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Assessment of a Nitrate Meter for Nitrogen Tests in Mineral and Organic Soils

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ABSTRACT. Nutrient management legislation in Ontario, Canada, has prompted an evaluation of alternative nitrogen (N) management techniques. Rapid, accurate methods of assessing soil nitrogen are required to assist in N management. A portable nitrate (NO_3^-) meter (Cardy) was evaluated for use in testing soil N for vegetable crops grown on organic and mineral soils. Cabbage, carrots, and onions were grown on both soils in Ontario, Canada, in 2000 and 2001. Nitrogen was applied at five rates to cabbage and carrots, and three rates to onions ranging from 0 to 200% of current provincial recommended N rates. At three growth stages throughout the growing season, soil samples were collected and subdi-

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vided. One subsample was used for Cardy meter analysis, and the other for laboratory analysis of $\text{NO}_3\text{-N}$. Cardy $\text{NO}_3\text{-N}$ readings overestimated laboratory results in most instances on mineral soil, but consistently underestimated laboratory results on organic soil. A conversion factor would be required for both soil types, and 10 or more samples should be analyzed from a particular field to reduce variability. Soil $\text{NO}_3\text{-N}$ readings were variable among years and crops. Compared with laboratory analysis, Cardy soil test results are available in a fraction of the time required for laboratory results and are less expensive when analyzing over 100 samples. Yield was assessed at harvest. Yields were generally unaffected by N rate, except in cabbage in 2000, suggesting that adequate N was present in most treatments. The Cardy meter is effective in determining N sufficiency or deficiency in the field. The Cardy NO_3^- meter has potential as a field soil N test to supplement a nutrient management system for vegetable crops as long as region-specific recommendations are established. [Article copies available for a fee from The Haworth Document Delivery Service: 1-800-HAWORTH. E-mail address: <docdelivery@haworthpress.com> Website: <<http://www.HaworthPress.com>> © 2005 by The Haworth Press, Inc. All rights reserved.]

KEYWORDS. Cardy meters, ion selective electrode, nutrient management, soil analysis

INTRODUCTION

Soil analysis is one of the most important field diagnostic techniques used for nutrient management of vegetable crops in Ontario. Although soil nitrogen (N) tests are widely available, N levels in the soil are not often a component of standard soil tests. Provincial recommendations for fertilizer N in vegetable crops are not based on soil N levels because there is not enough calibration data available in the province to allow for any adjustments to fertilizer recommendations based on soil test results (J. Lauzon, Department of Land Resource Science, University of Guelph, personal communication). Although the use of soil N testing in general has been minimal for vegetables in the province, the recent introduction of nutrient management legislation is expected to increase the importance of soil N, or nitrate-N ($\text{NO}_3\text{-N}$), testing. Soil N testing is recommended for adjusting fertilizer N applications prior to planting (Everaarts, 1993), and prior to sidedressing (Roth et al., 1992; Warncke, 1996). However, few studies have been conducted to test the feasibility

of using soil $\text{NO}_3\text{-N}$ concentrations for N management of vegetable crops in this environment. Furthermore, to be useful as a pre-plant, or pre-sidedress, N management tool, results have to be quickly available and accurate to avoid delays in planting or correction at sidedress.

Portable soil nitrate (NO_3^-) tests are now available to provide a rapid indication of the soil N status. Nitrate is rarely adsorbed by soil particles, making it readily available to be measured by electrode methods (Talibudeen, 1991). There is also a lack of interfering ions in soil that complicate an electrode method (Talibudeen, 1991). The Horiba 'Cardy' NO_3^- meter (Horiba Co., Kyoto, Japan), which is predominately used for sap analysis (Hartz et al., 1993; Westcott et al., 1993; Warncke, 1996; Delgado and Follett, 1998; Westerveld et al., 2004), also can be used for a soil NO_3^- test. Cardy meter readings for soil NO_3^- determination were correlated with conventional laboratory results for mineral soil (Hartz et al., 1993). In a previous study, a strong linear correlation (mean $r = 0.82$) was shown to exist between Cardy meter soil $\text{NO}_3\text{-N}$ readings and laboratory soil $\text{NO}_3\text{-N}$ results in mineral or organic soil (Westerveld et al., 2003a). This research suggests that the Cardy meter can be used effectively as a supplement for laboratory analysis to provide an indication of soil $\text{NO}_3\text{-N}$ concentration ranges. In a recent study, it was shown that the use of critical tissue N and $\text{NO}_3\text{-N}$ concentrations, the predominant method of using tissue analysis results in the province, was not effective for vegetable crops due to variability in the field and poor matching of field data to published critical values (Westerveld et al., 2003b). It is unknown whether similar problems exist for soil analysis.

The objective of this study was to assess the potential of the Cardy meter as a soil NO_3^- test to supplement a nutrient management system for cabbage, onions, and carrots on mineral or organic soil based on its cost, ease of use, time required for each test, variability of results, and the potential use of critical meter readings as an indicator of N sufficiency.

MATERIALS AND METHODS

Carrots (*Daucus carota* subsp. *sativus* (Hoffm.) Arkang.) and onions (*Allium cepa* L.) were grown at the University of Guelph–Muck Crops Research Station (44° 15'N 77° 90'W), Holland/Bradford Marsh, Ontario in 2000 and 2001. The organic soil (pH 6.5) is a Hemic Histosol, containing 60% organic matter. Onions, cv. Hamlet, were direct-seeded (36 seeds/m) on 5 May 2000 and 7 May 2001 in eight, 5-m long, row

plots (two rows 'Hamlet' and six guard rows), with a 40-cm row spacing. Total yield was assessed at harvest on 18 Sept. 2000 and 10 Sept. 2001 from a 2.3-m long section of an inside row of each plot. Carrots, cv. Idaho, were direct-seeded (80 seeds/m) on 28 July 2000 and 24 May 2001 in four raised beds (two raised beds 'Idaho' and two guard rows), with beds being 20 cm high, 86 cm apart, and 5 m in length. Total yield was assessed at harvest on 17 Nov. 2000 and 25 Oct. 2001 from a 2.3-m section of an inside row of each plot.

Cabbage (*Brassica oleracea* var. *capitata* L.), carrots, and onions were grown at the University of Guelph-Simcoe Campus (42° 51'N 80° 16'W), Simcoe, Ontario, in 2000 and 2001. The mineral soil (pH 5.8-7.0) is a Typic Hapludalf, having organic matter content between 0.5 and 1.5%. 'Atlantis' cabbage was seeded in the greenhouse in 200-cell plastic plug trays on 10 May 2000 and 27 Apr. 2001 and seedlings were transplanted into the field on 9 June 2000 and 30 May 2001. Cabbage plots consisted of four rows, spaced 75 cm apart, 7 m (2000) and 9 m (2001) in length, and with an in-row spacing of 45 cm. Total yield was assessed at maturity on 16 Aug., 30 Aug., and 11 Sept. 2000 and 17 Aug. and 5 Sept. 2001 from 4-m long sections of the middle two rows of each plot. 'Winner' onions were direct-seeded into the field (10 seeds/m) on 14 June 2000 or seeded in the greenhouse in 200 cell plastic plug trays on 19 Mar. and transplanted to the field on 16 May 2001 in four row plots, with row spacing of 75 cm, and with an in-row spacing of 15 cm. Rows were 7 m (2000) or 6.5 m (2001) in length. Total yield was assessed at harvest on 16 Oct. from a 5-m section of an inside row of each plot (2000), and 21 Aug. from a 3.5-m section of the inside two rows of each plot (2001). 'Annapolis' (2000) and 'Idaho' (2001) carrots were direct-seeded (80 seeds/m) on 14 June 2000 and 13 June 2001 in three row plots, with an in-row spacing of 35 cm, 7 m in length, and with three guard rows between plots. Total yield was assessed at harvest on 6 Nov. 2000 and 24 Oct. 2001 from 2-m sections of each row.

Nitrogen treatments are summarized in Table 1. Nitrogen rates were based on the current provincial recommendations for each crop and soil type (OMAFRA, 2000). Nitrogen was broadcast preplant in all treatments as calcium ammonium nitrate and was side-dressed as potassium nitrate.

Soil samples were collected for Cardy meter testing and laboratory analysis at the cupping, early heading, and mature growth stages for cabbage; at the early (49-69 days after seeding), mid-season (71-98 days after seeding), and late (97-126 days after seeding) growth stages (only early and mid-season stage on organic soil in 2000) for carrots;

TABLE 1. Nitrogen treatments applied to cabbage, onions, and carrots on mineral and organic soil in 2000 and 2001.

Crop	Soil type	Treatment (% of recommended)	N Applied (kg·ha ⁻¹)	
			Preplant	Sidedress
Cabbage cv. 'Atlantis'	Mineral	0	0	0
		50	64	21
		100	128	42
		150	192	63
		200	256	84
Spanish Onion cv. 'Winner'	Mineral	0	0	0
		100	80	40
		200	160	80
Yellow Cooking Onion cv. 'Idaho'	Organic	0	0	0
		100	90	0
		200	180	0
Carrots cvs. 'Annapolis' (2000), 'Idaho' (2001)	Mineral	0	0	0
		50	37.5	17.5
		100	75	35
		150	112.5	52.5
		200	150	70
Carrots cv. 'Idaho'	Organic	0	0	0
		50	30	0
		100	60	0
		150	90	0
		200	120	0

and at the 5-leaf, early bulbing, and mature growth stages for onions. Eight to ten soil cores, 15-20 cm deep, were collected from each replicate at each growth stage. The depth of the soil cores was chosen because it is consistent with current practices. Since carrots were grown on 20-cm high raised beds on organic soil, soil samples were between 15 and 35 cm below the top of the hill. Soil samples were combined and divided into two portions. One portion was sent for laboratory analysis. Samples from four replications on mineral soil in 2000, and the first sample date in 2001 on both soil types, and three replications in all other sampling dates, were frozen and sent at a later date to A&L Laboratories East, Inc. (London, Ontario, Canada) in 2000, and to the University of

Guelph Soil and Nutrient Laboratory (Guelph, Ontario, Canada) in 2001 for $\text{NO}_3\text{-N}$ analysis. Both laboratories used a KCl-extraction method and automated colorimetric analysis for soil $\text{NO}_3\text{-N}$ analysis according to the method described by Maynard and Kalra (1993). The other portions of the soil samples were oven dried (70°C for 48 hrs) and tested with a Horiba 'Cardy' Model C-141 NO_3^- meter. For Cardy $\text{NO}_3\text{-N}$ analysis of mineral soil, $\text{NO}_3\text{-N}$ was extracted using 30 mL potassium nitrate/aluminum sulphate extractant ($20\text{ mg}\cdot\text{L}^{-1}$ $\text{NO}_3\text{-N}$) mixed with 30 cc of dried soil, stirred by hand for 2 min, and filtered (extractant and procedures provided by Spectrum Technologies, Plainfield, IL). Drops of filtered solution were placed on the sensing area of the meter. For organic soil $\text{NO}_3\text{-N}$ analysis in 2000, $\text{NO}_3\text{-N}$ was extracted using 100 mL distilled water to 50 cc of moist soil, which was stirred by hand for 2 min, left undisturbed for 10 min, filtered, and tested with the 1:2 (v/v) extraction soilless media testing procedures provided by Spectrum Technologies. The soilless media procedure for organic soil in 2000 was ineffective, and in 2001, organic soil was tested using the mineral soil procedure described above but using 60 mL of extractant instead of 30 mL, mixed with 30 cc of dry soil due to excessive absorption of extractant into the dried organic soil. To adjust for the $20\text{ mg}\cdot\text{kg}^{-1}$ $\text{NO}_3\text{-N}$ concentration of the extractant, $20\text{ mg}\cdot\text{kg}^{-1}$ was subtracted from all readings. For 2001 on organic soil, $20\text{ mg}\cdot\text{kg}^{-1}$ was subtracted and readings were doubled to account for the extra dilution in this procedure relative to the volume of extractant used in the mineral soil. The Cardy meter was calibrated using a $20\text{ mg}\cdot\text{kg}^{-1}$ and $450\text{ mg}\cdot\text{kg}^{-1}$ $\text{NO}_3\text{-N}$ standard solution provided with the meter.

All plots were arranged in a randomized complete block design with four replications. Statistical analysis was conducted using the GLM and Univariate procedure of SAS Version 8.0 (SAS Institute, Cary NC), and the linear models section of Statistix V.4.1 (Tallahassee, FL). A type I error rate of 0.05 or less was considered to be statistically significant in all tests.

RESULTS AND DISCUSSION

Yield: Total yield increased with increasing N rate up to 155% of the recommended rate in cabbage plots in 2000. In 2001, yield was not affected by N rate. In both years, cabbage maturity was delayed up to three weeks by rates below the recommended rate, suggesting that an N deficiency occurred in both years (Westerveld et al., 2003c). Yields of

onions and carrots were unaffected by N rate on both soil types. Carrot yield on organic soil was low in 2000, a result that was likely due to late planting after spring flooding. The lack of yield response in carrots or onions was expected since previous research in similar climates has shown little or no effect of N on onions (Riekels, 1971; Hamilton and Bernier, 1975; Shock et al., 2004) and carrots (Hamilton and Bernier, 1975; Sanderson and Ivany, 1997). The lack of yield effect in these studies was attributed to efficient use of N by these crops, and high soil N levels. Overall, yield data indicate that soil N levels were adequate for optimal yield in all plots except for cabbage in both years.

Cardy Soil NO₃-N Readings: Compared to laboratory results on mineral soil, the Cardy meter overestimated soil NO₃-N concentrations by 20.0% (SE $\pm$ 3.77%). This value was used to adjust Cardy readings and allow for comparison between Cardy readings and laboratory results (Tables 2, 3, and 4). The differences were more evident in the lower concentration range (3 to 10 mg·kg⁻¹), and more variable in comparison to the laboratory results. However, since the objective of the soil test is to determine if the crop has sufficient supply of N, and since the Cardy meter is seldom more than 3 mg·kg⁻¹ above or below the laboratory results within this range, the test would still be useful as an indicator of N sufficiency. On organic soil in 2000, when a soilless medium procedure was used, the readings were not comparable to laboratory results. In 2001, when a modified mineral soil procedure was used, the Cardy meter underestimated laboratory soil NO₃-N concentrations by 52.2% (SE $\pm$ 1.33%). This value was used to adjust Cardy readings and allow for comparison between Cardy readings and laboratory results (Tables 2, 3, and 4). The reason for the large discrepancy between Cardy and laboratory results on organic soil is not entirely clear. It is possible that some of the NO₃⁻ is tightly bound in the organic soil due to anion exchange, which has been discussed by Toner et al. (1989), and cannot be fully extracted during the Cardy soil test. However, since the differences between Cardy readings and laboratory results were relatively consistent among crops and sampling dates, the mean difference values could be used as conversion factors for each soil type. In a preliminary report of this research, a strong linear correlation was shown between meter readings and laboratory results on both soil types (Westerveld et al., 2003a). Examples of one of the strongest and weakest comparisons between Cardy and laboratory results from this report are shown in Figure 1 and Figure 2, respectively. Consequently, meter readings can be used to supplement a nutrient management system once

TABLE 2. Comparison of converted Cardy meter soil NO₃-N readings to laboratory soil NO₃-N concentrations in cabbage plots on mineral soil at three growth stages in 2000 and 2001.

N rate (% of recommended)	Growth stage					
	Cupping			Heading		
	mg.kg ⁻¹			mg.kg ⁻¹		
	Cardy NO ₃ -N	Z	Lab. soil NO ₃ -N	Cardy NO ₃ -N	Z	Lab. soil NO ₃ -N
2000	0	5.0 (1.13) ^Y	5.5 (0.96)	6.5 (1.46)	5.0 (0.71)	7.8 (1.15)
	50	9.6 (2.19)	8.0 (1.00)	8.2 (1.10)	5.8 (1.44)	9.4 (2.27)
	100	9.3 (1.91)	7.0 (0.91)	6.7 (1.08)	4.8 (0.25)	9.6 (1.88)
	150	7.7 (1.40)	13.3 (2.39)	7.5 (2.23)	8.5 (2.10)	11.5 (2.19)
	200	12.1 (4.09)	11.8 (4.21)	8.8 (1.88)	6.3 (0.75)	11.3 (0.73)
2001	0	13.3 (1.23)	13.0 (0.83)	9.8 (1.53)	8.3 (0.91)	9.2 (5.28)
	50	26.2 (3.43)	28.6 (2.49)	29.2 (10.87)	19.2 (9.04)	11.9 (5.86)
	100	30.0 (4.89)	40.5 (5.90)	35.8 (9.67)	28.0 (5.97)	34.0 (10.73)
	150	50.0 (9.79)	62.3 (6.25)	61.5 (14.87)	49.3 (12.22)	40.0 (6.63)
	200	60.7 (13.23)	81.0 (3.49)	85.4 (9.24)	89.3 (10.37)	106.3 (22.92)

^Z Reported readings were adjusted from meter readings using the following equation: original Cardy readings X conversion factor = reported readings. The conversion factor used was calculated based on overall mean differences between Cardy meter readings and laboratory results for all plots. Mineral soil conversion factor = 0.833.

^Y Value is mean (standard error).

TABLE 3. Comparison of converted Cardy meter soil NO₃-N readings to laboratory soil NO₃-N concentrations at three growth stages for onions grown on mineral and organic soil in 2000 and 2001.

N rate (% of recommended)	Growth stage							
	5-leaf		Bulbing				Maturity	
	Cardy NO ₃ -N ^Z	Lab. soil NO ₃ -N	Cardy NO ₃ -N ^Z	Lab. soil NO ₃ -N	Cardy NO ₃ -N ^Z	Lab. soil NO ₃ -N	Cardy NO ₃ -N ^Z	Lab. soil NO ₃ -N
Mineral Soil	----- mg.kg ⁻¹ -----							
2000	0	16.9 (4.71) ^Y	13.8 (3.15)	9.6 (1.54)	7.8 (1.18)	4.6 (0.73)	7.3 (0.25)	
	100	45.8 (11.40)	51.0 (17.34)	19.2 (7.63)	25.3 (9.76)	11.7 (3.03)	15.8 (4.40)	
	200	193.8 (16.80)	153.8 (18.55)	81.5 (18.80)	71.8 (14.15)	61.1 (12.96)	67.5 (12.10)	
2001	0	11.7 (1.89)	11.1 (1.82)	20.7 (4.33)	19.7 (5.17)	28.2 (8.20)	14.4 (2.39)	
	100	30.0 (1.02)	32.4 (3.57)	28.3 (2.83)	31.8 (3.68)	36.5 (7.81)	36.6 (11.45)	
	200	69.0 (9.03)	76.2 (2.76)	59.2 (17.09)	44.2 (6.57)	80.7 (11.19)	67.4 (11.06)	
Organic Soil								
2000	0	31.5 (3.93)	41.1 (3.95)	36.5 (4.29)	26.5 (4.26)	32.8 (2.66)	35.5 (6.80)	
	100	37.5 (5.74)	82.6 (13.29)	45.3 (5.11)	37.9 (6.81)	35.8 (3.59)	78.7 (22.32)	
	200	48.3 (6.33)	173.1 (18.09)	43.5 (6.24)	92.1 (14.07)	39.3 (4.84)	79.8 (17.82)	
2001	0	213.2 (16.97)	238.7 (13.03)	217.4 (27.99)	162.2 (9.21)	160.9 (6.94)	156.5 (14.90)	
	100	328.1 (56.43)	371.4 (56.00)	302.0 (55.61)	260.7 (56.98)	252.9 (27.96)	185.3 (31.22)	
	200	439.9 (54.38)	510.7 (34.86)	349.0 (48.68)	339.0 (20.09)	358.4 (75.47)	263.2 (64.78)	

^Z Reported readings were adjusted from meter readings using the following equation: original Cardy readings X conversion factor = reported readings. The conversion factor used was calculated based on overall mean differences between Cardy meter readings and laboratory results for all plots. 2001 organic soil conversion factor = 2.09, mineral soil conversion factor = 0.833, 2000 organic soil conversion factor not used.

^Y Value is mean (standard error).

TABLE 4. Comparison of converted Cardy meter soil NO₃-N readings to laboratory soil NO₃-N concentrations at three growth stages for carrots grown on mineral and organic soil in 2000 and 2001.

N rate (% of recommended)	Growth stage							
	Early				Mid-Season			
	Cardy NO ₃ -N Z		Lab. soil NO ₃ -N		Cardy NO ₃ -N Z		Lab. soil NO ₃ -N	
	mg·kg ⁻¹							
Mineral Soil	0	8.8 (1.62) Y	11.3 (1.65)	7.5 (0.76)	8.3 (1.49)	6.7 (0.34)	6.8 (0.85)	
	50	14.0 (1.10)	21.0 (1.47)	8.2 (0.63)	10.0 (0.41)	6.7 (0.59)	8.8 (1.65)	
	100	28.3 (5.15)	32.3 (4.73)	12.3 (1.99)	12.8 (2.10)	7.1 (1.10)	7.0 (0.71)	
	150	41.3 (11.33)	46.0 (10.90)	25.0 (3.78)	27.5 (3.38)	9.4 (2.99)	9.3 (1.97)	
	200	56.5 (10.90)	54.5 (10.54)	31.3 (3.80)	29.8 (1.49)	7.5 (0.76)	8.3 (1.70)	
2001	0	3.3 (0.59)	6.9 (1.92)	3.2 (0.40)	7.1 (1.33)	2.9 (0.24)	5.3 (0.15)	
	50	11.3 (3.93)	12.9 (3.45)	3.3 (0.34)	6.7 (1.72)	3.2 (0.71)	6.3 (1.35)	
	100	19.8 (7.94)	20.4 (5.04)	4.6 (0.73)	6.6 (0.38)	4.2 (0.48)	5.9 (0.17)	
	150	46.1 (21.08)	45.0 (13.72)	19.0 (8.38)	24.4 (6.09)	3.8 (0.54)	6.6 (1.57)	
	200	46.1 (9.55)	40.6 (8.87)	11.7 (1.02)	22.4 (1.41)	4.4 (0.71)	6.5 (1.85)	
Organic Soil	0	22.5 (2.40)	142.1 (8.73)	19.3 (1.89)	130.9 (4.04)	--	--	
	50	24.3 (1.32)	190.7 (24.53)	23.8 (3.01)	--	--	--	
	100	28.0 (2.04)	248.9 (21.23)	26.5 (2.53)	286.0 (58.71)	--	--	
	150	30.0 (2.61)	303.0 (28.73)	28.8 (2.69)	--	--	--	
	200	33.0 (3.76)	314.0 (36.75)	30.5 (3.01)	269.5 (54.19)	--	--	

2001	0	405.5 (60.90)	445.6 (48.90)	358.4 (23.91)	383.0 (33.91)	210.0 (31.12)	214.1 (10.59)
	50	386.7 (54.97)	478.4 (97.90)	352.2 (14.11)	408.8 (48.46)	272.7 (19.19)	242.5 (14.04)
	100	418.0 (45.14)	368.5 (26.06)	326.0 (33.80)	401.4 (13.54)	233.0 (42.53)	209.4 (20.17)
	150	574.8 (73.15)	454.2 (41.14)	365.8 (43.10)	405.6 (15.55)	341.7 (48.15)	293.0 (36.07)
	200	517.3 (90.04)	512.5 (44.20)	501.6 (61.53)	547.0 (45.47)	309.3 (75.39)	317.4 (46.51)

Z Reported readings were adjusted from meter readings using the following equation: original Cardy readings X conversion factor = reported readings. The conversion factor used was calculated based on overall mean differences between Cardy meter readings and laboratory results for all plots. 2001 organic soil conversion factor = 2.09, mineral soil conversion factor = 0.833, 2000 organic soil conversion factor not used.

Y Value is mean (standard error).

FIGURE 1. Comparison between laboratory and Cardy meter NO₃-N concentrations for mineral soil planted to carrots at the early growth stage in 2000 (r = 0.98).

FIGURE 2. Comparison between laboratory and Cardy meter NO₃-N concentrations for mineral soil planted to cabbage at the heading stage in 2000 (r = 0.50).

a conversion factor is established for a particular soil type, or critical soil Cardy readings are established for specific crop growth stages. Although the comparison between Cardy readings and laboratory results, and Cardy readings, showed similar variability. Consequently, use of one, or a small number of samples for either Cardy or laboratory

testing would be equally ineffective. The Cardy meter would be effective in most cases in identifying N deficiency even if readings are 2 or 3 $\text{mg}\cdot\text{kg}^{-1}$ out of range below 10 $\text{mg}\cdot\text{kg}^{-1}$ $\text{NO}_3\text{-N}$. Either laboratory or Cardy meter readings apparently should be used only as a guide, since variability among samples is large for both tests.

Soil $\text{NO}_3\text{-N}$ concentrations decreased during the growing season in most plots (Tables 2, 3, and 4). However, the magnitude of the decrease depended on the crop. Soil $\text{NO}_3\text{-N}$ concentrations in the cabbage plot in 2000, and in the onion plot in 2001, showed little change over the season on mineral soil (Tables 2 and 3). Nitrate-N concentrations in the carrot plots on mineral soil decreased substantially between the early and late growth stages (Table 4). The differences among the crops probably reflect differences in mineralization rates of the soils, the length of the growing season, losses from the system over the season, and N uptake of each crop. The cabbage plot in 2000 showed little change in $\text{NO}_3\text{-N}$ concentrations among the N rates and sampling dates, a result that was probably due to 82% above normal rainfall in May and June, and significant leaching as a result. The carrot and onion plots on mineral soil in 2000 were seeded and fertilized after the heaviest rainfall. Soil $\text{NO}_3\text{-N}$ concentrations in general were higher in organic soil than in mineral soil (Tables 2, 3, and 4), a result that was expected based on the 60-75% organic matter that is available to be mineralized during the season.

Nitrate results from laboratory and Cardy readings were generally consistent over the two years of the trial. With mineral soil, there were no differences in Cardy soil $\text{NO}_3\text{-N}$ readings between the two years at the mid-season, and late sampling dates, for carrots and the bulbing stage for onions. There were no differences in laboratory soil $\text{NO}_3\text{-N}$ readings between the two years for the mid-season growth stage for carrots and the bulbing and mature growth stages for onions. In all other cases on mineral soil, $\text{NO}_3\text{-N}$ readings were different between the two years, or data could not be combined due to year by treatment interactions. Due to differences in soil testing procedure between the two years on organic soil, no soil $\text{NO}_3\text{-N}$ comparisons between the two years were possible.

Using yield as an indicator of N sufficiency, the cabbage crop required greater than 10 $\text{mg}\cdot\text{kg}^{-1}$ soil $\text{NO}_3\text{-N}$ to achieve optimal yields at all three sampling stages (Table 2). It was not possible to establish critical soil $\text{NO}_3\text{-N}$ concentrations for onions and carrots due to the lack of yield response to N application in these crops. It appears that critical soil

$\text{NO}_3\text{-N}$ concentrations would have to be established for each crop and each growth phase. The critical levels determined for cabbage, based on the results of the Cardy meter would have been similar to the critical levels that would be established based on laboratory analysis. Critical values may have to be adjusted based on soil type, but it is unknown how much of a difference in soil texture is necessary to warrant the establishment of another critical value. Nitrogen deficiencies are rare in vegetable crops because fertilizers are a relatively cheap input and growers apply more than adequate amounts to avoid the risk of nutrient deficiencies. The greatest benefit of the Cardy meter would be to identify cases of overuse of N and to prevent NO_3^- losses into ground and surface water.

Meter Use: The Cardy meter soil $\text{NO}_3\text{-N}$ test is a relatively simple procedure. Consequently, it can be performed easily without any background in laboratory techniques. However, the procedure does have multiple steps that require some time and effort. Mineral soil testing with the Cardy meter was done using the procedures outlined by Spectrum Technologies in the soil test kits, but using half the recommended amount of soil and extractant. Testing organic soil required some modifications. Based on 2000 results, it was determined that a soilless media procedure was ineffective for organic soil testing. In 2001, the mineral soil testing procedure was used, but due to complete absorption of extractant into the dried organic soil at the mineral soil rate, twice as much extractant had to be used as for mineral soil. This modified mineral soil procedure for organic soil testing appears to be successful in quantifying soil $\text{NO}_3\text{-N}$ concentrations, even though a conversion factor is required to equate the results with laboratory analyses.

Time Requirements: The time required in testing mineral or organic soil with the Cardy meter is partially dependent on the number of samples. Generally, 10 samples can be tested in one hour. There is also the additional time involved in drying the soil (1 to 48 hr, depending on method). However, waiting for the results of laboratory analysis can take at least 72 hr. Consequently, the Cardy meter soil test results are available in a fraction of the time required for laboratory results as long as rapid drying procedures are used.

Cost: Cardy meter soil testing may be relatively inexpensive compared to laboratory testing depending on the number of samples tested (Table 5). There is a substantial initial cost of the meter, replacement sensors, and soil test kits. However, as the number of samples increases, laboratory costs can exceed the cost of the meter. After 500 samples tested, approximately the number of samples required to adequately

manage around five fields or sites biweekly for about five years, the cost of laboratory analysis (\$5.00 to 8.00/sample plus shipping or delivery costs) would exceed the cost of the Cardy meter and soil test kits (\$1.36 to 1.60/sample plus labor costs for 6 min/sample) (Table 5).

The Cardy NO_3^- meter can provide an effective soil N test if used properly. The meter should be used as a guide to supplement a nutrient management system that includes additional methods of nutrient analysis. As with laboratory analysis, appropriate numbers (5-10/field and date) of soil tests would be required to adequately test $\text{NO}_3\text{-N}$ concentrations in the field. Readings are consistently within the range of laboratory results using a conversion factor, and can be obtained in a fraction of the time and cost required for laboratory analysis. The most appropriate use of Cardy meter readings appears to be region-specific critical soil $\text{NO}_3\text{-N}$ concentrations established for each crop and growth phase, because of variability induced by climate and soil type. These critical concentrations would not be difficult to establish due to the ease of use of the meter. Significant fertilizer and timesaving could be achieved using a Cardy NO_3^- meter to manage fertilizer N applications and to identify high levels of $\text{NO}_3\text{-N}$ in the field prior to and during the growing season.

TABLE 5. Cost comparison of Cardy nitrate ($\text{NO}_3\text{-N}$) meter tests to laboratory soil testing.

Cost	Cardy $\text{NO}_3\text{-N}$ Meter (field) ^Z	Laboratory Soil Testing ^Z
Initial	\$360	\$0
Additional	\$80 ^Y + \$40 ^X	\$5-\$8 ^W
After 100 Samples	\$440-\$520	\$500-\$800
After 500 Samples	\$680-\$800	\$2500-\$4000

^Z All costs are in U.S. dollars in 2004.

^Y Sensors replaced every 200 samples tested.

^X Soil test kits for 30-60 samples.

^W Per sample cost for total nitrogen and $\text{NO}_3\text{-N}$ analysis only.

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