Vegetable Production Best Management Practices to Minimize Nutrient Loss

T.K. Hartz

ADDITIONAL INDEX WORDS. **nitrogen, phosphorus, environment, water quality, runoff, leaching**

SUMMARY. **Nutrient loss from commercial vegetable fields has become a significant environmental issue in all the major vegetable-producing regions of the United States. Growers are facing potentially disruptive regulations aimed at improving the quality of both surface and ground water. Significant improvement in nutrient management will be required to meet this regulatory challenge. This paper discusses five practical, low-cost nutrient best management practices (BMPs). These BMPs are widely applicable, relatively inexpensive to implement, and can dramatically reduce nitrogen and phosphorus loss from vegetable fields. However, even with careful application of these BMPs, runoff and leachate from vegetable fields may periodically exceed environmental water quality standards, which are very stringent.**

Commercial vegetable production presents a unique environmental challenge. Vegetable crops have high product value, and exacting market standards for size, color and quality; high fertilizer rates and frequent irrigation are typically employed to ensure optimal growth. Many vegetable crops are shallowly rooted, which limits fertilization and irrigation efficiency. Extensive tillage is practiced, and fields often have little or no foliage cover for extended periods. Consequently, vegetable production carries substantial environmental risk. Nitrate pollution of groundwater is a widespread problem in vegetable producing regions of the U.S., as is the runoff of nitrogen (N) and phosphorus (P) into surface waters. Across the country, sediment and nutrient loss from vegetable fields has become a focus of regulatory interest, and more stringent regulation of production practices is likely.

Nationwide, regulatory agencies are urging adoption of BMPs to protect water quality. Presented here are five BMP concepts that are widely applicable and, if applied appropriately, can dramatically reduce nutrient and sediment loss from vegetable fields.

BMP 1. Use preplant soil testing to determine P fertilization

Soil testing for P availability has been an established practice for decades. Growers of agronomic crops commonly consider soil test P (STP) when developing field-specific fertilizer programs. However, many vegetable growers ignore STP when determining P application rates. A recent survey of lettuce (*Lactuca sativa*) and cauliflower (*Brassica oleracea* var. *botrytis*) fields in the coastal valleys of California (T.K. Hartz, unpublished data) found no correlation between STP and P fertilization rate (Fig. 1). While some growers assumed soil P sufficiency and eliminated P application in fields with STP as low as 40 mg·kg^{-1} bicarbonate-extractable P, others continued to apply P in fields with STP more than three times that level. This results in needless expense for the grower, and progressive enrichment of soil P status. Given the strong correlation between STP and P loss in runoff or leaching (Hartz and Johnstone, 2006; McDowell and Sharpley, 2001; Sharpley, 1995), greater reliance on soil testing to determine P fertilization will be essential to reduce P loss from vegetable fields.

Among the reasons growers are reluctant to use soil tests to guide P fertilization are lack of confidence that laboratory extraction tests accurately estimate soil P bioavailability, and uncertainty as to what soil test level represents the crop response threshold. While it is true that no common laboratory test (e.g., bicarbonate, Mehlich, or Bray extraction) precisely predicts P bioavailability

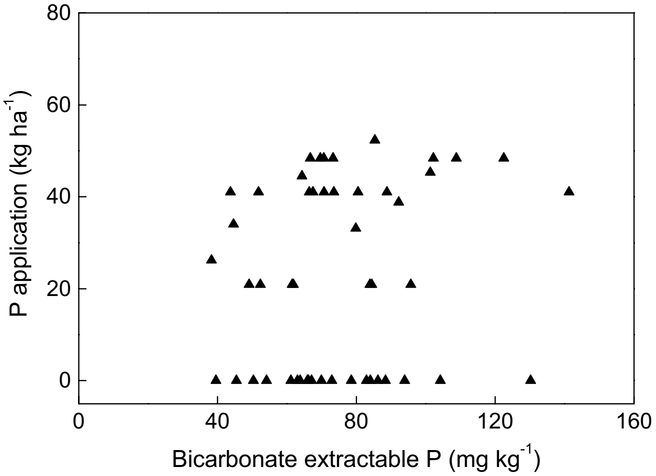

Fig. 1. Seasonal phosphorus (P) fertilization rate in lettuce and cauliflower fields as a function of bicarbonate-extractable soil P. Data from a 2004 survey of commercial fields in the coastal valleys of California (1 mg·kg^{-1} = 1 ppm; 1 kg·ha^{-1} = 0.8922 lb/acre).

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
2.54	inch(es)	cm	0.3937
1.1209	lb/acre	kg·ha^{-1}	0.8922
0.001	ppm	g·kg^{-1}	1000.
1	ppm	mg·kg^{-1}	1
1	ppm	mg·L^{-1}	1
2.2417	ton/acre	Mg·ha^{-1}	0.4461

Department of Plant Sciences, University of California, Davis, CA 95616.

across a wide range of soils and environmental conditions, these extraction tests are closely correlated with more direct measurements of soil P bioavailability such as P adsorbed on anion exchange resin (Burt et al., 2002; Hartz and Johnstone, 2006) or on iron-impregnated paper strips (Menon et al., 1997; Paulter and Sims, 2000). There is contradictory information regarding crop response thresholds; for example, reported STP thresholds for lettuce response have ranged from 25 $mg \cdot kg^{-1}$ (Reisenauer et al., 1983) to approximately 50 $mg \cdot kg^{-1}$ bicarbonate-extractable P (Johnstone et al., 2005). Growers may be warranted in using a small "insurance" application of P in fields with marginal STP. However, Figure 1 suggests that many vegetable growers persist in fertilizing fields with STP far exceeding the crop response threshold. This observation was corroborated by Johnstone et al. (2005), who, in a series of P fertilization trials in California lettuce fields, found that the cooperating growers applied P in 9 of 11 fields in which there was no response to P fertilization, including fields with >90 $mg \cdot kg^{-1}$ bicarbonate-extractable P.

To improve P management within the vegetable industry, both additional research to confirm crop-specific STP response thresholds and an expanded grower education campaign are needed. To be maximally effective in changing grower behavior such research, and any associated field demonstration projects, should be conducted on commercial farms because many growers harbor suspicions that research conducted in small plots on university facilities does not represent the "real-world" conditions on their farms. Also, growers may be more amenable to change when confronted with evidence that their neighbors are successfully utilizing soil test results to guide P application; Figure 1 documents that some growers have indeed eliminated P application in high-P soils. Convincing growers who continue to fertilize high-P fields to simply emulate their more efficient neighbors could significantly reduce P pollution potential.

BMP 2. Use an appropriate crop N fertilization template

Growers of a particular vegetable crop within a production region may use widely differing N fertilization programs. In conducting N fertilization trials in 10 commercial processing tomato (*Lycopersicon esculentum*) fields in central California, Krusekopf et al. (2002) found that grower N application varied among fields from 125 to 243 lb/acre N. Similarly, Breschini and Hartz (2002a) reported that, in fertilization studies in 15 California lettuce fields, seasonal N application by the cooperating growers ranged from 119 to 338 lb/acre N. While some variability was undoubtedly justified based on field-specific conditions, most of the difference in N rates among fields in these studies simply reflected different grower habits and attitudes. In the case of Krusekopf et al. (2002), no more than 100 lb/acre N was necessary to maximize tomato yield or fruit quality in any field, indicating that differing field conditions justified little of the variability in grower N rates.

Where available, university fertilizer rate recommendations can serve as a general N fertilization "template" for growers to plan seasonal fertilizer programs. In the absence of credible university recommendations, using the current industry average N rate as a template would allow the growers who fertilize most heavily to reduce what is clearly excessive N application. In either case, the general template should serve as an upper limit to seasonal N application, to be exceeded only where specific factors (such as abnormally heavy rainfall) can be identified that would justify greater fertilization. The template should be modified downward when field-specific factors (e.g., previous crop, preplant soil nitrate-nitrogen (NO_3-N) concentration, soil texture, and soil organic matter content) suggest an unusually high soil contribution to crop N fertility. However, the effects of these factors are difficult to quantify, given the complex interplay of N mineralization, denitrification, and leaching; in-season N monitoring is essential to confirm N fertilizer requirement.

BMP 3. Monitor in-season soil and plant N status

In commercial vegetable production only a small portion of seasonal N fertilization is usually applied preplant. This provides the opportunity to reevaluate N requirements during the season. In non-irrigated culture, or when furrow irrigation is used, most N is applied in one or two sidedressings before peak crop N uptake occurs. Most soil NO_3-N present at sidedressing will remain available for crop uptake, since crop N uptake rate is increasing at that point in the season, and subsequent in-season leaching losses tend to be small (Magdoff, 1991). Pre-sidedress soil nitrate testing (PSNT) can provide a direct measure of current mineral N concentration, eliminating the uncertainty associated with pre-plant estimates of soil N availability.

PSNT is a very useful tool for identifying fields in which additional N fertilization can be delayed or reduced. Originally developed for use with field corn (*Zea mays*) (Magdoff, 1991), this technique has been successfully adapted for use in cabbage (*B. oleracea* var. *capitata*), celery (*Apium graveolens* var. *dulce*), lettuce, sweet corn (*Z. mays* var. *saccharata*), and tomato production (Breschini and Hartz, 2002a; Hartz et al., 2000; Heckman et al., 1995, 2002; Krusekopf et al., 2002). Across crops and production regions, the soil NO_3-N threshold above which crop response to additional fertilization was unlikely ranged from approximately 20 to 25 $mg \cdot kg^{-1}$. In fields with soil NO_3-N below the response threshold, applying only enough fertilizer to bring the soil up to the threshold was an efficient practice (Breschini and Hartz, 2002a; Heckman et al., 2002). Sampling the top foot of soil has been the standard PSNT approach; for deep-rooted crops deeper soil sampling may be used, but the correlation of NO_3-N concentration of deeper samples with the surface foot of soil tends to be sufficiently strong to make deeper sampling unnecessary (Binford et al., 1992; Krusekopf et al., 2002).

The use of PSNT can be tailored to different cropping systems. For crops that typically receive only one sidedressing a single soil test is appropriate; for crops that receive multiple sidedressings, the test can be repeated prior to each. Where multiple sidedressings are applied, a lower PSNT response threshold may be appropriate than when a single sidedressing is done. Care must be exercised to collect samples representative of the active root zone, particularly avoiding zones of recent banded fertilizer application; while this may underestimate actual N availability, it avoids the economic risk of overestimating N availability and compromising crop production or quality. The potential to reduce N fertilization by using PSNT can be substantial; trials in commercial lettuce fields in California showed that seasonal N application could be reduced by >40% (Breschini and Hartz, 2002a; Hartz et al., 2000). The cost/benefit ratio of PSNT in these studies was very high, as Hartz et al. (2000) estimated that a reduction of 10 kg·ha^{-1} N would more than offset the monitoring costs.

PSNT can also be useful in drip-irrigated fields. With drip irrigation, N is often applied in small fertigations throughout the season, allowing a grower to tailor the fertigation program to match crop uptake (Hartz and Hochmuth, 1996). Early in the season PSNT can identify fields with significant residual NO_3-N, allowing a grower to delay the initiation of fertigation.

While PSNT has been shown to be a valuable tool in the production of a variety of crops in a wide range of production environments, it is not universally applicable. PSNT is maximally effective in situations where large sidedress N applications are made early in the cropping season, and in fields in which significant in-season leaching is unlikely. In vegetable production on light-textured soils in high rainfall environments, PSNT may have little applicability; under such circumstances other approaches (small N applications throughout the season, use of slow-release fertilizers, etc.) are more useful.

Plant tissue analysis is often advocated as a BMP. However, the practical value of plant analysis in improving N management in vegetable production has generally been overstated. An important limitation of plant analysis is that both leaf N and petiole NO_3-N are relatively insensitive indicators of current soil N availability, at least in fields of moderate to high N supply. Breschini and Hartz (2002a) provided evidence of such insensitivity in lettuce by documenting a lack of correlation between either midrib NO_3-N or leaf N and concurrently measured soil NO_3-N (Fig. 2). Pritchard et al. (1995) reported similar results with lettuce, concluding that plant analysis was an insensitive diagnostic tool for N management during the first half of the growing season, the time when most N application occurs. In lettuce, broccoli (*B. oleracea* var. *italica*), and cauliflower fertilization trials in Arizona, Sanchez (1998) showed that midrib NO_3-N incorrectly predicted crop response to sidedress N fertilization in approximately half of the trials. Westerveld et al. (2003) similarly found tissue analysis to be unreliable in predicting sidedress N requirement in cabbage, carrot (*Daucus carota*), and onion (*Allium cepa*) production in Canada.

A fundamental problem with tissue analysis is that cultivar- and field-specific factors confound the relationship between soil N availability and tissue N level. In both the reports of Breschini and Hartz (2002a) and Krusekopk et al. (2002), tissue N varied considerably more among fields than between N fertilizer rates within fields, even when those N rates varied by more than 100 kg·ha^{-1}.

Taken together, these reports strongly suggest that conventional plant tissue analysis, while a potentially useful technique to detect N deficiency, is generally ineffective in helping vegetable growers reduce unnecessary N application. In recent years an alternative approach to plant analysis, the evaluation of leaf color using the SPAD chlorophyll meter (Minolta Corp., Kyoto, Japan), has been extensively evaluated (Blackmer and Schepers, 1995; Piekielek and Fox, 1992; Schroder et al., 2000: Tremblay, 2004; Westerveld et al., 2004). The initial cost of the SPAD meter is substantial (approximately $1400), but there are no recurring costs for monitoring other than labor. The meter provides a leaf chlorophyll index (LCI), which is correlated with leaf N status. Since the relationship of leaf chlorophyll index (LCI) to leaf N can be confounded by cultivar, soil, and environmental factors, the comparison of LCI of a field to that of well-fertilized in-field "reference" plots increases the utility of the measurement (Schroder et al., 2000: Tremblay, 2004; Westerveld et al., 2004). Delaying additional fertilization as long as the field LCI remains within 5% to 10% of the reference plot LCI shows promise as a technique to improve N management.

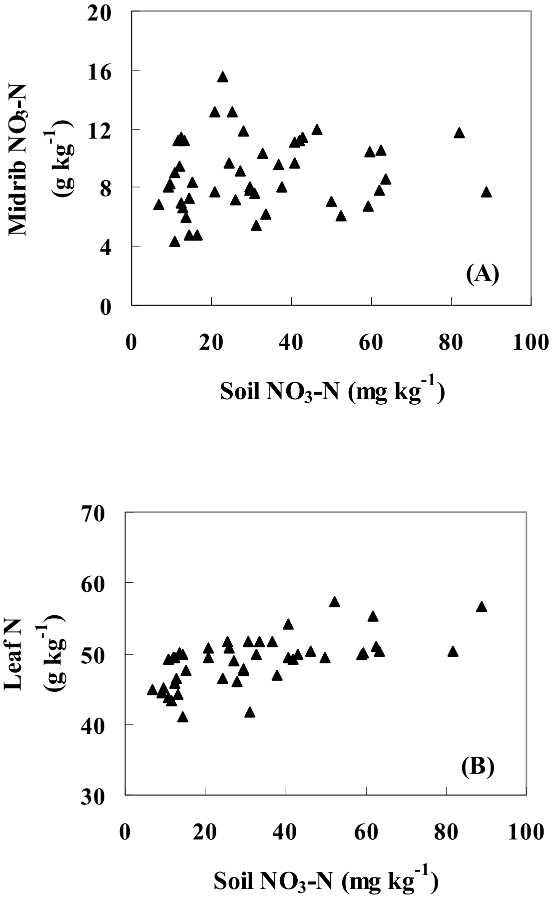

Fig. 2. Relationship between nitrate-nitrogen (NO_3-N) concentration in the top foot of soil and lettuce midrib NO_3-N (A) or whole leaf nitrogen (N) (B). Samples collected prior to second sidedress N application in the commercial fields described by Breschini and Hartz (2002a) (1 mg·kg^{-1} = 1 ppm; 1 g·kg^{-1} = 1000 ppm = 0.1%; 1 ft = 0.3048 m).

BMP 4: Manage irrigation efficiently

Efficient irrigation management is essential to minimize in-season nutrient losses. During the cropping season, relatively high soil N levels are maintained to ensure optimum crop growth. Soil NO_3-N >20 mg·kg^{-1} is common; at that concentration the soil solution of a sandy loam soil at field capacity moisture content would be about 100 mg·L^{-1} NO_3-N. Considering that the U.S. Environmental Protection Agency (USEPA) drinking water standard for NO_3-N is 10 mg·L^{-1}, and surface water standards to minimize eutrophication are even lower, it is likely that both runoff and leachate from that field would exceed water quality standards.

To be efficient, irrigation must have both high distribution uniformity [DU (a measure of how uniformly water is applied throughout the field)], and high irrigation efficiency [IE (the percentage of water applied that is beneficially used either by the crop or for leaching salts)]. High IE cannot be achieved without high DU. Furrow and sprinkler irrigation often achieve a DU <75% (Hanson, 1995). Improving DU to 85% may be possible through management improvements (land leveling, shortening furrow lengths, use of surge valves, adjusting sprinkler spacing, etc.). Once high DU is achieved, care must be taken to achieve high IE. Water application rate must be matched to soil infiltration rate to eliminate runoff; if runoff is unavoidable, a collection system to impound and reuse runoff is beneficial. Also, the water volume applied per irrigation must be appropriate to the rooting depth of the crop to minimize water and nutrient movement beyond the reach of the crop.

Efficient furrow and sprinkler irrigation practices are often technologically or economically impossible to achieve. Luckily, vegetable growers are increasingly converting to drip irrigation. Appropriately designed drip systems can realistically reach a DU >90%, and when managed with care can achieve IE of near 90%. Improved water management, combined with the ability to apply nutrients at will throughout the season, make drip irrigation a versatile tool for reducing water pollution potential. However, conversion to drip irrigation does not guarantee efficient irrigation or fertigation management. Breschini and Hartz (2002b) reported that celery growers often mismanaged drip irrigation, sacrificing water and nutrient use efficiency, and in some cases compromising celery quality.

BMP 5: Use crop rotation and cover crops to minimize nutrient loss

Compared with other annual crops (cereals, oil seeds, etc.) vegetable crops inherently have higher nutrient pollution potential. In addition to being more heavily fertilized, many vegetables are shallowly rooted (which limits N uptake at soil depths > 30–45 cm) and have a high N content in residue (which rapidly mineralizes upon soil incorporation). Even with appropriate fertilization and irrigation practices, following vegetable production significant quantities of mineral N may remain in the soil profile, at risk of loss to the environment. Crop rotation, and the use of cover crops during fallow periods, can minimize loss.

Rotating a shallowly rooted vegetable crop [lettuce, onion, potato (*Solanum tuberosum*), etc.] with a more deeply rooted crop allows for recovery of NO_3-N from lower soil depths. Crops such as sugar beet (*Beta vulgaris*), corn, and some cereals may extract N below 1.5-m depth (Thorup-Kristensen et al., 2003). Where vegetable cropping would normally be followed by an extended fallow period, production of a cover crop can provide the same benefit. Wyland et al. (1996) found that non-legume cover crops such as phacelia (*Phacelia tanacetifolia*) and annual rye (*Secale cereale*) planted after a broccoli crop reduced winter NO_3-N leaching by >60%.

Beyond soil NO_3-N recovery, cover cropping can dramatically reduce field runoff and associated sediment loss (Dabney et al., 2001). Miyao and Robbins (2000) and Joyce et al. (2002) reported that cover cropping following tomato production reduced winter runoff volume by up to 70%. Erosion control with cover crops has been well documented (Sarrantonio and Gallandt, 2003). Erosion control can be particularly important in fields with high STP, since sediment-bound P represents the vast majority of total P in runoff (Hartz and Johnstone, 2006).

There are both economic and cultural constraints to the use of crop rotation and cover cropping. Growing a deeply rooted rotational crop may have substantially lower profit potential than producing another shallowly rooted vegetable. Cover crop production may involve significant costs, complicate tillage practices, and disrupt spring planting schedules. However, adoption of these practices may be indispensable in some vegetable cropping systems to reduce nutrient losses.

BMPs for organic production

Organic vegetable production is often thought of as being more environmentally benign than conventional production, and in terms of water quality organic production does have advantages. The input of readily available N tends to be lower in organic systems, and cover crop production is a standard practice. However, significant nutrient loss may still occur with organic production. One potential problem is excessive soil P enrichment. Application of manure or manure compost to augment soil N supply is a common practice; application rates of 4–6 tons/acre are typical; depending on the material, each application may contain 200 lb/acre P or more. Repeated application can increase soil P to environmentally hazardous levels (Sims et al., 2000). To minimize P loss, organic growers should refrain from applying significant quantities of P, regardless of source, on fields with STP above the crop response threshold. In such fields a low-P organic material such as feather meal could be used to augment soil N supply.

Efficient irrigation is also important in organic production. Although soil NO_3-N concentration is generally lower than in conventional culture, in the weeks following legume cover crop incorporation significant quantities of NO_3-N can build up (Hu et al., 1997; Kuo et al., 1997). Inefficient irrigation during the establishment and early growth of the succeeding vegetable crop can result in significant NO_3-N leaching loss. Not only is this a potential water quality hazard, it may also lead to N deficiency later in crop development.

Are BMPs enough?

While appropriate application of these BMPs will minimize nutrient loss from vegetable fields, these practices alone may be insufficient to meet water quality standards. Concentrations of N and P in runoff and drainage are likely to periodically exceed desirable levels, even for conscientious growers. For groundwater, and for surface water designated for municipal use, the USEPA drinking water standard (10 mg·L^{-1} NO_3-N) will apply. In surface water in which eutrophication is an issue, even more stringent standards may be applied; target nutrient concentrations may be on the order of 2.0 and 0.1 mg·L^{-1} N and P, respectively. Meeting the drinking water NO_3-N standard may be possible in some cropping systems, but is unlikely in others. Brandi-Dohrn et al. (1997) found that with careful fertilization and winter cover cropping, the annual flow-weighted mean drainage NO_3-N concentration from an Oregon sweet corn field met the standard one year, and slightly exceeded it the next. In comparison, even with conservative fertilization and irrigation, Jackson et al. (1994) estimated seasonal leaching losses in a double-cropped lettuce field in California to be >90 lb/acre, which far exceeded an average of 10 mg·L^{-1} in field drainage.

The ability to consistently meet a more stringent NO_3-N standard for surface water is questionable under any conventional management scheme. Controlling P loss is also problematic. While runoff P from soils of low- to moderate P status may conform to the standard, soils at or above the crop response threshold are unlikely to (Hartz and Johnstone, 2006; McDowell and Sharpley, 2001). Drain tile effluent presents a special challenge. Since leachate P can be much higher than surface runoff P, leachate from fields of even moderate P status may be environmentally problematic (Hartz and Johnstone, 2006; Heckrath et al., 1995). This will be a long-term problem, since even in the absence of additional fertilization, reducing soil P availability will take years of cropping (Higgs et al., 2000; Kamprath, 1999).

Clearly, water quality issues relating to nutrients present a serious challenge to the commercial vegetable industry nationwide. Actions beyond the adoption of the BMPs outlined here may be required, and those actions may be highly disruptive to the industry.

Literature cited

Blackmer, T.M. and J.S. Schepers. 1995. Use of a chlorophyll meter to monitor nitrogen status and schedule fertigation for corn. J. Prod. Agr. 8:56–60.

Binford, G.D., A.M. Blackmer, and M.E. Cerrato. 1992. Relationships between corn yields and soil nitrate in late spring. Agron. J. 84:53–59.

Brandi-Dohrn, F.M., R.P. Dick, M. Hess, S.M. Kaufman, D.D. Hemphill, and J.S. Selker. 1997. Nitrate leaching under a cereal rye crop. J. Environ. Quality 26:181–188.

Breschini, S.J. and T.K. Hartz. 2002a. Presidedress soil nitrate testing reduces nitrogen fertilizer use and nitrate leaching hazard in lettuce production. HortScience 37:1061–1064.

Breschini, S.J. and T.K. Hartz. 2002b. Drip irrigation management affects celery yield and quality. HortScience 37:894–897.

Burt, R., M.D. Mays, E.C. Benham, and M.A. Wilson. 2002. Phosphorus characterization and correlation with properties of selected benchmark soils of the United States. Commun. Soil Sci. Plant Anal. 33:117–141.

Dabney, S.M., J.A. Delgado, and D.W. Reeves. 2001. Using winter cover crops to improve soil and water quality. Commun. Soil Sci. Plant Anal. 32:1221–1250.

Hanson, B.R. 1995. Practical potential irrigation efficiencies. Proc. First Intl. Conf., Water Resources Eng. Div., Amer. Soc. Civil Eng., San Antonio, Texas, 14–18 Aug. 1995. p. 1580–1584.

Hartz, T.K., W.E. Bendixen, and L. Wierdsma. 2000. The value of presidedress soil nitrate testing as a nitrogen management tool in irrigated vegetable production. HortScience 35:651–656.

Hartz, T.K. and G.J. Hochmuth. 1996. Fertility management of drip-irrigated vegetables. HortTechnology 6:168–172.

Hartz, T.K. and P.R. Johnstone. 2006. Relationship between soil P availability and P loss potential in runoff and drainage. Commun. Soil Sci. Plant Anal. (In press.)

Heckman, J.R., W.T. Hlubik, D.J. Prostak, and J.W. Patterson. 1995. Pre-sidedress soil nitrate test for sweet corn. HortScience 30:1033–1036.

Heckman, J.R., T. Morris, J.T. Sims, J.B. Sieczka, U. Krogmann, P. Nitzsche, and R. Ashley. 2002. Pre-sidedress soil nitrate test is effective for fall cabbage. HortScience 37:113–117.

Heckrath, G., P.C. Brookes, P.R. Poulton, and K.W.T. Goulding. 1995. Phosphorus leaching from soils containing different phosphorus concentrations in the Broadbalk experiment. J. Environ. Quality 24:904–910.

Higgs, B., A.E. Johnston, J.L. Salter, and C.J. Lawson. 2000. Some aspects of achieving sustainable phosphorus use in agriculture. J. Environ. Quality 29:80–87.

Hu, S., N.J. Grunwald, A.H.C. van Bruggen, G.R. Gamble, L.E. Drinkwater, C. Shennan, and M.W. Demment. 1997. Short-term effects of cover crop incorporation on soil carbon pools and nitrogen availability. Soil Sci. Soc. Amer. J. 61:901–911.

Jackson, L.E., L.J. Stivers, B.T. Warden, and K.K. Tanji. 1994. Crop nitrogen utilization and soil nitrate loss in a lettuce field. Fert. Res. 37:93–105.

Johnstone, P.R., T.K. Hartz, M.D. Cahn, and M.R. Johnstone. 2005. Lettuce response to phosphorus fertilization in high P soils. HortScience 40:1499–1503.

Joyce, B.A., W.W. Wallender, J.P. Mitchell, L.M. Huyck, S.R. Temple, P.N. Brostrom, and T.C. Hsaio. 2002. Seasonal changes in infiltration and soil water storage in conventional and alternative agricultural systems. Trans. Amer. Soc. Agr. Engr. 45:315–326.

Kamprath, E.J. 1999. Changes in phosphate availability of ultisols with long-term cropping. Commun. Soil Sci. Plant Anal. 30:909–919.

Krusekopf, H.H., J.P. Mitchell, T.K. Hartz, D.M. May, E.M. Miyao, and M.D. Cahn. 2002. Pre-sidedress soil nitrate testing identifies processing tomato fields not requiring sidedress N fertilizer. HortScience 37:520–524.

Kuo, S., U.M. Sainju, and E.J. Jellum. 1997. Winter cover cropping influence on nitrogen in soil. Soil Sci. Soc. Amer. J. 61:1392–1399.

Magdoff, F.R. 1991. Understanding the Magdoff pre-sidedress nitrate test for corn. J. Prod. Agr. 4:297–305.

McDowell, R.W. and A.N. Sharpley. 2001. Approximating phosphorus release from soils to surface runoff and subsurface drainage. J. Environ. Quality 30:508–520.

Menon, R.G., S.H. Chien, and W.J. Chardon. 1997. Iron oxide-impregnated filter paper (P_i test): II. A review of its application. Nutrient Cycling Agroecosystems 47:7–18.

Miyao, G. and P. Robins. 2000. Influence of fall-planted cover crop on rainfall run-off in a processing tomato production system. Acta Hort. 542:343–345.

Paulter, M.C. and J.T. Sims. 2000. Relationship between soil test phosphorus, soluble phosphorus, and phosphorus saturation in Delaware soils. Soil Soc. Amer. J. 64:765–773.

Piekielek, W.P. and R.H. Fox. 1002. Use of a chlorophyll meter to predict sidedress requirement for maize. Agron. J. 84:59–65.

Pritchard, K.H., T.A. Doerge, and T.L. Thompson. 1995. Evaluation of in-season nitrogen tissue tests for drip irrigated leaf and romaine lettuce. Commun. Soil Sci. Plant Anal. 26:237–257.

Reisenauer, H.M., J. Quick, R.E. Voss, and A.L. Brown. 1983. Chemical soil tests for soil fertility evaluation. p. 39–41. In: H.M. Reisenauer (ed.). Soil and plant testing in California. Calif. Coop. Ext. Bul. 1879.

Sanchez, C.A. 1998. Diagnostic tools for efficient N management of vegetables produced in the low desert. Project 95-0222 Final Report, California Department of Food and Agriculture Fertilizer Research and Education Program, Sacramento.

Sarrantonio, M. and E. Gallandt. 2003. The role of cover crops in North American cropping systems. J. Crop Prod. 8:53–74.

Schroder, J.J., J.J. Neetson, O. Oenema, and P.C. Struik. 2000. Does the crop or the soil indicate how to save nitrogen in maize production? Reviewing the state of the art. Field Crops Res. 66:151–164.

Sharpley, A.N. 1995. Dependence of runoff phosphorus on extractable soil phosphorus. J. Environ. Quality 24:920–926.

Sims, J.T., A.C. Edwards, O.F. Schoumans, and R.R. Simard. 2000. Integrating soil phosphorus testing into environmentally based agricultural management practices. J. Environ. Quality 29:60–71.

Thorup-Kristensen, K., J. Magid, and L.S. Jensen. 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. Adv. Agron. 79:227–302.

Tremblay, N. 2004. Determining nitrogen requirements from crop characteristics. Benefits and challenges. Recent Res. Dev. Agron. Hort. 1:157–182.

Westerveld, S.M., A.W. McKeown, C.D. Scott-Dupree, and M R. McDonald. 2003. How well do critical nitrogen concentrations work for cabbage, carrot and onion crops? HortScience 38:1122–1128.

Westerveld, S.M., A.W. McKeown, C.D. Scott-Dupree, and M R. McDonald. 2004. Assessment of chlorophyll and nitrate meters as field tissue nitrogen tests for cabbage, onions and carrots. HortTechnology 14:179–188.

Wyland, L.J., L.E. Jackson, W.E. Chaney, K. Klonsky, S.T. Koike, and B. Kimple. 1996. Winter cover crops in vegetable cropping system: impacts on nitrate leaching, soil water, crop yield, pests and management costs. Agr. Ecosyst. Environ. 59:1–17.