A DECADE OF CHANGE IN NUTRIENT MANAGEMENT:

A NEW NITROGEN INDEX

Photo by Anita Kear, USDA-ARS-NPA Soil Plant Nutrient Research Unit.

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The goal of nutrient management is to optimize nutrient's advantages, and minimize their disadvantages. Nutrient use efficiency has to consider the effect and link between a field's soil, the crop, the weather, and hydrology, along with the practices being used on the property, such as irrigation, fertilizer, and manure management. This is a tall order. In addition, a nutrient manager's decisions have the potential to increase the use efficiency of one element, while simultaneously reducing the efficiency of a second nutrient, increasing its losses (Delgado and Lemunyon, 2006). Luckily, a new nitrogen index tool has been developed to coincide with multiple nutrients in varying scenarios. The goal to develop a nitrogen index is not new, and for the past twenty years various nitrogen indexes have been built (Follett et al., 1991, Shaffer and Delgado, 2002). This "new" index is based on the previous work, but is considered new for three reasons: 1) expanded/combined information, 2) international input, and 3) the ease of use while connecting to phosphorus indexes and simulation models. The Nitrogen Index Tool version 1.0 builds also on the modeling software, "Nitrate Leaching and Economic Analysis Package (NLEAP)," Shaffer et al. (1991) and diminishes many limitations to the annual index portion of that model producing a tool that considers the breakthroughs of the past decade in nutrient management research.

In 1999, major research by Sharpley et al. reported that while managers were focusing on the effects of nitrogen in manure applications, soil phosphorus concentrations were rising to excessive levels with potential adverse affects. In 2001, they also pointed out using less tillage in a farm operation is good to reduce off-site transport of phosphorous, but it can potentially contribute to a higher nitrate-nitrogen leaching. Looking at multiple nutrients is the wave of the future, and tools need to be in place to help nutrient managers with complicated decisions. In addition to the Sharpley research, a 2001 meeting between the U.S. Department of Agriculture's (USDA) Natural Resources Conservation Service conservationist and nutrient managers and the Agricultural Research Service's (ARS) researchers, and other University and Extension Cooperators reinforced the need for a new second generation nitrogen index tool that could be used parallel to the new phosphorus indexes. Hence, the new Nitrogen Index tool version 1.0.

The Shaffer and Delgado (2002) discussion in the *Journal of Soil and Water Conservation* on what the framework for a new nitrogen-leaching tool should look like was a direct outgrowth of that 2001 meeting. They describe a need for a three-tier approach to the development of a tool to ensure flexibility of improvements and refinement of accuracy. Shaffer and Delgado (2002) saw tier one requiring a quick, non-numeric input to separate out the potential top third nitrate leaching potentials—meaning those with a high potential for leaching. Tier two would be a more comprehensive look at nitrate leaching potentials by using databases or application models to introduce off-site effects and local interpretation to produce a nitrogen index tool. The third tier would involve those difficult situations where it is necessary to incorporate detailed research models, field data, interpretation, and normalization. The new Nitrogen Index tool version 1.0 is a tier one tool, but can quickly become a tier two analysis if it is combined with the NLEAP model and additional inputs.

Our new Nitrogen Index version 1.0 tool is connected to the Microsoft Windows© version of the NLEAP model (including the revised simulation model being developed) in a Windows Excel© environment. This facilitates the connection to already established phosphorus index files making simultaneous evaluations of nitrogen and phosphorus. With both indexes on the computer screen at once, changes to management scenarios can be conducted with instantaneous analysis of the results facilitating the decision making process to achieve a balance among practices, efficiencies, and losses.

To ground-truth the development of this specific tool, the general subject was presented at the Soil and Water Conservation Society professional meetings during the past five years.

To ground-truth the development of this specific tool, the general subject was presented at the Soil and Water Conservation Society professional meetings during the past five years. Consultants, farmers, practitioners, conservationists, and other related professionals need these kinds of tools that can help identify and assess management scenarios to quickly evaluate the effect of management practices of various combinations of crops, soils, weather, irrigation, slope, erosion, and other local and site-specific conditions.

In the Society's 2000 and 2001 "Nutrient Management in the USA" symposia, a series of papers described the advances in the management of nitrogen and phosphorus and were published in this journal in 2002. The quantification of losses of nitrogen (Delgado, 2002) and phosphorus (Lemunyon and Daniel, 2002) clearly show some of the significant difference among the pathways for these two elements. The fate and transport of phosphorus (Sharpley et al. 2002) and nitrogen (Follett and Delgado 2002) was also covered in these symposia.

Connection with other indices

Sharpley et al. (2003) reported the development and implementation of 47 phosphorus indexes across the United States. The fact that this version of the nitrogen index can be easily coupled to already established phosphorus indexes, helps to synchronize the simultaneously evaluations of not only nitrogen and phosphorus, but provides the potential to couple it to salinity, potassium, erosion, or micronutrient indexes in the future. Use may be beneficial given the current interest about nutrient losses to water sources, nutrient management for animal feeding operations, and establishment of new standards for nutrient management (NRCS 590).

This is the very reason we call this index "new." This is the first time that a nitrogen risk index is linked to a phosphorus index, allowing the evaluation of management practices on nitrogen risk loss subcomponents; nitrogen surface off-site transport risk loss subcomponent, and a nitrogen risk atmospheric loss subcomponent as presented by the framework of Shaffer and Delgado (2002).

What has been especially exciting about this project, is the incorporation of countries outside the United States to contribute to the building of a tool to be used across National boundary lines. There was a recent joint symposium titled, "Precision Conservation in North America," sponsored again by the Soil Water Conservation Society, and the Soil Science Society of America, the Canadian Soil Science Society, and the Mexican Soil Science Society. Since 2001, the ARS' nitrogen index Fort Collins, Colorado group started cooperating across different agroecosystems of the United States, Argentina (2005), Canada (2003), China (2003), Mexico (2004), and Puerto Rico (2001) in exchanging information, conducting evaluations and in some cases establishing new experiments to test the new Nitrogen Index version 1.0. Some of our international cooperators are contributing to the new USDA-ARS –SPNR 2006 to 2011 research plans in developing, testing, and evaluating a new nitrogen index.

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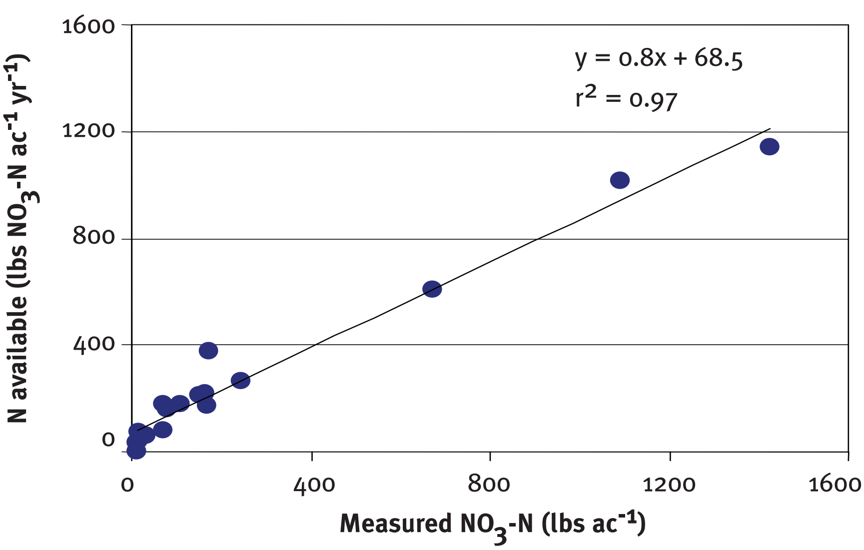
Figure 1.
Nitrogen index NO_3-N available (NAL) to leach versus measured NO_3-N after crops growing season.



The current Nitrogen Index 1.0 version is able to predict nitrogen dynamics across widely different scenarios for crops such as corn, wheat, potato, winter cover rye, and barley. There is the need to continue evaluation and testing and refine the capability to assess effects of nitrogen management on air, surface, and leaching nitrogen risks of national and international agricultural systems. Figure 1 shows the accuracy of our new nitrogen index to predict residual soil nitrate-nitrogen dynamics in field sites located in the southcentral-Colorado, USA; northestern-Colorado, USA; Schijiazhuang, China; and Alberti, Argentina.

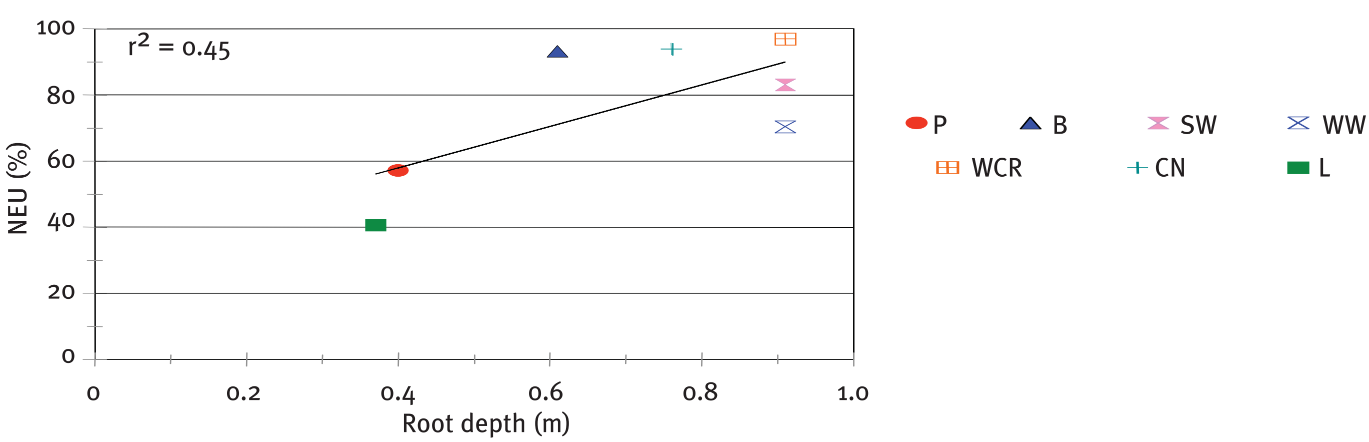
Sharpley et al. (1999 and 2001) clearly proposed the need to join nitrogen analyses to the phosphorus index and the group developed a joint nitrogen- and phosphorus- index published by Heathwaite et al. (2000). The Nutrient Management computer program, NMAN, developed in Ontario also displays P and N indexes simultaneously (OMAFRA, 2003). There is continued interest in the development of new tools for nitrogen management. This is especially true, now that we are advancing in the field of precision conservation (Shaffer and Delgado, 2002; Berry et al., 2003; 2005)—a new term to describe natural resource management that uses geographic information systems (GIS). Precision conservation incorporates precision irrigation (Sadler et al., 2005), remote sensing (Delgado and Bausch, 2005), and site-specific management zones (Delgado et al., 2005) to reduce off-site transport of nitrogen. There is potential to develop precision conservation plans that integrate nutrient management across the landscape (Kitchen et al., 2005; Lerch et al., 2005; Balkom et al., 2005; Terra et al., 2005). The approach taken to produce the Nitrogen Index 1.0 differs from other approaches because it provides a nitrogen index that has three subcomponents—leaching, surface transport, and air transport. Shaffer and Delgado (2002) reported that the nitrate-nitrogen leaching index should be generalized into an environmental nitrogen loss index involving nitrate-nitrogen leaching, nitrogen losses from surface runoff and erosion, and atmospheric losses as N_20, $N0_x$, and NH_3.

The interest in developing a current and more accurate second generation nitrogen index was also just proposed by a group at the University of California Center for Water Resources, who recommended the Nitrate Leaching Hazard Index developed for irrigated agriculture (Wu et al., 2005). The index of Wu and his colleagues can be used to provide information to growers so they can voluntarily select management practices that reduce nitrate-nitrogen for underground water resources.

The Nitrogen Index version 1.0 accounts for rooting depths, as Figures 2, 3, and 4 show, and the correlation between root depths and nitrogen use efficiencies, nitrate leaching and potential for nitrate mining or recovering of nitrates from underground water (Delgado, 2001). The Nitrogen Index version 1.0 has a large number of drop-down menus, facilitating the use of a series of scenarios. Although qualitative in rankings, our nitrogen index is based on quantitative nitrogen balances, keeping track of inputs and outputs, and soil nitrogen dynamics for the entered scenarios on an annual basis. This approach is similar to the annual nitrogen index of Pierce et al (1991) that was included in the DOS version of the NLEAP model (Shaffer et al. 1991). The index projects and combines, nitrogen dynamics such as nitrogen mineralization from the soil organic matter, nitrogen mineralization from crop residues, residual soil nitrate-nitrogen, nitrate-nitrogen leached, and nitrogen losses from denitrification and ammonia volatilization.

Figure 5 shows the factors that are ranked into the nitrogen index. This test joins the new nitrogen index file to the

Figure 2.
Correlation between the simulated nitrogen use efficiency (NUE) and the mean rooting depth of potato (P), barley (B), spring wheat (SW), winter wheat (WW), winter cover rye (WCR), canola (CN), and lettuce (L) grown in commercial farm operations in the San Luis Valley (Delgado, 2001).



NOTE
The Nitrogen Management Version 1.0 Tool is intended for nutrient management. The USDA developers or other cooperative institutions do not guarantee the use of this electronic file. The user assumes all the risk for using this file and for interpreting the results. Names are necessary to report factually of available data; however the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may be suitable. The mention of commercial names is just to present the facts. USDA and other cooperating institutions do not guarantee the function for the product, nor do we recommend the use of any product over the use of another.

Figure 3.
Correlation between the simulated nitrogen leached below the root zone (NLRZ) and the mean rooting depth of potato (P), barley (B), spring wheat (SW), winter wheat (WW), winter cover rye (WCR), canola (CN), and lettuce (L) grown in commercial farm operations of the San Luis Valley (Delgado, 2001).

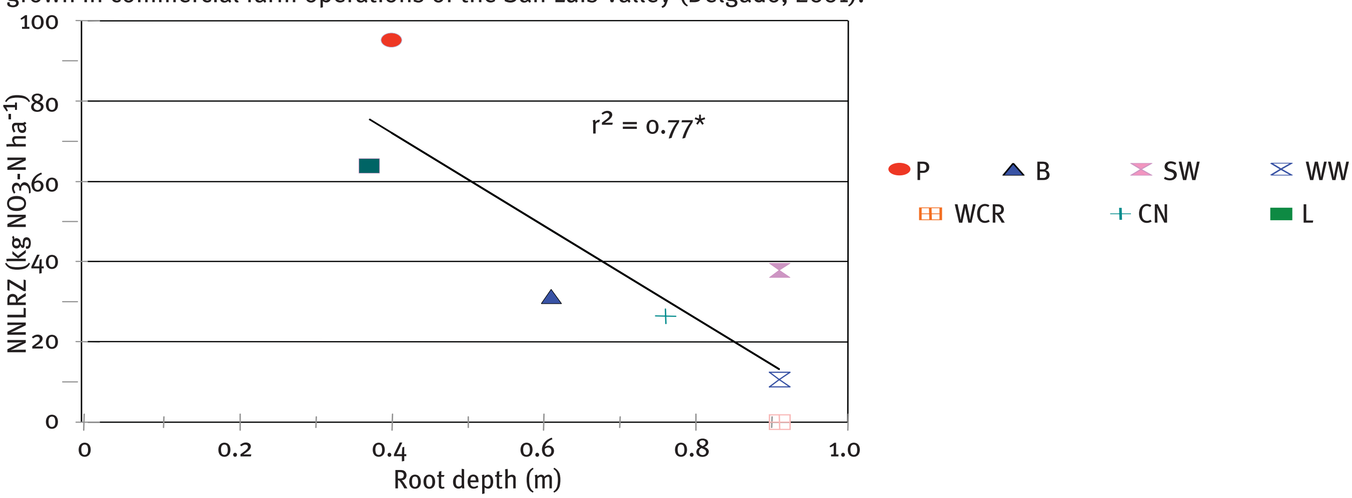


Figure 4.
Correlation between the simulated root zone nitrogen (N) mining potential and the mean rooting depth of potato (P), barley (B), spring wheat (SW), winter wheat (WW), winter cover rye (WCR), canola (CN), and lettuce (L) grown in commercial farm operations in the San Luis Valley (Delgado, 2001).

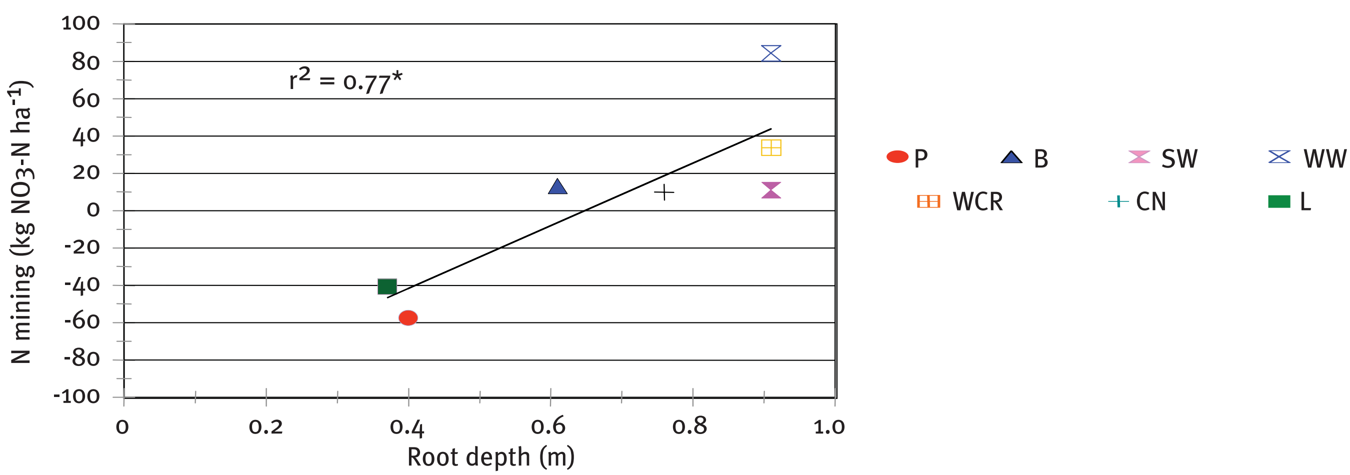


Figure 5.
Nitrogen Index Version 1.0: Ratings and column factors for leaching, surface transport, and air quality.

	Nitrogen index rating							
Site characteristic	None or very low	Low	Medium	High	Very high	Nitrate leaching	Surface transport	Air quality
	0	2	4	6	8			
N index								
Water leaching index	Very low Nitrate leaching risk >0<1	Low Nitrate leaching risk ≥1 & <2	Medium Nitrate leaching risk >2≤10	High Nitrate leaching risk >10≤16	Very high Nitrate leaching risk >16			
Column factor	**0**	**2**	**4**	**6**	**8**	**X**		
Nitrogen available to leach potential	Very low Nitrate leaching <25 lb N ac^{-1}	Low Nitrate leaching >25<50 lb N ac^{-1}	Medium Nitrate leaching >50<100 lb N ac^{-1}	High Nitrate leaching >100<150 lb N ac^{-1}	Very high Nitrate leaching >150 lb N ac^{-1}			
Column factor	**0**	**2**	**4**	**6**	**8**	**X**		
Estimated nitrate leaching	Very low Nitrate leaching <25 lb N ac^{-1}	Low Nitrate leaching >25<50 lb N ac^{-1}	Medium Nitrate leaching >50<100 lb N ac^{-1}	High Nitrate leaching >100<150 lb N ac^{-1}	Very high Nitrate leaching >150 lb N ac^{-1}			
Column factor	**0**	**2**	**4**	**6**	**8**	**X**		
Nitrogen budget use method	None applied	Follow N recommendations split N application (sprinkler drip irrigation)	10-15% over N recommendations	15% over N state recommendations	25% over n state recommendations			
Column factor	**0**	**1**	**2**	**3**	**4**	**X**	**X**	**X**
N susceptible volatilization method	None applied	Placed with planter deeper than 2 ft.	Incorporated <2 days after application or irrigation immediately after application	Incorporated or irrigation more than 7 days after application	Surface application without irrigation			
Column factor	**0**	**2**	**4**	**6**	**8**			**X**
Proximity of nearest field edge to named stream or lake	Very low >1000 ft	Low 500-1000 ft	Medium 200-500 ft	High 30-200 ft	Very high 30 ft			
Column factor	**0**	**2**	**4**	**6**	**8**		**X**	
Rooting depths and crop rotation	5 ft and deeper rooted crop rotation	3 to 5 ft deeper rooted crop and rotation with shallower crops	1.5 to 3 ft	<1.5 ft and rotation with deep rooted crop	<1.5 ft and no deep rooted crops in rotation			
Column factor	**0**	**2**	**4**	**6**	**8**	**X**		
Aquifer leaching potential risk (ALPR)	Very low	Low	Medium	High	Very high			

Figure 5. Continued.

Column factor	0	2	4	6	8	X		
Tile drainage	No tile drainage	Mitigate with pumping wetland, wood chips, and >10,000 ft to water body	Same as low but >1,000 ft to water body	Same as low but <1,000 ft to water body	Drains to ditch, creek, or stream and no mitigation			
Column factor	**0**	**2**	**4**	**6**	**8**	**X**		
NH3 volatilization	Very low NH3 volatilization <20 lb N ac^{-1}	Low NH3 volatilization >20<30 lb N ac^{-1}	Medium NH3 volatilization >30<50 lb N ac^{-1}	High NH3 volatilization >50<75 lb N ac^{-1}	Very high NH3 volatilization >75 lb N ac^{-1}			
Column factor	**0**	**2**	**4**	**6**	**8**			**X**
Denitrification	Very low Denitrification <25 lb N ac^{-1}	Low Denitrification >25<50 lb N ac^{-1}	Medium Denitrification >50<75 lb N ac^{-1}	High Denitrification >75<100 lb N ac^{-1}	Very high Denitrification >100 lb N ac^{-1}			
Column factor	**0**	**2**	**4**	**6**	**8**			**X**
Soil erosion (wind & water)	Very low <1 t ac^{-1}	Low 1 - 3 t ac^{-1}	Medium 3 - 5 t ac^{-1}	High 5 - 15 t ac^{-1}	Very high >15 t ac^{-1}			
Column factor	**0**	**2**	**4**	**6**	**8**		**X**	
Runoff class (runoff class table 2)	Very low or negligible	Low	Medium	High	Very high			
Column factor	**0**	**2**	**4**	**6**	**8**		**X**	
Irrigation erosion (See QS note)	Not irrigated or furrow irrigation	Tailwater recovery or QS <6 for very erodible soils or QS <10 for resistent soils	QS >10 for erosion resistant soils	QS >10 for erodible soils	QS >6 for very erodible soils			
Column factor	**0**	**2**	**4**	**6**	**8**		**X**	
Vegetative buffer	>100 ft wide	65 - 100 ft wide	20 - 65 ft wide	<20 ft wide	No buffer			
Column factor	**0**	**2**	**4**	**6**	**8**		**X**	
Subtotal nitrate leaching component	**0 - 10**	**>10 - 22**	**>22 - 33**	**>33 - 45**	**>45 - 56**			
Subtotal surface transport component	**0 - 7**	**>7 - 15**	**>15 - 28**	**>28 - 34**	**>34 - 40**			
Subtotal air atmospheric component	**0 - 7**	**>7 - 15**	**>15 - 22**	**>22 - 28**	**>28 - 32**			
Total index points	**0 - 24**	**>24 - 52**	**>52 - 83**	**>83 - 107**	**>107 - 128**			
N hazard class	**None or very low**	**Low**	**Medium**	**High**	**Very high**			

New Mexico phosphorous index, and the factors ranked reflect this. This index can be edited very easily to join it to the respective local phosphorous index. Figure 6 shows an example of the results from one site. Both nutrients received a very low ranking since the phosphorus index indicates that phosphorus management can be implemented using nitrogen management base scenarios. The phosphorus index is medium, meaning that there is no environmental problem with phosphorus management.

One advantage of how the group designed the index is that the user can look at sensitivity analysis and evaluate how management scenarios or practices impact subcomponents such as leaching, surface transport and air quality. Additionally the user can use his own coefficient of losses for each site or combination if they are available, otherwise the index uses default values. There are also spreadsheets that will flag potential areas of attention to nutrient managers with the development of instant graphs and management recommendations. Figure 7 shows an example from the flag areas and some of the recommendations that show up immediately in the screen after entering the inputs. These graphs will be done instantaneously as the user finishes entering the data. Even in the case presented here, where the general N index across nitrate leaching, surface transport and air quality (gaseous losses) indicates low to medium phosphorus or nitrogen management problems, however specific flags show: 1) the nitrogen released from the previous crop was high and should be accounted for, and 2) the nitrate available to leach (NAL) at the end of the year is potentially high and management practices to reduce the nitrate available to leach should be implemented.

Figure 6.
Example of results from a joint nitrogen (N) and phosphorus (P) index analysis with the Nitrogen Index Version 1.0.

	Subtotal: Nitrate leaching component	Rank	Subtotal: Total surface transport component	Rank	Subtotal: Air quality atmospheric component	Rank	N index	Rank
Very low	0 – 10		0 – 7		0 – 7	X	0 – 24	
Low	>10 – 22	X	>7 – 15		>7 – 15		>24 – 52	X
Medium	>22 – 33		>15 – 28	X	>15 – 22		>52 – 83	
High	>33 – 45		>28 – 34		>22 – 28		>83 – 107	
Very high	>45 – 56		>34 – 40		>28 – 32		>107 – 128	

	Information about P index file linked to the N index file	
Very low	0	
Low	10	
Medium	17	X
High	27	
Very high	37	
Excessive	47	

P hazard class: Medium

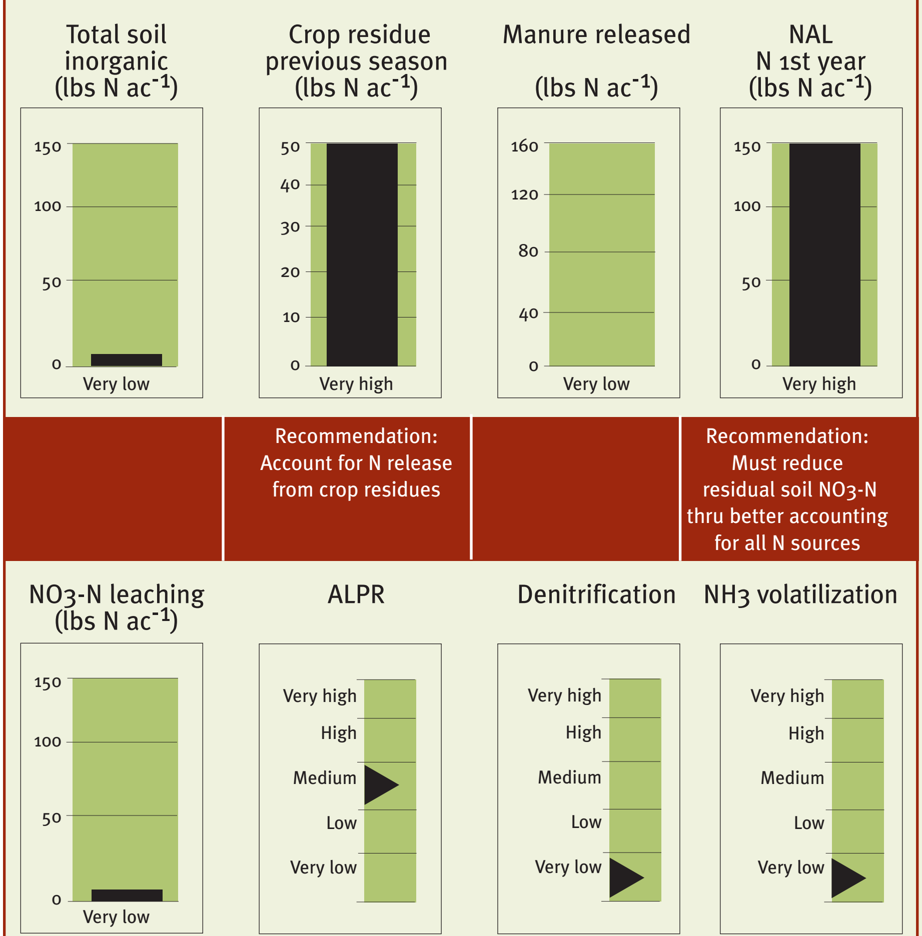
Total P index points: 25

Phosphorus application classification: N based

The future

This upcoming July in Keystone, Colorado, our group will be presenting at the Soil and Water Conservation Society a symposium titled, "Recent Advances in Nitrogen Management for Water Quality." We are looking forward to presenting this management tool and making it available to users. Although preliminary analysis shows that the nitrogen index has the capability to assess the effect of management practices across different agroecosystems in the United States and internationally, there is also the need to continue testing and evaluating the nitrogen index potential. There are some limitations and the index is not very sensitive to sudden leaching changes driven by a sudden event (e.g. a high precipitation or irrigation event). The effect of these events will depend on the amount of water and or texture of the soils. Similarly these events can also trigger denitrification and surface runoff events that cannot be assessed with the index. In general, the index is capable of assessing effects of most management practices on nitrogen transport use efficiencies and losses, but we need to continue assessing its' capabilities and limitations. We propose that this is a good tool that can be used by managers to evaluate nitrogen and phosphorus jointly and that there is the continuing need to conduct joint symposiums where scientists and conservation practitioners can come together with other interested members and the general public to present recent advances in soil and water conservation and nutrient management.

Figure 7.
Example of flags with recommendations for specific nitrogen index evaluation.



References cited

Balkcom, K.S., J.S. Terra, J.N. Shaw, D.W. Reeves, and R.L. Raper. 2005. Soil management system and lanscape position interactions on nutrient distribution in a coastal plain field. Journal of Soil and Water Conservation 60(6):431-437.

Berry, J.R., J.A. Delgado, R. Khosla, and F.J. Pierce. 2003. Precision conservation for environmental sustainability. Journal of Soil and Water Conservation 58(6):332-339.

Berry, J.K., J.A. Delgado, F.J. Pierce, and R. Khosla. 2005. Applying spatial analysis for precision conservation across the landscape. Journal of Soil and Water Conservation 60(6):363-370.

Benning, J.L. and C.S. Wortmann. 2005. Phosphorous indexes in four Midwestern states: An evaluation of the differences and similarities. Journal of Soil and water Conservation 60(5):221-227.

Bock, B.R. and G.W. Hergert. 1991. Fertilizer nitrogen management. Chapter 7. Pp. 139-164. In: Managing Nitrogen for Groundwater Quality and Farm Profitability. R.F. Follett, D.R. Keeney, and R.M. Cruse (eds.) Soil Science Society of America, Madison, Wisconsin.

Davis, J.G., K.V. Iverson, and M.F. Vigil. 2002. Soil testing for different phosphorus pools in cropland soils of the Great Plains. Journal of Soil and Water Conservation 57(6): 479-484.

Delgado, J.A. 2004. Use of best management practices and a nitrogen leaching index to maximize N recovery and protect ground water for high risk cropping systems–landscape combinations. CD-ROM Proceedings of the Nitrogen Forum. Ontario, Canada, March 3-4, 2004.

Delgado, J.A. 2002. Quantifying the loss mechanism of nitrogen. Journal of Soil and Water Conservation 57(6):389-398.

Delgado, J.A. 2001. Use of simulations for evaluation of best management practices on irrigated cropping systems. Pp. 355-381. In: Modeling carbon and nitrogen dynamics for soil management. M.J. Shaffer, L. Ma, and S. Hansen (eds.) Lewis Publishers, Boca Raton, Florida.

Delgado, J.A. and R.F. Follett. 2004. Quantification of the nitrogen losses in agricultural systems including the potential use of a nitrate leaching index tool to assess potential impacts to groundwater. Proceedings of the XXXII Mexican Soil Science Society November 8 - 10, 2004, Leon, Mexico (CD-ROM).

Delgado, J.A. and J. Lemunyon. 2006. Nutrient management. Pp. 1157-1160. R. Lal (ed.) Encyclopedia Soil Science. Markel and Decker, New York, New York.

Delgado, J.A. and W. Bausch. 2005. Potential use of precision conservation techniques to reduce nitrate leaching in irrigated crops. Journal of Soil and Water Conservation 60(6):379-387.

Delgado, J.A., R. Khosla, W.C. Bausch, D.G. Westfall, and D. Inman. 2005. Nitrogen fertilizer management based on site specific management zones reduces potential fro nitrate leaching. Journal of Soil and Water Conservation 60(6):402-410.

Delgado, J.A., R.F. Follett, J.L. Sharkoff, M.K. Brodahl, and M.J. Shaffer. 1998. NLEAP facts about nitrogen management. Journal Soil and Water Conservation 53(4):332-337.

Delgado, J.A., R.T. Sparks, R.F. Follett, J.L. Sharkoff, and R.R. Riggenbach. 1999a. Use of winter cover crops to conserve soil and water quality in the San Luis Valley of South Central Colorado. Pp. 125-142. Soil quality and soil erosion. R. Lal (ed.) CRC Press, Boca Raton, Florida.
Eghball, B., B.J. Wienhold, J.E. Gilley, and R.A. Eigenberg. 2002. Mineralization of manure nutrients. Journal of Soil Water Conservation 57(6):470-472
Follett, R.F. D.R. Keeney and R.M. Cruse (eds.) 1991. Managing nitrogen for groundwater quality and farm profitability. Soil Science Society of America, Madison, WI. 357 pp.
Follett, R.F. and J.A. Delgado. 2002. Nitrogen fate and transport in agricultural systems. Journal Soil Water Conservation 57(6):333-335.
Flynn, R., M. Sporcic, and L. Scheffe. 2000. Draft phosphorous assessment tool. U.S. Department of Agriculture Natural Resources Conservation Service Technical Note Agronomy No. 57. Publications Distribution Center, Albuquerque, New Mexico, 4 pp.
Harmel, R.D., H.A. Torbert, P.B. Delaune, B.E. Haggard, and R.L. Haney. 2005. Evaluation of some phosphorous indices on new application sites in Texas. Journal Soil and Water Conservation 60(1):29-42
Heathwaite, L., A. Sharpley and W. Gburek. 2000. A conceptual approach for integrating phosphorous and nitrogen management at watershed scales. Journal Environmental Quality 29:158-166.
Kitchen, N.R., K.A. Sudduth, D.B. Myers, R.E. Massey, E.J. Sadler, R.N. Lerch, J.W. Hummel, H.L. Palm 2005. Development of a conservation-oriented precision agriculture system: II. Crop production assessment and plan implementation. Journal of Soil and Water Conservation 60(6):421-430.
Kogelmann, W.J., H.S. Lin, R.B. Bryant, D.B. Beegle, A.M. Wolf, and G.W. Petersen. 2004. A statewide assessment of the impacts of phosphorous index implementation in Pennsylvania. Journal Soil and Water Conservation 59(1):9-18.
Lemunyon, J.L. and T.C. Daniel. 2002. Quantifying phosphorus losses from the agricultural system. Journal of Soil and Water Conservation 57(6):399-401.
Lerch, R.N., N.R. Kitchen, R.J. Kremer, W.W. Donald, E.E. Alberts, E.J. Sadler, K.A. Sudduth, D.B. Myers, and F. Ghidey. 2005. Development of a conservation-oriented precision agriculture system: I. Water and soil quality assessment. Journal of Soil and Water Conservation 60(6):411-421.
Mallarino, A.P., B.M. Stewart, J.L. Baker, J.D. Downing, and J.E. Sawyer. 2002 Phosphorus indexing for cropland: An overview and basic concepts of the Iowa phosphorus index. Journal of Soil and Water Conservation 57(6):440-447.
Meisinger, J.J. and G.W. Randall. 1991. Estimating nitrogen budgets for soil-crop systems. Chapter 5. Pp. 85-124. In: Managing nitrogen for groundwater quality and farm profitability. R.F. Follett, D.R. Keeney and R.M. Cruse (eds.) Soil Science Society of America, Madison, Wisconsin.
Ontario Ministry of Agriculture and Rural Affairs (OMAFRA) 2005. Fundamentals of Nutrient management Training Course. Course materials. Queen's Printer, Ontario.
Ontario Ministry of Agriculture and Rural Affairs (OMAFRA) 2003. NMAN sotware. www.omafra.gov.on.ca/english/nm/nman/default.htm. Created 10 December 2003.
Pierce, F.J., M.J. Shaffer, and A.D. Halvorson. 1991. Screening procedure for estimating potentially leachable nitrate-nitrogen below the root zone. Chapter 12. Pp. 259-283. In: Managing nitrogen for groundwater quality and farm profitability. R.F. Follett, D.R. Keeney and R.M. Cruse (eds.) Soil Science Society of America, Madison, Wisconsin.
Sadler, E.J., R.G. Evans, K.C. Stone, and C.R. Camp, CR. 2005. Opportunities for conservation with precision irrigation. Journal of Soil and Water Conservation 60(6):371-379.
Schendel, E.K., H. Schreier, and L.M. Lavkulich. 2004. Linkages between phosphorous index estimates and environmental quality indicators. Journal Soil and Water Conservation 59:243-251.
Shaffer, M.J. 1997. NLEAP model for predicting nitrogen efficiency in irrigated cropping systems. Pp. 198-204. In: Proceedings of the Western Nutrient Management Conference. March 6-7, 1997, Salt Lake City, Utah.
Shaffer, M.J., A.D. Halvorson, and F.J. Pierce. 1991. Nitrate leaching and economic analysis package (NLEAP): Model description and application. Chapter 13. Pp. 285-322. In: Managing nitrogen for groundwater quality and farm profitability. R.F. Follett, D.R. Keeney and R.M. Cruse (eds.) Soil Science Society of America, Madison, Wisconsin.
Shaffer, M.J. and J.A. Delgado. 2002. Essentials of a national nitrate leaching index assessment tool. Journal of Soil and Water Conservation 57(6):327-335.
Sharpley, A.N., P.J.A. Kleinman, R.W. McDowell, M. Gitau, and R.B. Bryant. 2002. Modeling phosphorus transport in agricultural watersheds: Processes and possibilities. Journal of Soil and Water Conservation 57(6):425-439.
Sharpley, A.N., P. Kleinman, and R. McDowell. 2001. Innovative management of agricultural phosphorous to protect soil and water resources. Journal Communication Soil Science Plant Analysis 32(7 & 8):1071-1100.
Sharpley, A.N., T. Daniel, T. Sims, J. Lemunyon, R. Stevens, and R. Parry. 1999. Agricultural phosphorus and eutrophication. U.S. Department of Agriculture Agricultural Research Service No. ARS-149. 37 pp.
Sharpley, A.N., J.L. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburuk, P.A. Moore, Jr., and G. Mullins. 2003. Development of phosphorus indices for nutrient management planning strategies in the United States. Journal of Soil and Water Conservation 53(3):137-151.
Terra, J.A., D.W. Reeves, J.N. Shaw, and R.L. Raper. 2005. Impacts of landscape attributes on carbon sequestration during the transition from conventional to conservation management practices on a coastal plain field. Journal of Soil and Water Conservation 60(6):438-446.
Torbert, H.A., R.D. Harmel, K.N. Potter, and M. Dozier. 2005. Evaluation of some phosphorous index criteria in cultivated agriculture clays. Journal Soil and Water Conservation 60(1):21-29.
U.S. Department of Agriculture-Soil Conservation Service (USDA-SCS). 1988. National Agronomy Manual. 2nd Edition, Washington, D.C.
Van Es, H.M. and J.A. Delgado. 2006. Nitrate leaching index. Pp. 1119–1121. In: Encyclopedia soil science. R. Lal (ed.) Markel and Decker, New York, New York.
Van Es, H.M., K.J. Czymmek, and Q.M. Ketterings. 2002. Management effects on nitrogen leaching and guidelines for a nitrogen leaching index in New York. Journal of Soil and Water Conservation 57(6):499-504.
Vigil, M.F., B. Eghball, M.L. Cabrera, B.R. Jakubowski, and J.G. Davis. 2002. Accounting for seasonal nitrogen mineralization: An overview. Journal of Soil and Water Conservation 57(6):464-469.
Williams, J.R. and D.E. Kissel. 1991. Water percolation: An indicator of nitrogen-leaching potential. Chapter 4. Pp. 59-83. Managing nitrogen for groundwater quality and farm profitability. R.F. Follett, D.R. Keeney and R.M. Cruse (eds.) Soil Science Society of America, Madison, Wisconsin.
Wu, L., J. Letey, C. French, Y. Wood, and D. Bikie. 2005 Nitrate leaching hazard index developed for irrigated agriculture. Journal Soil and Water Conservation 60(3):90A-95A.

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