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Nitrogen Requirements and N Status Determination of Lettuce

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***Abstract*. As concern over NO_3-N pollution of groundwater increases, California lettuce growers are under pressure to improve nitrogen (N) fertilizer efficiency. Crop growth, N uptake, and the value of soil and plant N diagnostic measures were evaluated in 24 iceberg and romaine lettuce (*Lactuca sativa* L. var. *capitata* L., and *longifolia* Lam., respectively) field trials from 2007 to 2010. The reliability of presidedressing soil nitrate testing (PSNT) to identify fields in which N application could be reduced or eliminated was evaluated in 16 non-replicated strip trials and five replicated trials on commercial farms. All commercial field sites had greater than 20 $mg \cdot kg^{-1}$ residual soil NO_3-N at the time of the first in-season N application. In the strip trials, plots in which the cooperating growers' initial sidedress N application was eliminated or reduced were compared with the growers' standard N fertilization program. In the replicated trials, the growers' N regime was compared with treatments in which one or more N fertigation through drip irrigation was eliminated. Additionally, seasonal N rates from 11 to 336 $kg \cdot ha^{-1}$ were compared in three replicated drip-irrigated research farm trials. Seasonal N application in the strip trials was reduced by an average of 77 $kg \cdot ha^{-1}$ (73 $kg \cdot ha^{-1}$ vs. 150 $kg \cdot ha^{-1}$ for the grower N regime) with no reduction in fresh biomass produced and only a slight reduction in crop N uptake (151 $kg \cdot ha^{-1}$ vs. 156 $kg \cdot ha^{-1}$ for the grower N regime). Similarly, an average seasonal N rate reduction of 88 $kg \cdot ha^{-1}$ (96 $kg \cdot ha^{-1}$ vs. 184 $kg \cdot ha^{-1}$) was achieved in the replicated commercial trials with no biomass reduction. Seasonal N rates between 111 and 192 $kg \cdot ha^{-1}$ maximized fresh biomass in the research farm trials, which were conducted in fields with lower residual soil NO_3-N than the commercial trials. Across fields, lettuce N uptake was slow in the first 4 weeks after planting, averaging less than 0.5 $kg \cdot ha^{-1} \cdot d^{-1}$. N uptake then increased linearly until harvest (≈9 weeks after planting), averaging ≈4 $kg \cdot ha^{-1} \cdot d^{-1}$ over that period. Whole plant critical N concentration (N_c, the minimum whole plant N concentration required to maximize growth) was estimated by the equation N_c ($g \cdot kg^{-1}$) = 42 − 2.8 dry mass (DM, $Mg \cdot ha^{-1}$); on that basis, critical N uptake (crop N uptake required to maintain whole plant N above N_c) in the commercial fields averaged 116 $kg \cdot ha^{-1}$ compared with the mean uptake of 145 $kg \cdot ha^{-1}$ with the grower N regime. Soil NO_3-N greater than 20 $mg \cdot kg^{-1}$ was a reliable indicator that N application could be reduced or delayed. Neither leaf N nor midrib NO_3-N was correlated with concurrently measured soil NO_3-N and therefore of limited value in directing in-season N fertilization.**

The coastal valleys of central California produce nearly 60,000 ha of lettuce annually, more than half of the nation's supply. In this region, lettuce is typically produced in rotation with other leafy vegetables. Production systems are characterized by two to three crops per year with frequent irrigation and heavy N fertilization. Water quality monitoring in the agricultural watersheds in this region has shown that both surface water and groundwater often exceed the federal drinking water standard of 10 $mg \cdot L^{-1}$ NO_3-N. Vegetable growers are under increasing regulatory pressure to improve both their fertilization and irrigation practices to protect environmental water quality. Recently proposed regulations would require growers to report N fertilization rates and to bring N loading from fertilizer and irrigation water into approximate balance with crop N uptake. In this region, lettuce N uptake has been reported to average 130 $kg \cdot ha^{-1}$ for iceberg and 107 $kg \cdot ha^{-1}$ for romaine (Breschini and Hartz, 2002). However, a recent field survey found that lettuce received an average seasonal N fertilization rate of 184 kg N/ha (Hartz et al., 2007), suggesting that significant N rate reduction would be required to meet these new regulations.

Studies on lettuce response to N fertilization have reported widely varying results. Seasonal N rates required to maximize crop yield have ranged from 100 to 150 $kg \cdot ha^{-1}$ (Gardner and Pew, 1972, 1974, 1979; Tei et al., 2003) to greater than 220 $kg \cdot ha^{-1}$ (Hoque et al., 2010; Welch et al., 1979). Much of this variability may be attributed to field-specific factors affecting crop yield potential and N fertilizer efficiency; these factors include plant population, precipitation, irrigation efficiency, residual soil NO_3-N, and soil N mineralization potential. Given the high crop value and strict market standards for lettuce, growers commonly use standard fertilization programs with little field-specific modification; they are reluctant to modify current N fertilizer practices without a sound understanding of the interaction of these factors and reliable diagnostic techniques to guide field-specific N fertilization.

Adding to the uncertainty regarding efficient N management of lettuce, California growers continue to modify production practices to increase yield. Average lettuce yield rose ≈11% between 2000 and 2010 (Monterey County Agricultural Commissioner, 2000, 2010); factors potentially responsible included modified planting configurations that increased plant population and widespread adoption of drip irrigation. We undertook this study to develop detailed information on lettuce N requirements under current production practices used in California's central coast region and to critically evaluate the value of soil and plant diagnostic techniques to guide in-season N fertilizer management.

Materials and Methods

Lettuce N uptake and response to N fertilization were evaluated in 24 field trials in the Salinas Valley of California from 2007 through 2010. Sixteen of these were non-replicated strip trials in commercial fields comparing a reduced N fertilization regime with the growers' standard N fertilization program. Replicated comparisons of reduced N management strategies and growers' N management were conducted in five additional commercial fields. All commercial fields had been in long-term rotations of cool-season vegetables. The remaining three trials, conducted at a research facility, were replicated N rate comparisons.

Strip trials. Sixteen commercial lettuce fields were selected in 2009 and 2010 to evaluate the reliability of PSNT in identifying fields in which N fertilization could be reduced or delayed with no loss of marketable yield. The fields, which were seeded between 21 Mar. and 1 Aug., were selected based on the presence of at least 20 $mg \cdot kg^{-1}$ NO_3-N in the top 30 cm of soil after crop thinning (typically 14 to 21 d after planting); this soil NO_3-N threshold was suggested by prior research on lettuce (Breschini and Hartz, 2002; Hartz et al., 2000). Twelve fields were planted with iceberg cultivars and four fields with romaine. The Salinas Valley is

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Table 1. Effect of sidedress N reduction on aboveground lettuce fresh biomass, and biomass nitrogen (N), in the commercial strip trials.

Trial	Lettuce type	Germination water date	Soil texture	Soil NO_3-N ($mg\cdot kg^{-1}$)[z]	Seasonal N ($kg\cdot ha^{-1}$)		Fresh biomass ($Mg\cdot ha^{-1}$)		Biomass N ($kg\cdot ha^{-1}$)	
					Grower N	Reduced N	Grower N	Reduced N	Grower N	Reduced N
1	Iceberg	21 Mar.	Clay	36	144	25	80	78	140	136
2	Iceberg	1 Apr.	Silty clay	20	138	40	109	101	190	177
3	Iceberg	11 Apr.	Clay loam	48	132	29	82	85	152	151
4	Iceberg	30 May	Clay	55	143	48	85	86	158	160
5	Iceberg	22 June	Silty loam	33	112	50	101	99	157	171
6	Iceberg	1 July	Sandy clay loam	20	203	115	107	107	174	168
7	Iceberg	1 July	Silty clay loam	24	89	36	85	85	145	146
8	Iceberg	15 July	Sandy clay loam	48	190	119	86	85	147	148
9	Iceberg	16 July	Clay	32	85	36	84	84	136	134
10	Iceberg	16 July	Silty clay	71	190	119	119	113	200	197
11	Iceberg	1 Aug.	Clay	46	144	25	126	128	189	188
12	Iceberg	18 May	Clay loam	36	216	151	71	71	95	91
13	Romaine	6 June	Clay	29	148	114	74	78	158	169
14	Romaine	27 June	Sandy clay loam	20	142	47	79	78	164	124
15	Romaine	1 Aug.	Sandy clay loam	23	148	98	77	76	136	120
16	Romaine	1 Aug.	Clay	68	179	108	74	75	152	139
Avg					150	73	90	89	156	151

[z] Post-thinning, before treatment initiation.

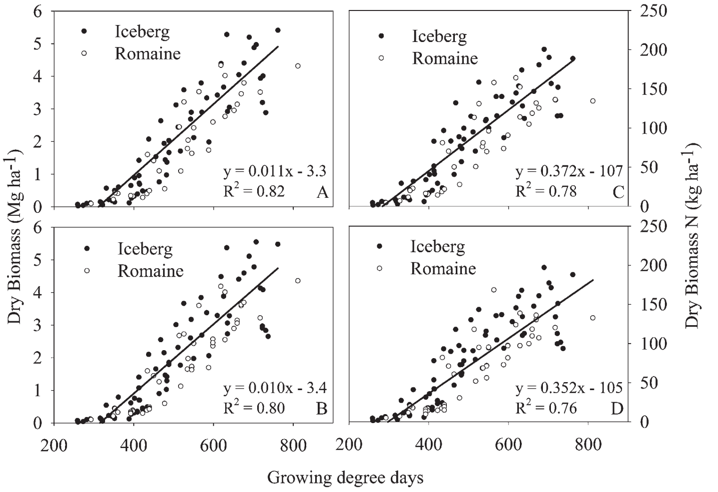

Fig. 1. Lettuce aboveground dry biomass, and dry biomass nitrogen (N), as a function of cumulative growing degree-days in the strip trial fields; grower N treatment (**A** and **C**) and reduced N treatment (**B** and **D**). Growing degree-days were calculated using 5 and 30 °C threshold temperatures.

essentially rain-free during the lettuce production period, and growers use a variety of irrigation systems and irrigation schedules. Most fields are irrigated with well water. Wells vary widely in NO_3-N concentration with most wells between 2 and 20 $mg\cdot L^{-1}$. All fields were sprinkler-irrigated for stand establishment with two fields switched to drip irrigation and one field switched to furrow irrigation after establishment. Soil texture ranged from sandy clay loam to clay. The planting configuration was either two plant rows per 1-m raised bed or five to six plant rows per 2-m raised bed; plant population varied from 72,000 to 112,000 ha. Preplant N fertilization was banded in the beds at rates ranging from 0 to 40 $kg\cdot ha^{-1}$.

Before the first sidedress N application, a strip plot in the center of each field was identified to receive a reduced N fertilization regime. These strip plots were the length of the field × 12 to 24 beds wide and averaged 0.4 ha. The width of the strip plot was set to accommodate one pass of the commercial harvest crew and equipment, which varied by grower. In all fields, the grower applied an N sidedressing 20 to 28 d after planting. Sidedress applications were typically applied in bands 5 to 10 cm deep in the bed; a variety of N fertilizers were used. The strip plot received either no sidedressing (14 fields) or a half rate sidedressing (two fields) at the cooperating growers' discretion. After the first sidedressing, the reduced N plots received all subsequent N fertilization applied by the grower, whether by additional sidedressing or by fertigation.

Soil samples (0 to 30 cm depth in the plant row) were taken before the first N sidedressing and repeated on 7- to 10-d intervals until harvest. Samples were collected separately from the head and tail ends of the reduced N plot. Samples of the grower N regime from the head and tail ends of the field were collected from the areas adjacent to the reduced N plot; samples drawn from each side of the reduced N plot were blended so that for each sampling date, a total of four composite samples per field was collected; each comprised of eight to 10 cores. Matching samples of whole plants and recently mature leaves were also collected at each soil sampling date after the initial N sidedressing. Each of the four composite samples per field per collection date contained 12 whole plants and 20 leaves; the leaves were subsequently divided into blade and midrib samples. Plant, leaf, and midrib samples were oven-dried at 65 °C to a constant weight and ground to pass a 40-mesh screen. N concentration of whole plants and leaf blades was determined by a N gas analyzer (Model FP-528; LECO Corp., St. Joseph, MI). Midrib NO_3-N was measured by flow injection analysis (Lachat Instruments, Milwaukee, WI) after extraction with 2% acetic acid. Field-moist soil was extracted in 2 N KCl and analyzed for NO_3-N by the flow injection method. Plant population was determined based on post-thinning plant counts in four representative 4 m wide × 30-m long strips within the trial area of each field.

Just before commercial harvest, aboveground biomass was determined by the collection of 32 randomly selected whole plants in both the head and tail ends of the reduced N plot and in the adjacent grower N plots, as previously described. Subsamples were oven-dried, weighed, and analyzed for total N concentration. During the commercial harvest, the harvest crews recorded marketable yield separately in the reduced N strip and in the adjacent areas receiving the full grower N regime.

Replicated trials. Five replicated field trials were conducted in drip-irrigated commercial lettuce fields between 2007 and 2009. Three fields were planted with iceberg and two fields with romaine cultivars. All of the fields were sprinkler-irrigated for stand establishment and then switched to drip irrigation. Soil texture ranged from loam to clay loam. Fields were planted between 3 Mar. and 2 Aug. N fertilization treatments differed among fields based on the grower practices. Within fields, up to four levels of seasonal N application were established by eliminating

Table 2. Effect of nitrogen (N) fertigation on lettuce fresh biomass, and biomass N, in the replicated commercial drip-irrigated trials.

Trial	Yr	Lettuce type	Germination water date	Soil texture	Soil NO_3-N ($mg \cdot kg^{-1}$)[z]	N treatment	Number of fertigations	Seasonal N ($kg \cdot ha^{-1}$)	Fresh biomass ($Mg \cdot ha^{-1}$)	Biomass N ($kg \cdot ha^{-1}$)
1	2007	Iceberg	5 June	Loam	20	Grower	3	189	96 a[y]	116 a
						Reduced 1	1	103	93 a	102 b
						Reduced 2	0	47	81 b	94 b
2	2007	Iceberg	15 June	Loam	27	Grower	4	192	87 a	115 a
						Reduced 1	2	72	91 a	113 a
						Reduced 2	0	20	83 a	100 a
3	2007	Romaine	15 Aug	Loam	21	Grower	2	129	77 a	114 a
						Reduced	1	75	77 a	97 b
4	2008	Iceberg	3 March	Clay loam	20	Grower	4	236	94 a	128 a
						Reduced 1	3	183	97 a	133 a
						Reduced 2	2	140	92 a	111 a
						Reduced 3	1	86	84 b	108 a
5	2009	Romaine	2 Aug	Loam	21	Grower	3	175	77 a	134 a
						Reduced	3	144	77 a	132 a

[z] Post-thinning, before treatment initiation.

[y] Means within columns and trials separated using the REGWQ multiple range test.

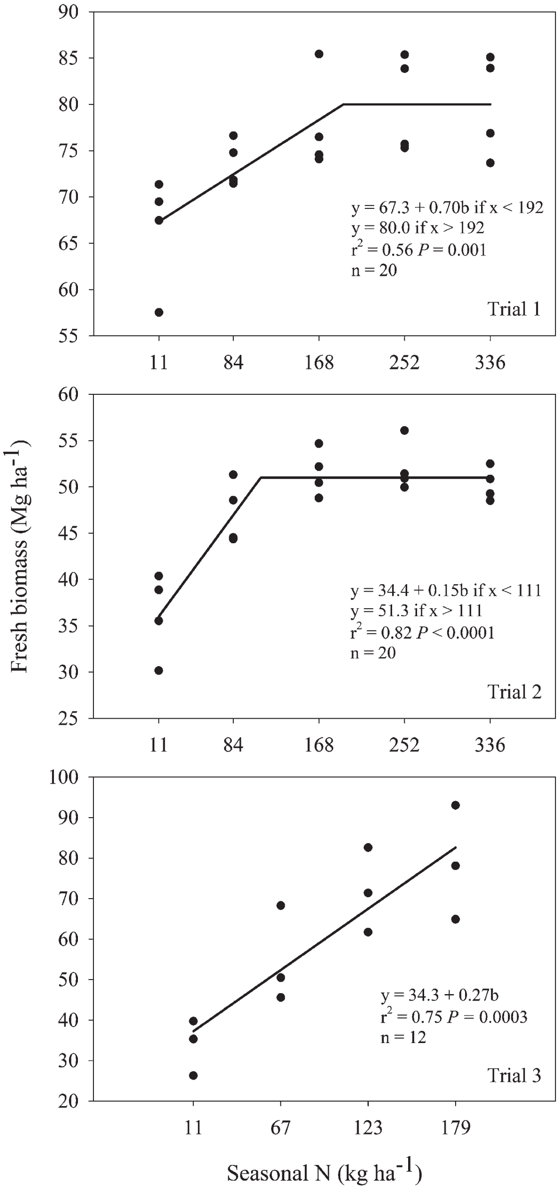

Fig. 2. Lettuce fresh biomass as affected by seasonal nitrogen (N) rate in research farm trials; linear-plateau models fit by the method of Waugh et al. (1973).

one or more of the grower N fertigations. All fields had soil NO_3-N greater than 20 $mg \cdot kg^{-1}$ (0 to 30 cm depth) at the time of the initial in-season N application. A randomized complete block experimental design was used in all fields with four replications per N treatment. Individual plots were four 1-m beds wide × 9 to 15 m long. Data were collected on the middle two beds of each plot. Soil, whole plant, leaf, and midrib sampling was done on 7- to 10-d intervals as previously described. The final plant sampling was conducted just before commercial harvest. Fresh and dry biomass of 24 randomly selected whole plants per plot was determined.

Three additional N rate trials were conducted between 2009 and 2010 at the Hartnell College research farm in Salinas, CA. All trials were seeded with romaine cultivars and grown using drip irrigation. Each trial was organized in a randomized complete block design with four replications (Trials 1 and 2) or three replications (Trial 3) per N rate. Each plot consisted of two 1 m wide beds 50 m long. Seasonal N rates ranged from 11 to 336 $kg \cdot ha^{-1}$ (Trials 1 and 2) and from 11 to 179 $kg \cdot ha^{-1}$ (Trial 3). N was applied preplant (11 $kg \cdot ha^{-1}$) and in three fertigations at ≈4, 5, and 6 weeks post-planting. Soil NO_3-N (0 to 30 cm depth) at the first N fertigation was 13, 9, and 7 $mg \cdot kg^{-1}$ in Fields 1, 2, and 3, respectively. At commercial maturity, aboveground biomass was determined on 80 randomly selected whole plants per plot.

Calculation of growing degree-days. To allow comparison of lettuce growth across fields and production seasons, growing degree-days (GDDs) were calculated from air temperature data provided by the California Irrigation Management Information System (Pruitt et al., 1987). GDDs were calculated using a single sine method (Allen, 1976) with upper and lower thresholds of 30 and 5 °C, respectively. GDD accumulation began on the day of the first irrigation rather than at seeding because seeding was typically done in dry soil.

Statistical analysis. Parallel line analysis was used to compare the regression slopes of romaine and iceberg lettuce dry biomass accumulation over time using SigmaPlot (Systat Software, Inc., San Jose, CA). All other statistical analyses were conducted using the SAS statistical package (SAS Institute, Cary, NC). Comparison of the crop biomass of the grower and reduced N management treatments in the strip trials was done with the GLM procedure using fields as replications to evaluate the reliability of the 20 mg·kg^{-1} PSNT residual soil NO_3-N threshold as a diagnostic tool to improve N management. Comparison of lettuce biomass among N treatments in the replicated commercial trials was accomplished using the GLM procedure and the REGWQ multiple range test. Optimum N rates in the research farm trials were estimated by the linear-plateau model described by Waugh et al. (1973) using the NLIN procedure.

Results

Aboveground lettuce fresh biomass in the reduced N treatment was not different from the grower N management treatment in the strip trials (P = 0.92), confirming the reliability of PSNT in identifying fields in which the first sidedress N application could be reduced or delayed (Table 1). Across the 16 fields, total fresh biomass at harvest averaged 89.9 and 89.3 Mg·ha^{-1} in the grower N and reduced N treatments, respectively. Marketable yield was obtained from the commercial harvest crews in 12 of the fields, and the reduced N treatment averaged 41.0 Mg·ha^{-1} compared with 40.8 Mg·ha^{-1} in the grower N treatment (P = 0.97). Seasonal N application (including preplant fertilization) averaged 150 and 73 kg·ha^{-1} in the grower N and reduced N treatments, respectively. Aboveground biomass N in the reduced N treatment averaged 151 kg·ha^{-1} compared with 156 kg·ha^{-1} in the grower N treatment, suggesting inefficient use of the N applied at first sidedressing, which averaged 77 kg·ha^{-1}.

Lettuce showed a characteristic growth pattern across the strip trial fields (Fig. 1A–B). Aboveground dry biomass accumulation averaged less than 0.3 Mg·ha^{-1} over the first 300 GDD (≈3 to 4 weeks at Salinas Valley temperatures) and then increased in a linear fashion until harvest. There was no significant difference between iceberg and romaine lettuce in DM accumulation [regression slopes during the rapid growth phase were not significantly different (P = 0.51)]. There was a trend toward higher DM with increasing plant population [DM (Mg·ha^{-1}) = 0. 00003 (plants/ha) +1.44, r^2 = 0.14, P = 0.08]. Biomass N accumulation followed the same pattern as biomass accumulation (Fig. 1C–D). N uptake during the linear growth phase averaged 0.38 kg/GDD across N treatments and fields; at 10 to 12 GDD/d during the production season, daily aboveground N accumulation averaged ≈3.8 to 4.6 kg·ha^{-1}.

The replicated commercial trials also demonstrated that N fertigation could be reduced below current grower practice with no reduction in crop biomass (Table 2). Significant fresh biomass reduction was observed in only two of five fields and only in treatments in which multiple N fertigations were eliminated. In both cases of biomass reduction, the midseason soil NO_3-N had decreased to less than 10 mg·kg^{-1}. A significant response to N fertigation was observed in all research farm trials (Fig. 2). Seasonal N rates between 111 and 192 kg·ha^{-1} were sufficient to maximize fresh biomass, somewhat higher than observed in the other trials. The research farm trials began with lower residual soil NO_3-N (7 to 13 mg·kg^{-1}), and they followed a fallow period, whereas most of the commercial fields were planted after residue incorporation from a spring crop.

Collectively, these 24 trials provided extensive data on lettuce growth and plant N status on which to apply the "critical N concentration" concept (N_c, the minimum whole plant N concentration required to maximize growth; Greenwood et al., 1991; Fig. 3). Data points identified as N-deficient represented treatments in replicated trials in which DM was significantly (P < 0.05) below that of the highest N rate in that trial on a given sample date. Data points identified as "grower N" represented the grower N management in the strip trials and the replicated commercial trials plus the highest N rate in the research farm trials. Points identified as "reduced N" represented reduced N treatments from all strip trials plus reduced N treatments from replicated trials for which DM was not statistically different (P > 0.05) from the grower N treatment on a given sample date. The critical N equation [N_c = 45.6 DM (Mg·ha^{-1})$^{-0.357}$], developed in a 3-year study of lettuce in Italy by Tei et al. (2003), generally distinguished N deficiency from sufficiency. However, that equation had been validated only for DM values between 0.9 and 3.4 Mg·ha^{-1} and was clearly inappropriate for earlier growth stages. We empirically fit a linear function (N_c = 42.0 – 2.8 DM), which distinguished N-deficient from N-sufficient samples with reasonable accuracy across the entire season.

Based on the empirically derived N_c equation, the crop N uptake required to maintain whole plant N above the N_c (critical N uptake, N_{upt} = –2.8 DM^2 + 42 DM) was compared with actual crop N uptake of the grower N treatment in the commercial field trials (Fig. 4). Aboveground DM at harvest in the grower N treatment ranged from 2.4 to 5.4 Mg·ha^{-1}, and N uptake ranged from 94 to 200 kg·ha^{-1}, averaging 145 kg·ha^{-1}. The calculated N_{upt} ranged from 86 to 145 kg·ha^{-1}, averaging only 116 kg·ha^{-1}, indicating that a substantial amount of "luxury" uptake occurred

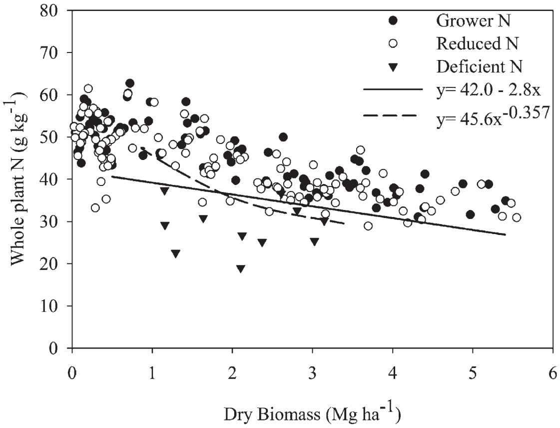

Fig. 3. The relationship between dry biomass (DM) and whole plant nitrogen (N) concentration. Dashed line represents plant critical N concentration (N_c = 45.6 DM$^{-0.357}$) from Tei et al. (2003). Solid line represents N_c as an empirically derived linear function (N_c = 42.0 – 2.8 DM).

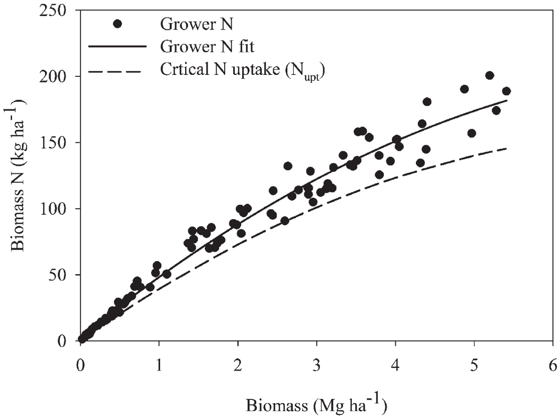

Fig. 4. Whole plant nitrogen (N) (all commercial field trials) as function of dry biomass (DM) for grower N treatment. Solid line represents grower N uptake (y = –2.8 DM^2 + 48 DM + 3); dashed line represents critical N uptake (N_{upt}, y = –2.8 DM^2 + 42 DM).

in these fields. N_{upt} during the rapid growth phase ranged between 3 and 4 kg·ha^{-1}·d^{-1} for Salinas Valley summer conditions.

Neither leaf N nor midrib NO_3-N was correlated with concurrently measured soil NO_3-N during either early growth (less than 1.5 Mg·ha^{-1} biomass) or the heading stage (greater than 1.5 Mg·ha^{-1}; Fig. 5). This insensitivity across a wide range of soil NO_3-N suggested that these tissue diagnostics provided no insight on current soil N availability. Leaf N was correlated with whole plant N (Fig. 6A). However, there was substantial variability in that relationship, indicating that leaf N was not a dependable surrogate for whole plant N. Midrib NO_3-N was not correlated with whole plant N (Fig. 6B). Based on the limited number of N-deficient leaf and midrib samples encountered in this study, empirically derived critical levels appeared to be ≈40 g·kg^{-1} leaf N and 6 g·kg^{-1} midrib NO_3-N throughout the season (Fig. 7). However, the separation between deficient and sufficient samples was not clear, and applying these critical levels would have resulted in unnecessary fertilization in some fields. Given the limitations just described, using either tissue N diagnostic to guide N fertilization, in the absence of soil NO_3-N data, would not be warranted.

The average soil NO_3-N concentration in the top 30 cm at harvest in the strip trials was 20 and 14 mg·kg^{-1} for the grower N and reduced N treatments, respectively (Fig. 8). This difference in soil NO_3-N of 6 mg·kg^{-1} represented 23 kg N/ha in the top 30 cm, assuming a typical bulk density of 1.4 g·cm^{-3}. Taking into account the slight increase in crop N uptake (≈5 kg·ha^{-1}) obtained in the grower N treatment in these fields, less than half of the extra 77 kg·ha^{-1} N applied in that treatment was accounted for at harvest, suggesting substantial in-season leaching below 30 cm. At harvest, soil NO_3-N was less than 10 mg·kg^{-1} in the reduced-N treatment in nine of the 14 fields in which data were collected and below that level in the grower N treatment in six fields. This documented that high-yield lettuce production can be managed to minimize residual soil NO_3-N at the end of the season.

Discussion

Lettuce growth was maximized by seasonal N fertilization rates substantially below current typical grower practices. The reduced N treatment in the strip plot trials received an average of only 73 kg N/ha and produced biomass equivalent to the more heavily fertilized grower N treatment. In the replicated commercial fertigation trials, the lowest seasonal N rate achieving maximum biomass averaged only 102 kg N/ha. The presence of high residual soil NO_3-N in these fields, which is common in this production system (especially after a spring crop), was a major factor limiting fertilizer N requirements. In the absence of substantial residual soil NO_3-N, fertilizer N requirements would undoubtedly

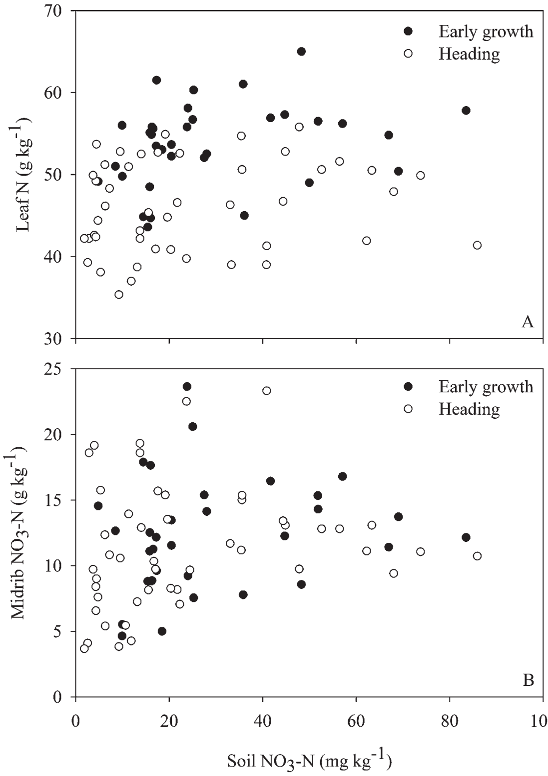

Fig. 5. Relationship between root zone soil NO_3-N and leaf nitrogen (N) (**A**) or midrib NO_3-N (**B**). Early growth and heading stages defined as dry biomass less than 1.5 Mg·ha^{-1} and greater than 1.5 Mg·ha^{-1}, respectively.

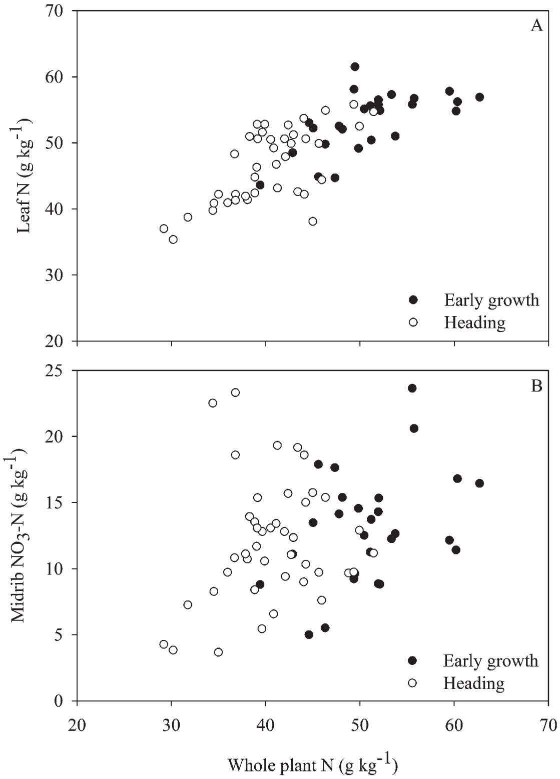

Fig. 6. Relationship between whole plant nitrogen (PN) concentration and leaf N (LN) concentration at the early growth (LN = 0.50 PN + 27.9, r^2 = 0.40) and heading stages (LN = 0.76 PN + 15.7, r^2 = 0.46, **A**). Relationship between PN concentration and midrib NO_3-N concentration at the early growth and heading stages (**B**). Early growth and heading stages defined as dry biomass less than 1.5 Mg·ha^{-1} and greater than 1.5 Mg·ha^{-1}, respectively.

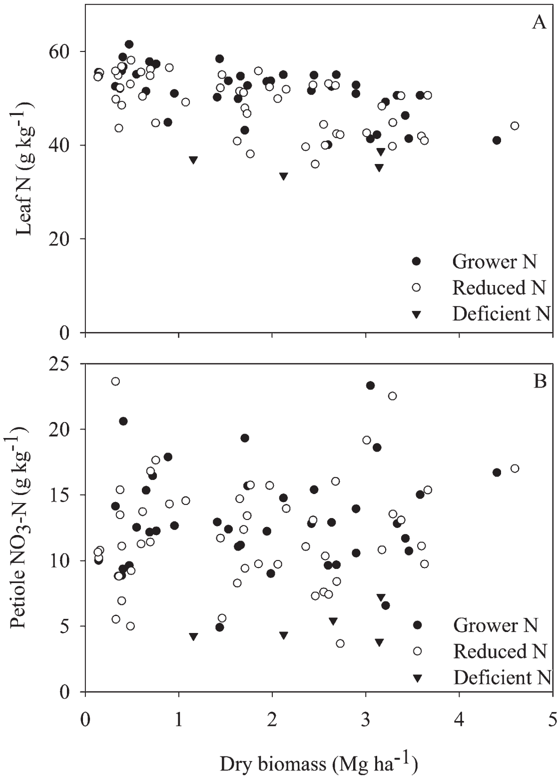

Fig. 7. Leaf nitrogen (N) (**A**) and midrib NO$_3$-N (**B**) as a function of dry biomass; data include all growth stages from all fields.

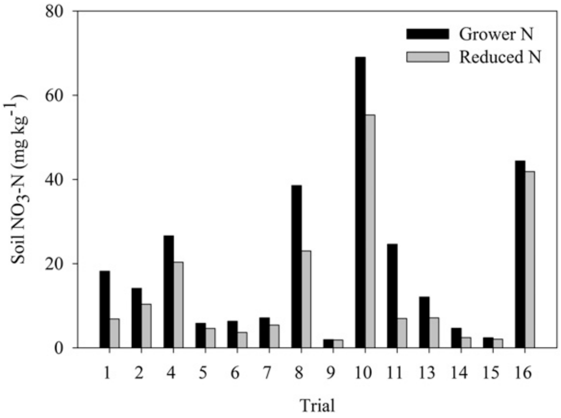

Fig. 8. Residual soil NO$_3$-N in the surface 30 cm at harvest in the strip trial fields.

be higher, as was the case in the research farm trials.

Crop uptake of the extra N applied in the grower N treatment was minimal. On average the apparent fertilizer recovery (AFR) of the N applied by growers at the first sidedressing was only 7% in the strip trials. In the replicated commercial fertigation trials, crop N uptake in the grower N treatment was on average only 13 kg·ha^{-1} higher than the lowest reduced N treatment that produced equivalent biomass, representing an AFR of 16% for the extra N applied by growers. Greenwood et al. (1989) reported that AFR in lettuce declined as N rate increased; at N rates greater than 100 kg·ha^{-1}, AFR was less than 15%. In this production system where multiple crops are produced annually, the overall AFR of N applied to a spring crop may be improved by subsequent recovery by a summer-planted crop. However, lettuce is shallowly rooted with most roots concentrated in the top 30 cm of soil (Jackson, 1995). The potential for NO$_3$-N leaching during the germination irrigation for the summer crop is substantial, and leaching losses with winter precipitation would be even more significant. Jackson et al. (1994) found that annual NO$_3$-N leaching loss in a double-cropped lettuce field in the Salinas Valley was ≈150 kg·ha^{-1}.

The reliability of PSNT in identifying lettuce fields in which N sidedressing can be reduced or delayed confirmed earlier California studies (Breschini and Hartz, 2002; Hartz et al., 2000). PSNT has been successfully applied to other crops, including cabbage (*Brassica oleracea* L. var. *capitata* L.; Heckman et al., 2002), celery (*Apium graveolens* L.; Hartz et al., 2000), and corn (*Zea mays* L.; Fox et al., 1989; Heckman et al., 1995); action thresholds have ranged from 20 to 30 mg·kg^{-1} soil NO$_3$-N. Most prior research on PSNT evaluated this approach as a once per season test to determine sidedress N requirements. However, for high-value vegetable crops on which multiple in-season N applications are common, repeated soil testing would allow growers more flexibility and confidence. Breschini and Hartz (2002) successfully demonstrated such a system in lettuce, testing soil NO$_3$-N up to three times per crop and on each occasion applying only enough N to bring the soil up to a 20 mg·kg^{-1} NO$_3$-N threshold.

Based on the observed lettuce N uptake requirements in the weeks before harvest (3 to 4 kg·ha^{-1}·d^{-1}), and the assumption that most N uptake occurs in the top 30 cm of soil, plant N uptake would be expected to reduce root zone soil NO$_3$-N by no more than 1 mg·kg^{-1}·d^{-1}. Soil testing for the final time 2 weeks before expected harvest, and limiting N application to no more than the amount required to return the soil to 20 mg·kg^{-1} NO$_3$-N, should provide sufficient mineral N for maximum crop productivity while finishing the season with a moderate level of residual soil NO$_3$-N. The observation that soil NO$_3$-N at harvest in the reduced N treatment was less than 10 mg·kg^{-1} in most fields confirmed that such low season-ending soil NO$_3$-N was not growth-limiting. Minimizing residual soil NO$_3$-N at harvest is a crucial element in a groundwater protection program.

In contrast to the documented use of soil NO$_3$-N monitoring to guide in-season N fertilization, plant-based diagnostics were less useful. The close agreement of our data with that of Tei et al. (2003) regarding N_c suggested that whole plant N was a robust measure of N sufficiency. Early-season whole plant N could be a practical monitoring technique, and our empirical N_c equation suggested a pre-heading critical threshold of ≈40 g·kg^{-1}. As plants get larger, whole plant sampling becomes impractical. The correlation between leaf N and whole plant N was unsatisfactory to make it a precise surrogate for whole plant N. Leaf N was not correlated with soil NO$_3$-N over a range of soil values from very high (greater than 40 mg·kg^{-1}) to potentially growth-limiting (less than 5 mg·kg^{-1}). Maier et al. (1990) and Westerveld et al. (2003) found that leaf N critical level varied by cultivar and location. Such confounding effects may explain the variability in published diagnostic guidelines. Lorenz and Tyler (1983) reported a leaf N sufficiency threshold for lettuce at harvest of 25 g·kg^{-1}, whereas Jones et al. (1991) suggested 38 g·kg^{-1}. Our data agreed with Jones et al.

The practical value of midrib NO$_3$-N monitoring was particularly questionable. Midrib NO$_3$-N was unrelated to either soil

NO_3-N or whole plant N. Midrib (petiole) NO_3-N has been shown to be affected by environmental conditions unrelated to soil N availability (Bates, 1971; Maynard et al., 1976) or to crop N uptake (MacKerron et al., 1995). The much higher degree of variability in midrib NO_3-N encountered in the present study (samples ranged from 4 to 24 $g \cdot kg^{-1}$) compared with either whole plant N or leaf N suggested that the rate of nitrate reduction in the plant was influenced by factors unrelated to soil NO_3-N availability or plant N status.

All plant-based N monitoring techniques share a fundamental limitation as a water quality protection practice. They can provide an indication of current crop N status. However, given the insensitivity of plant diagnostics to soil NO_3-N availability, a sufficient tissue N value provides no indication of future N fertilization requirements and therefore cannot accurately identify fields where in-season N application can be reduced or delayed.

In summary, seasonal N uptake in commercial lettuce fields averaged 145 $kg \cdot ha^{-1}$ with uptake over the last half of the growing season averaging $\approx$4 kg N/ha/d. Current commercial N fertilization rates can be reduced substantially with no reduction of crop yield. PSNT was a reliable technique on which to base N fertilization. Leaf N and midrib NO_3-N monitoring were of limited value in guiding in-season N management.

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