) and underscore the importance of irrigation management to N fertilizer use efficiency.

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