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Presidedress Soil Nitrate Testing Reduces Nitrogen Fertilizer Use and Nitrate Leaching Hazard in Lettuce Production

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Abstract. **Trials were conducted in 15 commercial fields in the central coast region of California in 1999 and 2000 to evaluate the use of presidedress soil nitrate testing (PSNT) to determine sidedress N requirements for production of iceberg and romaine lettuce (*Lactuca sativa* L.). In each field a large plot (0.2–1.2 ha) was established in which sidedress N application was based on presidedress soil NO_3-N concentration. Prior to each sidedress N application scheduled by the cooperating growers, a composite soil sample (top 30 cm) was collected and analyzed for NO_3-N. No fertilizer was applied in the PSNT plot at that sidedressing if NO_3-N was >20 mg·kg^{-1}; if NO_3-N was lower than that threshold, only enough N was applied to increase soil available N to ≈20 mg·kg^{-1}. The productivity and N status of PSNT plots were compared to adjacent plots receiving the growers' standard N fertilization. Cooperating growers applied a seasonal average of 257 kg·ha^{-1} N, including one to three sidedressings containing 194 kg·ha^{-1} N. Sidedressing based on PSNT decreased total seasonal and sidedress N application by an average of 43% and 57%, respectively. The majority of the N savings achieved with PSNT occurred at the first sidedressing. There was no significant difference between PSNT and grower N management across fields in lettuce yield or postharvest quality, and only small differences in crop N uptake. At harvest, PSNT plots had on average 8 mg·kg^{-1} lower residual NO_3-N in the top 90 cm of soil than the grower fertilization rate plots, indicating a substantial reduction in subsequent NO_3-N leaching hazard. We conclude that PSNT is a reliable management tool that can substantially reduce unnecessary N fertilization in lettuce production.**

The use of nitrogen fertilizer is coming under increased scrutiny in many parts of the United States due to concern over nitrate contamination of groundwater. Groundwater nitrate contamination is of particular concern in the coastal valleys of central California, where many wells now exceed the U.S. Environmental Protection Agency drinking water standard of 10 mg·kg^{-1} NO_3-N. Vegetable production dominates agriculture in these valleys, with lettuce by far the most common crop. Seasonal N application >200 kg·ha^{-1} is common for lettuce production (Hartz et al., 2000), substantially more than crop N uptake, and perhaps three times the amount of N removed in harvested product (Doerge et al., 1991; Zink and Yamaguchi, 1962). Similar imbalance between the amount of N applied and that removed in harvested product exists for the other common vegetable crops grown in rotation with lettuce in this region.

Such high rates of fertilization are due in part to conflicting research results, and in part to economic relationships. Gardner and Pew (1972, 1974) found that head lettuce yield peaked with N at 100–150 kg·ha^{-1}, while Welch et al. (1979) and MacKay and Chipman (1961) reported yield increase up to at least 250 kg·ha^{-1}. Given the high potential value of lettuce (frequently exceeding $10,000 per ha), exacting market standards for size and appearance, and the low cost of fertilizer N (currently ≈$0.80–1.20 per kilogram) there has been little economic incentive to minimize N application in the absence of regulatory pressure. Such pressure is now being brought to bear.

Presidedress soil nitrate testing (PSNT) is a potential strategy for minimizing unnecessary N application. PSNT has been widely shown to identify corn fields in which crop response to sidedressed N was unlikely (Fox et al., 1989; Heckman et al., 1995; Magdoff, 1991; Meisinger et al., 1992; Schmitt and Randall, 1994; Spellman et al., 1996). These studies reported that a soil NO_3–N concentration (top 30 cm) greater than ≈20 mg·kg^{-1} when corn was 15 cm tall (the stage at which sidedressing is usually done) indicated that no sidedress N was required to achieve maximum yield. Hartz et al. (2000), working in California, found this 20 mg·kg^{-1} NO_3-N threshold successfully identified lettuce and celery fields in which sidedress N application could be delayed or eliminated. They did not attempt to use PSNT to predict sidedress N requirements in fields below 20 mg·kg^{-1}. The current study was undertaken to evaluate the utility of PSNT as a general N management technique in lettuce production, regardless of residual soil NO_3-N concentration. Our main objective was to document the effects of N management using PSNT on crop yield and quality, N application, and postseason NO_3-N leaching potential across a wide range of field conditions and management practices representative of the commercial industry.

Materials and Methods

Fifteen trials were conducted in commercial lettuce fields in the central coast region of California in 1999 and 2000. These fields were direct seeded from March through July, for harvest June through September (Table 1). Soils varied in texture from sandy loam to clay. A standard planting configuration of two plant rows per 1.0-m raised bed was used. Plant population varied among fields from 56,000 to 72,000 plants/ha. All trials were initially irrigated by sprinklers, with some fields switched to furrow irrigation during head development. In-season precipitation was negligible in all fields. All fields were chosen randomly, without reference to residual soil NO_3-N concentration.

In the center of each field a single plot was established in which sidedress N application was based on presidedress soil NO_3-N level. Prior to each sidedress N application sched-

Table 1. Location, soil type, and harvest dates for the lettuce trial sites.

Field	Field location	Soil type	Planting date	Harvest date
		1999		
1	Salinas	clay loam	23 Apr	1 July
2	Soledad	clay loam	25 Mar	16 June
3	Soledad	silt loam	21 Mar	7 June
4	Salinas	clay	21 Mar	14 June
5	Castroville	clay loam	4 June	12 Aug
6	Chualar	sandy loam	25 June	31 Aug
7	Soledad	clay loam	20 June	27 Aug
8	Salinas	clay	18 July	28 Sept.
9	Salinas	clay loam	16 July	24 Sept.
10	Soledad	silt loam	23 July	30 Sept.
11	Castroville[z]	clay loam	15 July	22 Sept.
		2000		
12	Pajaro Valley[z]	loam	22 May	24 July
13	Pajaro Valley[z]	clay loam	24 May	28 July
14	Castroville[z]	clay	5 July	6 Sept.
15	Soledad[z]	silt loam	15 July	13 Sept.

[z]Romaine lettuce field; all other fields were planted with iceberg lettuce cultivars.

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uled by the cooperating grower, composite soil samples (top 30 cm) were collected in both the PSNT plot and an adjacent plot receiving the grower's standard N regime. Soil was collected in the planted row to avoid sampling concentrated bands of fertilizer applied earlier in the season; for each plot at least 12 soil cores were collected and blended before analysis. Plots ranged in size among fields from ≈0.2–1.2 ha. Each plot covered the entire length of the field to ensure that variability in N status caused by irrigation effects was included.

Soil samples from the PSNT plots were analyzed for NO_3-N concentration by the "quick test" method described by Hartz et al. (2000). If soil NO_3-N exceeded 20 mg·kg^{-1}, no sidedress application was made at that time in the PSNT plot. At lower NO_3-N concentration the amount of sidedress N applied to the PSNT plot at that sidedressing varied based on the application schedule in Table 2. This schedule was calculated to bring the top 30 cm of soil approximately up to the 20 mg·kg^{-1} N threshold level, based on a typical mineral soil bulk density of 1.4 g·cm^{-3}. Most fields received two sidedress N applications, typically one following thinning (SD-1), and the second 2–4 weeks later at the "cupping" growth stage (SD-2). Five fields received a third sidedressing, while two fields received only one. Soil NO_3-N estimates from the "quick test" procedure were compared with NO_3-N concentration in 2 N KCl extracts of field-moist soil analyzed by the diffusion-conductivity technique of Carlson et al. (1990).

Plant N status was evaluated at SD-2 and at harvest. At SD-2 whole, recently expanded leaves, and midribs from such leaves, were collected. At harvest, tissue from harvested heads and from crop residue was collected. After oven drying and grinding the whole leaf, head and residue samples were analyzed for total N concentration by combustion (Carlo-Erba 1500, Fisons Instruments, Beverly, Mass). Midribs were extracted in 2% acetic acid and analyzed for NO_3-N concentration by the method of Carlson et al. (1990). To allow calculation of aboveground biomass N accumulation, 12 representative whole plants per N treatment per field were harvested, separated into marketable head and residue, and the dry mass of each determined.

Plots were harvested at commercial maturity by experienced personnel provided by the growers. Data collected included percentage of plants that were marketable, and marketable yield (number of cartons/ha if packaged for fresh market, or bulk mass/ha if harvested for processing into packaged salad mixes). In nine trials in 1999, the effect of N fertilization on postharvest quality was evaluated on 24 heads per N treatment per field. The heads were stored for 10–14 d at 5 °C, above the optimal storage temperature (Maynard and Hochmuth, 1997), to simulate the stress of improper commercial handling. The heads were then evaluated for visual quality, decay severity, and degree of discoloration from bruising or russet spotting. Visual quality was rated on a scale of 1 to 10, with 10 being ideal and 5 indicating the limit of marketability. Decay and discoloration were rated on a scale of 1 to 5, with 1 indicating no decay or discoloration, and 5 indicating severe decay or discoloration.

To document the fate of grower-applied N in excess of that applied in the PSNT plots, additional soil sampling was conducted at SD-1 and at harvest. Samples were collected to 90-cm depth, by 30-cm increments. Twelve soil cores per plot were collected from the planted row. NO_3-N concentration in 2 N KCl extracts of field-moist soil were determined by the method previously described. The change in soil profile NO_3-N concentration over the growing season was calculated.

The structure of the trials allowed no within-field statistical comparison. However, to statistically compare PSNT with grower N management across fields an overall ANOVA was performed, using each field as a replication.

Table 2. Amount of N applied at sidedressing, based on presidedress soil NO_3-N concentration.

Soil NO_3-N range[z] (mg·kg^{-1})	Sidedress N application (kg·ha^{-1})
0–5	90
5–10	57
10–15	45
15–20	22

[z]Estimated by the 'quick test' procedure

Results and Discussion

Initial (pre-SD-1) soil NO_3-N concentration ranged from 10 to 59 mg·kg^{-1}, averaging 32 mg·kg^{-1} (Table 3). Cooperating growers applied a seasonal average of N at 257 kg·ha^{-1}, including one to three sidedressings containing an average of 194 kg·ha^{-1} N. By contrast, total N applied in PSNT plots was 43% lower, with a reduction in sidedress N of 57%. The majority of N savings in the PSNT plots occurred at SD-1; in 11 of the 15 trials, SD-1 was eliminated; two fields received no sidedress N at all. NO_3-N concentration in irrigation water varied among sites from 4–16 mg·kg^{-1}. Assuming that in-season irrigation was ≈25–30 cm (Jackson et al., 1996), NO_3-N contained in the water was modest, averaging <25 kg·ha^{-1}.

Despite the large difference in fertilizer application at SD–1, PSNT and grower plots had similar midrib NO_3-N at SD-2, averaging 7.7 and 7.8 g·kg^{-1}, respectively. Most fields were above the 6 g·kg^{-1} sufficiency level for California-grown lettuce suggested by Lorenz and Tyler (1983). In fields 3 and 8, midrib NO_3-N concentration was low for both grower and PSNT plots (averaging 3.1 and 3.4 g·kg^{-1}, respectively), but N did not appear to be growth-limiting since whole-leaf total N in both plots in both fields was substantially above the 30 g·kg^{-1} sufficiency standard suggested by Lorenz and Tyler (1983). Across fields, mean whole-leaf N at SD-2 was 44 and 43 g·kg^{-1} in grower and PSNT plots, respectively. The diagnostic value of midrib NO_3-N at this growth stage was questionable, since it was not correlated ($P = 0.05$) to concurrently measured soil NO_3-N or whole-leaf total N. Both plots in all fields had total N concentration in harvested heads above the 25 g·kg^{-1} sufficiency level of Lorenz and Tyler (1983).

Total aboveground biomass N accumulation in the grower plots averaged only 5–6 kg·ha^{-1} higher than the PSNT plots despite the application of an additional 110 kg·ha^{-1} N, an exceedingly low uptake efficiency. Romaine lettuce averaged only 107 kg·ha^{-1} N in the grower plots compared to 130 kg·ha^{-1} N for iceberg lettuce.

Overall, there was no significant difference in marketable yield between the PSNT

Table 3. Soil NO_3-N concentration at sidedress 1 (SD-1), number of sidedress N applications, and seasonal N application rates.

Field	Soil NO_3-N[z] at SD-1	No. of sidedress applications	Total seasonal N (kg·ha^{-1})[y] Grower	Total seasonal N PSNT	Total sidedress N (kg·ha^{-1})[x] Grower	Total sidedress N PSNT
			1999			
1	27	3	365	198	331	163[x]
2	18	2	380	213	336	168[x]
3	37	3	240	138	213	111
4	10	3	304	257	235	190[w]
5	26	1	178	57	136	17[x]
6	59	3	309	131	180	0
7	39	2	343	161	230	44
8	15	2	222	163	161	104
9	26	2	282	146	247	111[x]
10	53	2	232	126	106	0
11	55	1	195	77	153	37[x]
			2000			
12	29	2	134	45	134	45
13	20	2	185	141	134	90
14	43	2	231	164	134	67
15	26	3	258	185	187	115[v]
Mean	**32**		**257**	**147**	**194**	**84**

[z]NO_3-N concentration by laboratory analysis.
[y]Represents all N applications, including preplant fertilization and early season water-run applications.
[x]Includes late-season water-run application in addition to sidedressing.
[w]Received 56 kg·ha^{-1} N at SD-3 through application error.
[v]Received 48 kg·ha^{-1} N at SD-3 through application error.

and grower treatments (Table 4). In individual fields either the PSNT or grower plots had as much as a 17% yield advantage, but these differences could be attributed to within-field spatial variability in vigor and plant population rather than an N response. The percentage of plants harvested was similar between treatments, and tissue N levels were generally well above established sufficiency standards.

There were no N treatment effects on postharvest quality (Table 4). Visual quality of the heads declined substantially during postharvest storage, but was still above the marketability threshold. The incidence of decay and discoloration was slight in most fields.

The NO_3-N "quick test" provided a reasonable estimate of soil NO_3-N across the wide range of concentration encountered in this study (r = 0.93, Fig. 1). While clearly less accurate than laboratory analysis, the quick test allowed timely, on-farm estimation of soil NO_3-N at relatively low cost (the NO_3-N test strips are <$0.50 each). The 20 $mg \cdot kg^{-1}$ NO_3-N threshold employed was robust enough to accommodate the degree of error associated with the quick test procedure, and spatial variability of soil NO_3-N.

From SD-1 to harvest, PSNT plots showed a large decline in NO_3-N in the upper 30 cm of soil (>12 $mg \cdot kg^{-1}$), while the decline in grower plots was only 5 $mg \cdot kg^{-1}$. Grower plots showed an increase in soil NO_3-N in the 30–90 cm region while PSNT plots showed a decline. Over the entire 0–90 cm soil profile the grower plots were enriched by an average of 3 $mg \cdot kg^{-1}$ NO_3-N, while the PSNT plots showed a decline of 5 $mg \cdot kg^{-1}$; this difference was significant at $P = 0.05$.

Nitrogen rates used by the cooperating growers were clearly higher than necessary to achieve maximum lettuce yield and quality. Despite a number of studies that suggested maximum lettuce yields could be obtained with 100–150 $kg \cdot ha^{-1}$ N (Gardner and Pew, 1972, 1974; Knott and Tavernetti, 1944; Lorenz and Minges, 1942), California growers are hesitant to use such conservative N rates. PSNT offers an objective mechanism to tailor sidedress N application to field-specific conditions.

Hartz et al. (2000) found a 20 $mg \cdot kg^{-1}$ PSNT threshold to be effective in identifying fields in which sidedressing could be delayed or eliminated without affecting crop yield. They did not attempt to use PSNT to determine sidedress rates in fields below the NO_3-N threshold level. The current study found that adjusting N sidedress application to bring soil NO_3-N up to the 20 $mg \cdot kg^{-1}$ threshold maintained lettuce productivity and quality. Neither of these PSNT studies was structured to include an N-deficient treatment; consequently, the 20 $mg \cdot kg^{-1}$ NO_3-N threshold employed may be higher than necessary. Further work is warranted to evaluate that issue. However, widespread adoption of the PSNT technique as employed here could substantially reduce industry-wide N use, perhaps by 40% or more.

Midrib NO_3-N testing to determine crop N status is widely used by commercial lettuce growers. This study calls into question the

Table 4. Effect of N treatment on lettuce yield and postharvest quality.

Field	N treatment	Marketable yield[z] (cartons/ha) 24s[y]	30s[y]	Total	Bulk mass ($kg \cdot ha^{-1}$)	% of plants harvested	Postharvest rating Visual quality	Decay	Discoloration
					1999				
1	Grower	2,380		2,380		78	6.8	1.8	1.3
	PSNT	2,207		2,207		74	6.7	1.5	1.5
2	Grower	1,878	185	2,063		81	7.1	1.3	1.8
	PSNT	1,804	181	1,985		80	7.2	1.3	1.8
3	Grower	2,100	227	2,327		90	7.0	2.1	2.5
	PSNT	2503	230	2,733		94	7.1	1.9	2.3
4	Grower	1,470	801	2,271		86	6.9	1.6	1.6
	PSNT	1,638	541	2,179		82	6.8	1.8	1.5
5	Grower	2,503		2,503		76	6.5	2.1	1.7
	PSNT	2,427		2,427		72	7.1	1.9	2.0
6	Grower				36,800				
	PSNT				38,800				
7	Grower	2,530		2,530		84	6.1	2.5	2.3
	PSNT	2,691		2,691		81	6.8	2.3	2.1
8	Grower	2,009	304	2,313		84			
	PSNT	1,913	282	2,195		83			
9	Grower	1,161		1,161		47	6.4	2.3	2.2
	PSNT	1,161		1,161		50	6.6	2.1	2.1
10	Grower	2,570	10	2,580		87	6.9	2.0	2.0
	PSNT	2,392	57	2,449		89	6.7	1.7	2.1
11	Grower				36,500		7.3	1.8	1.0
	PSNT				33,500		7.2	1.5	1.0
					2000				
12	Grower	2,318		2,318		93			
	PSNT	2,587		2,587		95			
13	Grower	2,184		2,184		81			
	PSNT	2,120		2,120		90			
14	Grower				41,800				
	PSNT				46,900				
15	Grower	2,829		2,829		99			
	PSNT	2,884		2,884		99			
Mean	**Grower**	**2,161**	**127**	**2,288**	**38,400**	**82**	**6.7**	**1.9**	**1.8**
	PSNT	**2,194**	**108**	**2,302**	**39,700**	**83**	**6.9**	**1.8**	**1.8**
		NS	NS	NS	NS	NS	NS	NS	NS

[z]Cartons/ha if boxed for fresh market; bulk weight if harvested for processing into salad mixes.
[y]Head count per carton.
[NS]PSNT and grower plots not significantly different across fields at $P = 0.05$.

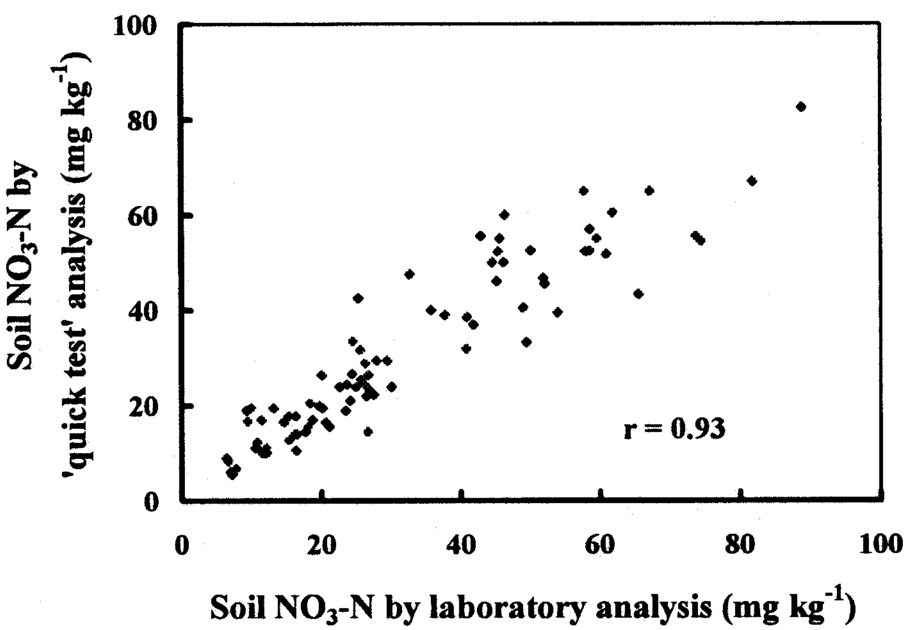

Fig. 1. Accuracy of the soil NO_3-N "quick test" procedure for estimation of soil NO_3-N concentration.

value of that technique to determine field-specific sidedress N requirements. At SD-1, the point at which the majority of N savings was realized by PSNT, plants are so small that insufficient tissue is available to collect the standard midrib sample. Furthermore, at SD-2 there was no correlation between midrib NO_3-N and currently available soil NO_3-N. Clearly, factors other than soil N availability have profound effects on midrib NO_3-N, severely limiting the value of that analysis at this early growth stage. We conclude, as did Hartz et al. (2000) and Pritchard et al. (1995), that soil testing is more appropriate than midrib testing to evaluate field N status, at least until SD-2.

Much of the excess fertilization in grower plots occurred early in the growing season; most of the N reduction in PSNT plots occurred at SD-1. Since more than 65% of lettuce N uptake occurs in the final third of the growing season (Gardner and Pew, 1979; Zink and Yamaguchi, 1963) heavy early-season applications are inherently inefficient. The similarity between N treatments in tissue N concentration at SD-2, and in biomass N accumulation, suggested that lettuce plants do not take up much of the fertilizer that is routinely applied early in the season.

Lettuce is an ideal crop on which to employ PSNT because lettuce has modest N requirements; biomass N accumulation averaged <130 $kg \cdot ha^{-1}$ in the test fields. Other common cool-season vegetables such as broccoli, cauliflower and celery typically contain >200 $kg \cdot ha^{-1}$ N at harvest (Doerge et al., 1991; Feigin et al., 1982; Letey et al., 1983; Welch et al., 1985). Effective use of PSNT for those crops may require either a higher soil NO_3-N threshold, or additional soil nitrate sampling later in the cropping cycle.

Lettuce is a shallowly rooted crop that is irrigated frequently (Jackson and Stivers, 1993). Therefore, substantial NO_3-N may be leached from the root zone, as shown by the net accumulation of NO_3-N in the 30–90 cm section of the soil profile of the grower plots. This accumulation of NO_3-N parallels the findings of Jackson et al., (1994), who reported that a double-cropped lettuce field lost as much as 150 $kg \cdot ha^{-1}$ N from nitrate leaching even with conservative fertilization (≈92 $kg \cdot ha^{-1}$ N per crop). The net NO_3-N decline in the top 90 cm of soil in PSNT plots suggested that subsequent leaching hazard had been substantially reduced, compared to the conventional grower N management.

In summary, PSNT was shown to be a reliable technique to minimize unnecessary sidedress N application. If widely adopted by the California industry a significant reduction in overall N usage could be achieved, with substantial reduction in groundwater pollution potential.

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