

# Best Management Practices for Fertilizer



*Dr. C.S. (Cliff) Snyder,  
Southeast Director  
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This publication is one of a series on fertilizer best management practices (BMPs), prepared by regional directors of the Potash & Phosphate Institute (PPI)/Potash & Phosphate Institute of Canada (PPIC). This effort is in cooperation with the Foundation for Agronomic Research (FAR) toward fulfilling the goals of a 3-year Conservation Innovation Grant (68-3A75-5-166) from the USDA-Natural Resources Conservation Service (NRCS). The intent of these publications is to help develop the BMP definition process in such a way that environmental objectives are met without sacrificing current or future production or profit potential and in full consideration of the newer technologies relevant to fertilizer use. The concept of applying the right fertilizer at the “right rate, right time, and right place” is a guiding theme in this series.

## Fertilizer BMPs for Cotton in the Midsouth— How Does Your Farm Measure Up?

**THERE** is a lot of discussion about best management practices (BMPs) for agriculture, motivated by increasing energy costs and economic pressures. Much of this interest in BMPs among farmers is associated with the increasing awareness that how we manage our soils and landscapes can have a large impact on the surrounding environment. As stewards of the land, farmers in the Midsouth and Southeast U.S. have strived to implement soil conservation practices to improve their soil and water stewardship. Reductions in soil erosion and increased moisture conservation have led to higher crop yields and enhanced whole-farm economics.

Fertilizer nutrients play a major role in meeting the crop yield and quality goals of modern agriculture. Better crop and soil management has resulted in higher crop yields. This, in turn, has increased the need to replace the nutrients removed by the larger crop harvests. How we handle these fertilizer inputs provides the foundation for fertilizer BMPs and positive economic returns from fertilizer use.

BMPs focus on site-specific recommendations, intensive management, improved efficiency and effectiveness, and environmentally sound use of crop production inputs. It is important that these management practices be proven in research and verified through field evaluation. It is important to also remember that BMPs are site-specific; they vary from one region to the next and one farm to the next depending on current and historic soil, climate, crop, and management expertise.

Three general management practices foster the effective and responsible use of fertilizer nutrients. These are:

- 1) Matching nutrient supply with crop requirements,
- 2) Fertilizer application, and
- 3) Minimizing nutrient loss or transport from fields.

Within each of these general categories, there are specific practices that could be classified as BMPs.

### **1. Matching Nutrient Supply with Crop Requirements**

This involves using all the available information to establish the soil nutrient status and crop requirements prior to making fertilizer application decisions. Specific BMPs include soil testing, setting realistic yield goals, and balancing nutrient inputs with crop removal at optimum soil test levels.

#### **a) Soil Testing**

The main science-based tool used to estimate the soil nutrient supply on agricultural lands is soil testing. The success of the soil testing process is based on: soil samples taken from representative areas in a field, analysis using a chemical extraction appropriate for the soils in the region, correlation of soil test values with plant nutrient uptake or crop yield, and calibration with different nutrient application rates at different soil test levels (Dahnke and Olson, 1990; Cox, 1994). Resulting fertilizer recommendations would be based on how a particular crop responded to a nutrient, using the average response from a multi-year and multi-site data set. Given that a number of non-fertility factors impact final crop yield (environmental conditions, pests, etc.), remember that fertilizer recommendations based on correlation with a field response database may account for only 50 to 60% of the yield variation in the field (Dahnke and Olson, 1990; Cox, 1994; Sabbe and Marx, 1987). This helps explain why fertilizer recommendations are often made based on yield potential, a reflection



Agronomic market development information provided by:  
**Dr. C.S. (Cliff) Snyder, Southeast Director  
Potash & Phosphate Institute (PPI)  
P.O. Drawer 2440, Conway, AR 72033-2440  
Phone: (501) 336-8110; Fax (501) 336-8110  
E-mail: csnyder@ppi-far.org  
Website: www.ppi-ppic.org/southeast**

of soil water availability, ability to irrigate effectively, and other management conditions for a specific field (Boquet and Coco, 1997; Gerik et al., 1998; Maples et al., 1990; McConnell et al., 2004; McConnell et al., 1998).

Periodic soil testing of all the fields on a farm acts as an excellent gauge of nutrient sustainability for crop production. These soil test results become part of a record keeping system, including prior soil test data, fertilizer and manure applications, and crop harvest nutrient removal. Together, this information can be used to determine whether soil fertility is increasing, decreasing, or remaining constant.

If nutrient levels in a soil are allowed to decline to the point of limiting yield potential, substantial economic losses and losses in inherent soil fertility can be expected (Mitchell et al., 2005). Failure to use adequate nutrient rates can lead to a decline in soil fertility and productivity. On a high-phosphorus (>100 ppm Mehlich 1 P) Portsmouth sandy loam soil in North Carolina, soil test P declined to half the original values in less than 6 to 8 years as a result of harvest nutrient removal and other factors, in a corn-soybean rotation (McCollum, 1991). Depletion of reserve soil fertility takes years of restoration with fertilizer and/or manure to regain optimum productivity.

#### b) Plant Nutrient Analysis

The term plant nutrient analysis refers to the total or quantitative analysis of nutrients in plant tissue. Unlike tissue sap testing, a qualitative measure of nutrient content, plant nutrient analysis works with soil sampling to evaluate soil fertility and overall nutrient availability. Plant nutrient analysis is used in-crop (during active crop growth) to help evaluate nutrient deficiencies and help direct corrective action on the current crop, or future crops (Bell et al., 2003). It can be a powerful tool in adding accuracy to the monitoring process as nutrient management plans are implemented. While a range of nutrient concentrations is often provided to help guide the plant nutrient analysis interpretation, concentrations can vary with crop, variety, plant part sampled, growth stage when sampled, environment, geographic area, and other factors. Collecting samples from both 'poor' and 'good' areas of a field growing the same crop can be a useful means of identifying nutrient limitations in crop production, especially when soil samples are taken from the same area as the plant samples (Snyder, 1998).

#### c) Establishing Realistic Yield Goals

A realistic yield goal should be developed from past performances in a field and current information about those factors which have dominant effects on yield. Available water, via rainfall and/or irrigation, is one of the major factors affecting crop yields. Nutrients also play an important role in improving the use of water by crops by increasing the amount of yield per unit of water used (Stewart, 2001). As a result, a field-specific yield goal is determined based on available soil moisture, precipitation probabilities

for the region, crop water use, and soil residual nutrient levels. For nitrogen (N) specifically, the result is usually an average fertilizer recommendation (Maples et al., 1990). Replicated in-field tests with different N rates are sometimes used for local calibration with corn (Lory and Scharf, 2003) and may also be beneficial in cotton.

A common approach to setting realistic yield goals is selecting a value somewhere between an above average yield and a maximum yield you have achieved on that specific field, or one of similar production and management history. Setting a target of 10% above the 3- to 5-year average of crops not suffering a severe yield loss due to drought, excessive rainfall, or pests is also a commonly suggested method. This requires that individual field records be maintained, and that only those fields of similar production potential be considered in making estimates. An example for a cotton yield is shown below and considers the best 4 of the previous 5 years, scaled up by 10%. While short of the maximum yield grown, it does provide a means of striving for yield increases. It is important to remember that, over time, yield goals will increase as long as the average yield continues to increase.

Year	Cotton yield (lb of lint/A)	
1997	1,320	
1999	890	<b>Average yield = 1,265 lb of lint/A (not using 1999)</b>
2001	1,055	<b>Highest yield = 1,415 lb of lint/A</b>
2003	1,415	<b>Realistic yield goal = 1,265 x 1.10 = 1,392 lb of lint/A</b>
2005	1,270	

#### d) Nutrient Budgets

Frequently, crop advisers and farmers find that they can make fairly good estimates of crop nutrient requirements based on what was grown previously and what was applied in a specific field. Information such as previous crop yield, soil drainage class, tillage system, and crop residue management can all be used to estimate the status of a nutrient such as N. For most cotton fields, the year-to-year variation in plant-available supply of phosphorus (P) and potassium (K) is usually relatively minor, and annual application based on a balance between soil test levels and crop requirements can avoid depletion or over application. A balanced nutrient budget should never be considered an appropriate replacement for frequent soil testing, given the absolute need to use soil testing to establish a nutrient supply starting point. Often, this type of balancing (input vs. removal) assessment is carried out in the years between which comprehensive soil sampling is conducted.

There are nutrient removal information sources available on the internet. Check out the PPI/PPIC website >[www.ppi-ppic.org/nutrientremoval](http://www.ppi-ppic.org/nutrientremoval)<.

While the values in these tables represent averages from field sampled crops, using your own information is always the best source whenever possible.

## 2. Fertilizer Application

The way fertilizers are managed can have a major impact on the efficiency of nutrient use by crops and potential impact on the surrounding environment. In all instances, we are striving to improve fertilizer-use efficiency by increasing the pounds of lint per acre for each unit of nutrient applied, without sacrificing yield potential. This is especially true for N, the major nutrient removed from the soil by cotton and most annual grain crops, and perennial forages. Efficient fertilizer management means paying close attention to the “Four Rights” of fertilizer application.

### a) Right Rate and Balance of Nutrients

Most crop advisers have heard about Liebig’s Law of the Minimum, which states that the yield of a crop will be determined by the element present in the most limiting quantity. In other words, the deficiency of one nutrient cannot be overcome by the excess of another. Soil testing and use of crop nutrient uptake and removal information are important guides to ensure that balance among soil available nutrients plus applied fertilizer prevents nutrient deficiencies from limiting crop yields, or some nutrients from being used inefficiently.

An example of proper nutrient balance is illustrated in a cotton study conducted in Tennessee (Figure 1). Improved P nutrition, in both disk-till and no-till systems, raised yields and increased the lint yield per pound of N applied. Being sure to provide adequate P and K nutrition can enhance crop recovery of applied N.

### b) Right Fertilizer Form

Plants take up the bulk of their nutrients from the soil in forms which are best suited to their use in the crop. Nitrogen is taken up as nitrate ( $\text{NO}_3^-$ ) and ammonium ( $\text{NH}_4^+$ ), P as primary ( $\text{H}_2\text{PO}_4^-$ ) or secondary ( $\text{HPO}_4^{2-}$ ) orthophosphate, K in its elemental form ( $\text{K}^+$ ), and S mostly as sulfate ( $\text{SO}_4^{2-}$ ). Fertilizers are formulated to be either in these plant-available forms, or converted to these forms after

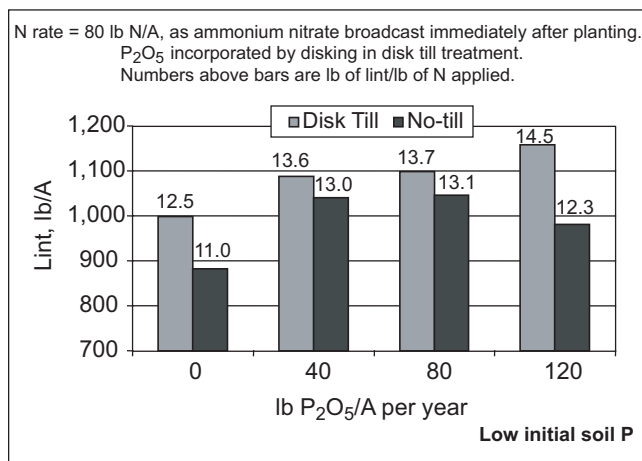


Figure 1. Adequate soil P improves 6-year average cotton yields and response to applied N in Tennessee. Source: Howard et al., 2001.

application to the soil. In some instances, this conversion limits immediate use by the plant, requiring specific application management for efficient use. An example of this is elemental S, which must first be converted to  $\text{SO}_4$  to be plant-available, a process that requires surface application of the fertilizer and up to 12 months for the conversion to be completed. In other instances, a fertilizer form may be selected to delay conversion to a plant-available form, minimizing potential losses from the soil. Fall N application for spring planted crops is not an acceptable practice for cotton in the Midsouth and Southeast.

Placing urea-containing N fertilizers beneath the soil surface and crop residues can reduce the volatile losses of ammonia, minimize immobilization in surface residues, increase yields, and enhance fertilizer effectiveness (Howard and Essington, 1998; Kissel, 1988). Responses to source and rate of N may differ between no-till corn (Figure 2) and no-till cotton (Figure 3) because of the greater amount of crop residue left on the soil surface with corn.

### c) Right Placement

An important part of optimizing crop response to a fertilizer nutrient is ensuring that the nutrient is placed in such a way that it provides rapid uptake by the crop, and reduces potential losses. The mobility of a nutrient in the soil plays a large role in how important placement is. Research in drier regions (e.g. wheat in Northern Great Plains) has shown that when broadcast-applied on low P soils, optimum P rates can be twice those required when P is seed placed or side banded, and incorporation with tillage is sometimes required to improve exposure to plant roots. Early research with cotton by Nelson and others (1949) showed that placement of P becomes less critical as soil test P increases from low to high levels.

Placement can be a powerful management tool to

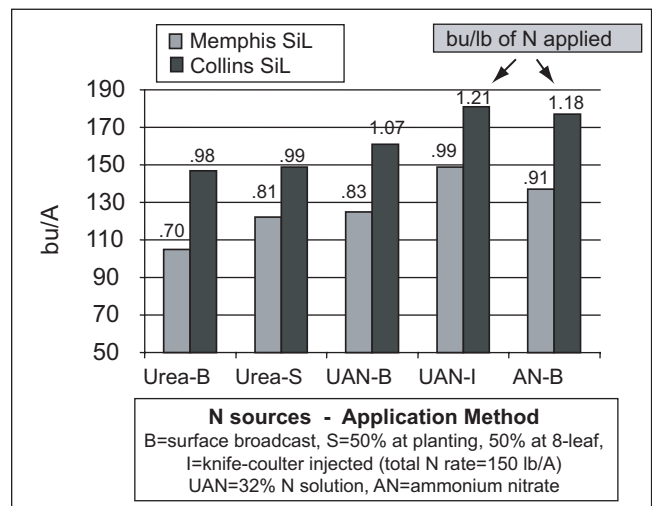
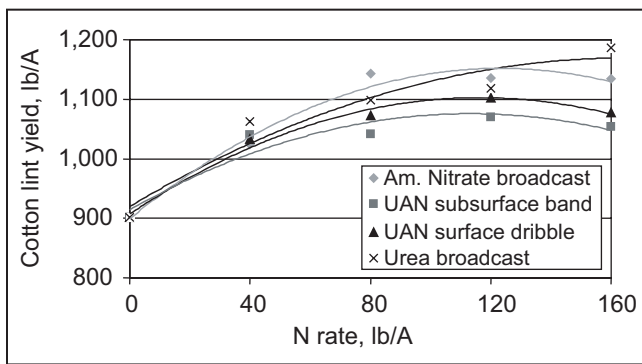


Figure 2. No-till corn response to N source and placement in Tennessee. Source: Howard and Essington (1998).

## Fertilizer BMPs for Cotton in the Midsouth

Practice	Best Practice	Making Progress	Improvements Required
<b>Diagnostic</b>			
Soil testing	Annually test for N where justified by university research. More frequent than every 3 years for P and K.	Less than one-fourth to one-third of fields tested each year.	Never test, or last soil test more than 5 years old.
Plant tissue analysis	Routinely use tissue sampling to evaluate effectiveness of fertility program.	Occasionally use tissue sampling for diagnostic purposes.	No tissue samples collected.
Yield goals set	Develop crop- and field-specific yield goals based on measured yield history and crop sequence.	Develop yield goals for each crop on the farm, regardless of field.	No yield goals considered in planning, or arbitrary or unrealistic yield goals are used.
Nutrient budgets	Consider last year's crop removal and this year's realistic yield goal, in matching fertilizer applied with current soil test results.	Consider crop nutrient removal based on a desired yield goal, or replace last year's removal regardless of soil test level.	No consideration for crop nutrient removal or past production.
<b>Fertilizer Application</b>			
Right balance	Meet the specific needs of all nutrients.	Fertilizers applied as a fixed blend based on N needs.	N rates set with no consideration to other nutrient needs or variation among fields.
Right form	Consider N form appropriate for soil and crop system when selecting fertilizer types and application timing.	Incorporate broadcast urea or UAN within 24 to 48 hours, especially on soils with high pH and high soil temperatures.	Unaware of any form effects. Surface broadcast urea or UAN with no incorporation in warm weather.
Right placement	Place N beneath surface residues, and place at least some of the less mobile nutrients in the root zone near seed. Limit applications near grassed waterways and drainage areas.	Broadcast and incorporate all fertilizer throughout surface soil.	Broadcast application, no incorporation.
Right timing	Consider timing of crop uptake and plant source availability when planning time of application. Split applications according to crop growth stage, soil, and irrigation regime	Apply all N at or before seeding, infrequently split applications	All nutrients applied well in advance of planting.
Site-specific management	Evaluating field variation when making fertilizer application decisions.	Fields are grouped based on the dominant soil-landscape formation.	No consideration of field variability in fertilizer application.
<b>Minimizing Nutrient Losses</b>			
Leaching avoidance on sensitive soils and landscapes	Full use of N BMPs: soil NO <sub>3</sub> testing, split N application, fall cover crops, groundwater monitoring.	Use of half the BMPs at left.	No consideration of potential leaching losses or use of BMPs.
Conservation tillage	Seed using a low disturbance one-pass or two-pass direct seeding system.	Minimum tillage used to maintain reasonable (30%) residue cover.	Frequent tillage with the majority of the residue buried or burned.
Buffer or vegetative filter strips	Have buffer or filter strips next to surface waters and reduce tillage near the area to minimize soil transport.	No buffer or filter maintained, but use no-till adjacent to surface water edge.	Surface water resources not considered in management of fertilizers.



**Figure 3. 10-year average response of cotton to N rate and source in Mississippi.** Source: Parvin et al., 2003.

minimize N losses. Where there is an accumulation of surface residues, it is important to place urea-containing N fertilizers beneath the residues (**Figures 2 and 3**). Under ideal conditions, the goal is to apply the N so that it is in the plant-available form and close proximity to the plant roots.

Per-unit production costs can be reduced by increasing fertilizer efficiency. When broadcast urea is applied onto a residue-covered surface of a no-till field and not incorporated, yield may be significantly reduced. When incorporation is not an option with surface applied fertilizer N, selecting a less volatile form such as  $\text{NH}_4\text{NO}_3$ , or timing application of urea-containing fertilizers ahead of a rainfall or irrigation (avoiding runoff or significant leaching), can help minimize N losses.

Proper incorporation of P fertilizer or poultry litter into soil can significantly reduce the runoff losses of P. Concentrations and mass losses of P in runoff are not always affected by the P application rate, as shown in a worse-case-scenario study in the North Carolina Piedmont (**Table 1**).

Adoption of conservation tillage, to reduce loss of soil and attached nutrients, can significantly improve runoff water quality (MDMSEA, 2001).

#### d) Right Timing

The demand for a nutrient by a growing crop generally varies through the growing season, with the highest uptake associated with the period of most rapid growth. Timing fertilizer applications so they provide a plant-available supply of nutrients when the crop needs them is the desired goal. Research in the South has generally shown that when all the N is applied preplant for nonirrigated cotton, yield is optimized (Ebelhar, and Welch, 1996; McConnell and Mozaffari, 2004). In irrigated environments, cotton yields and uptake efficiency are often improved with split applications:  $\frac{1}{4}$  to  $\frac{1}{2}$  preplant with the remainder applied before flowering. Plants subject to a deficiency during peak growth periods may not recover to achieve full yield potential.

Where fertilizers are subject to transformation in the soil, application timing can play a critical role in optimizing crop nutrient response. Nitrogen is likely the nutrient which

**Table 1. Flow-weighted runoff losses of different P forms from inorganic fertilizer and broiler litter applied at different P rates, following soil incorporation and then 30 min. of simulated rainfall (>3 in./hr) the day of application.**

P source	P application rate, lb/A	Runoff P mass losses, lb/A		
		Reactive P <sup>1</sup>	Algal available P <sup>2</sup>	Total P <sup>3</sup>
Control	0	0.03	0.18	0.23
P fertilizer	20	0.05	0.42	0.53
	60	0.02	0.16	0.26
	100	0.05	0.27	0.33
Broiler litter	14	0.03	0.21	0.32
	30	0.04	0.28	0.48
	44	0.04	0.28	0.38
	73	0.08	0.38	0.62

<sup>1</sup>Runoff passed through a 0.45-micrometer filter.

<sup>2</sup>Extraction with 0.1M sodium hydroxide and unfiltered before measurement.

<sup>3</sup>Acid digestion of unfiltered samples.

Source: Tarkalson and Mikkelsen, 2004.

is influenced most by the soil moisture and temperature conditions, which demands management attention. Nitrogen source, placement, timing, and tillage system can all affect crop yields and N effectiveness.

In recent years, some farmers have been delaying N applications in corn and cotton until the stand has emerged. While this can be a successful practice on fertile alluvial soils with a high N mineralization potential (McConnell and Mozaffari, 2004), it may not be an acceptable practice on less fertile or less productive soils which have limited N mineralization capacities. On sandy soils, split applications and use of less mobile N forms may enhance crop yields and fertilizer N recovery (Karlen et al., 1996).

#### e) Site-Specific Nutrient Management

Fertilizing soils rather than fields is an emerging BMP that continues to gain in popularity with technology development. Using some form of field diagnostic, such as intensive soil sampling, soil sensing (Davis et al., 1997), yield mapping, or scouting records, whole fields are divided into management units where the fertilizer application used is independent of the rest of the field. This form of site-specific fertility management assures that nutrient needs are properly identified and appropriate corrective fertilizer applications are made only where required. This management practice can take into account the natural variation in soil fertility and nutrient supply. However, the nutrient maps and recommendations should consider the level of confidence associated with the estimated soil nutrient values (Birrell et al., 1996).

Aerial imagery and optical plant sensors are being developed which use the crop color and biomass as an indication of N sufficiency (Fridgen and Varco, 2004; Scharf and Lory, 2002). These types of sensing have the

potential to provide farmers a practical means of varying the N rate on-the-go. Local calibration of the technology will be needed to make it more useful and economically feasible. In instances where field variability of N is large, this type of application prevents the over-application characteristic of fixed field rates in those areas where the soil N supply is sufficient. Considerable work is underway with corn (Doerge, 2002; Kitchen et al., 1995; Scharf et al., 2005), but there are few cotton studies to draw upon in the Midsouth (Earnest and Varco, 2005).

Tools such as the pre-sidedress soil  $\text{NO}_3$  test, soil profile  $\text{NO}_3$ -N tests, plant tissue nutrient analysis (Bell et al, 2003), in-the-field chlorophyll measurements on cotton leaves, crop canopy reflectance measurements (ground, aerial, and satellite based), and yield and biomass monitoring on a site-specific basis may help improve N management decisions at various times in the year.

### 3. Minimizing Nutrient Transport Off Fields

From an environmental impact perspective, the goal of land managers should be to retain soil and associated nutrients within the boundaries of a field and the rooting zone of the crops grown. Fertilizer application based on soil testing and realistic yield goals helps to ensure that proper rates are recommended and applied. This improves plant nutrient use efficiency and lessens the potential for residual nutrients to accumulate to excessive levels in a field and pose an environmental threat.

#### a) Nutrient Leaching

Retention of soluble nutrients in the rooting zone of crops ensures efficient recovery and efficient use in food production systems. Leaching occurs when excessive residual nutrients are left in the soil profile and moved below the rooting zone (36 to 48 in. or more) by precipitation. While leaching can be a problem in sandy soils in the humid South (Wiatrick et al., 2002), nitrate-N may not build in silt loam to silty clay loam soil profiles under cotton when the N rate is appropriate for the soil moisture/irrigation regime and the crop yield potential (McConnell et al., 1996). While there are no reported incidences of P leaching when fertilizer is used at soil test recommended rates, leached P has been reported with the application of livestock and poultry manure at rates grossly in excess of crop requirements.

While excess nutrients can result in leaching, withholding needed fertilizer may be more damaging to the environment than applying fertilizer. When N is applied alone, and not in balance with required P, more leached N has been found below the crop rooting zone of corn (Schlegel et al., 1996). Ensuring an agronomic balance of applied fertilizer N with P improved the recovery of N by the crop and removal in the harvested crop, which left less residual N in the soil for leaching below the rooting zone. Use of the pre-sidedress nitrate test (PSNT) (Savoy, 1999) has been shown to be of benefit for improved corn N management in

some humid areas, and has led to reduced nitrate-N leaching (Durieux et al., 1995).

#### b) Conservation Tillage, Soil Erosion, and Carbon Sequestration

Farmers in the South are increasingly adopting conservation tillage practices. The retention of crop residues on the soil surface has significantly reduced the water erosion loss of soil, while at the same time improving moisture conservation and cotton yields (Mitchell et al., 2005). When fertilized according to soil test recommended rates, increased cotton yields may lead to higher levels of crop residues returned to the surface of conservation-till fields for erosion protection.

Proper crop nutrition increases crop yields, increases crop biomass, can raise soil organic matter (carbon) content and can improve the soil supply of organic N. The amount of crop residue returned to the soil is often directly attributed to the positive benefits of fertilization. By allowing crops to capture more carbon dioxide ( $\text{CO}_2$ ) from the atmosphere, more stable soil organic matter can be produced and less atmospheric  $\text{CO}_2$ ...a greenhouse gas...may be released. In long-term rotation studies with cotton in Alabama, yields were found to be highly correlated with soil organic matter content (Mitchell et al., 2002).

#### c) Field Buffer Strips

The movement of N and P into surface waters with eroded soil poses a serious threat to aquatic ecosystems. Some N and P movement into surface waters may result if relatively water soluble N and P sources are applied when there is a high probability of runoff-producing storm events. Some nutrients are required for the healthy function of aquatic ecosystems, but too much can lead to a decline in aquatic ecosystem productivity. Stopping soil erosion from agricultural lands has been a high priority for all farmers. Any eroded soil means loss of nutrients, organic matter, and future crop productivity. The adoption of conservation practices such as no-till, strip-till, and buffer strips adjacent to surface water have been shown to reduce this unwanted movement of nutrients (Snyder, 1999). In many instances where no-till field management has been adopted, soil erosion and water runoff have been significantly reduced.

### Taking Stock of Your Fertilizer Management

**For many farmers and crop advisers, it is time to take stock of how you measure up in the use of fertilizer BMPs. Using the reference chart on pages 4 and 5, evaluate the number of practices under which you rank in the first two categories.** If a suitable fit in these top two categories is not found, you may want to re-evaluate some current management practices. Ensuring that we have either achieved, or are working towards, fertilizer BMPs is an important measure of production system success. ■

## References

- Bell, P.F., D.J. Boquet, E. Millhollon, S. Moore, W. Ebelhar, C.C. Mitchell, J. Varco, E.R. Funderburg.
- C. Kennedy, G.A. Breitenbeck, C. Craig, M. Holman, W. Baker, and J.S. McConnell. 2003. Relationships between leaf-blade nitrogen and relative seedcotton yields. *Crop Sci.* 43:1367–1374.
- Birrell, S.J., K.A. Sudduth, and N.R. Kitchen. Nutrient mapping implications of short-range variability. p. 207–216. *In* P.C. Robert, R.H. Rust and W.E. Larson (eds.), *Proc. 3<sup>rd</sup> Intl. Conf. on Precision Agriculture*. ASA-CSSA-SSSA. Madison, WI.
- Boquet, D.J. and A.B. Coco. 1997. Yield response of cotton to row spacing, nitrogen rate, and plant population density. *Louisiana Agric.* 40(2):22-23.
- Boquet, D.J., R.L. Hutchinson, and G.A. Breitenbeck. 2004. Long-term tillage, cover crop, and nitrogen rate effects on cotton: plant growth and yield components. *Agron. J.* 96:1443–1452.
- Cox, F.R. 1994. Current phosphorus availability indices; characteristics and shortcomings. p. 101-113. *In* J.L. Havlin and J.S. Jacobsen (eds), *Soil Testing : Prospects for Improving Nutrient Recommendations*. SSSA Special Publication No. 40. SSSA. Madison, WI.
- Dahnke, W.C. and R.A. Olson. 1990. Soil test correlation, calibration, and recommendation. p. 45-71. *In* R.L. Westerman (ed.), *Soil Testing and Plant Analysis*. 3<sup>rd</sup> edition. SSSA. Madison, WI.
- Davis, J.G., N.R. Kitchen, K.A. Sudduth, and S.T. Drummond. 1997. Using electromagnetic induction to characterize soils. *Better Crops* 81(4):6-8.
- Durieux, H.J., Brown, E.J. Stewart, J.Q. Zhao, W.E. Jokela, and F.R. Magdoff. Implications of nitrogen management strategies for nitrate leaching potential: roles of nitrogen source and fertilizer recommendation system. *Agron. J.* 87:884-887.
- Earnest, R. and J.J. Varco. 2005. Crop reflectance as an indicator of cotton growth and nitrogen availability. p. 2571-2576. *In* Proc. of the Beltwide Cotton Conference. National Cotton Council, Memphis TN.
- Ebelhar, M.W. and R.A. Welch. 1996. Cotton response to multiple split applications of nitrogen. *Proc. of the Beltwide Cotton Conference* 2:1345-1348. National Cotton Council, Memphis TN.
- Fridgen, J.L. and J.J. Varco. 2004. Dependency of cotton leaf nitrogen, chlorophyll, and reflectance on nitrogen and potassium availability. *Agron. J.* 96:63-69.
- Gerik, T.J., D.M. Oosterhuis, and H.A. Torbert. 1998. Managing cotton nitrogen supply. *Advances in Agronomy* 64:115-147.
- Howard, D.D., M.E. Essington, J. Logan, R.K. Roberts and W.M. Percell. 2001. Phosphorus and potassium fertilization of disk-till and no-till cotton. *Cotton Science* 5:144-155.
- Karlen, D.L., P.G. Hunt, and T.A. Matheny. 1996. Fertilizer <sup>15</sup>nitrogen recovery by corn, wheat, and cotton grown with and without pre-plant tillage on a Norfolk loamy sand. *Crop Sci.* 36:975-981.
- Kissel, D.E. 1988. Management of urea fertilizers. North Central Regional Ext. Publ. 326, 8 p. Kansas St. Univ., Manhattan, KS (URL: <http://www.oznet.ksu.edu/library/crps12/NCR326.pdf>).
- Kitchen, N.R., D.F. Hughes, K.A. Sudduth, and S.J. Birrell. 1995. Comparison of variable rate to single rate nitrogen fertilization application: Corn production and residual soil NO<sub>3</sub>-N. p. 427-442 *In* P.C. Robert, R.H. Rust and W.E. Larson.(eds.) *Site-Specific Management for Ag Systems*. ASA-CSSA-SSSA, Madison, WI.
- Lory, J.A. and P.C. Scharf. 2003. Yield goal versus delta yield for predicting fertilizer nitrogen need in corn. *Agron. J.* 95:994–999.
- Maples, R.L., W.N. Miley, and T.C. Keisling. 1990. Nitrogen recommendations for cotton and how they were developed in Arkansas. p. 33-39. *In* W.N. Miley, and D.M. Oosterhuis (eds.), *Nitrogen Nutrition in Cotton: Practical Issues*. Am. Soc. Agron. Madison, WI.
- McCullum, R.E. 1991. Buildup and decline in soil phosphorus: 30-year trends on a Typic Umbraquult. *Agron. J.* 83:77-85.
- McConnell, J.S., B.A. Meyers, and M. Mozaffari. 2004. Long-term irrigation methods and nitrogen fertilization rates on cotton production: the last three years of the McConnell-Mitchell plots. p. 34-38. *In* N.A. Slaton and W.E. Sabbe (eds.), *Soil Fertility Studies* 2003. Arkansas Agric. Exp. St. Res. Series 515.
- McConnell, J.S. and M. Mozaffari. 2004. Yield, petiole nitrate, and node development responses of cotton to early season nitrogen fertilization. *J. Plant Nutr.* 27(7):1183-1197.
- McConnell, J.S., W.H. Baker, and R.T.C. Kirst. 1998. Yield and petiole nitrate concentrations of cotton treated with soil-applied and foliar-applied nitrogen. *J. Cotton Sci.* 2:143–152.
- McConnell, J.S., W.H. Baker, and B.S. Frizzell. 1996. Distribution of residual nitrate-nitrogen in long-term fertilization studies of an Alfisol cropped to cotton. *J. Environ. Qual.* 25:1389-1394.
- MDMSEA. 2001. The Mississippi Delta management Systems Evaluation Areas projects, 1995-1999. *In* R.A. Rebich and S. Knight (eds.), *Mississippi Agricultural and Forestry Experiment Station Information Bulletin* 377.
- Mitchell, C.C., D. Delaney, and K.S. Balkcom. 2005. Cullars Rotation: The South's oldest continuous soil fertility experiment. *Better Crops* 89(4):5-9.
- Mitchell, C.C., D.W. Reeves, and D. Delaney. 2002. Conservation tillage in Alabama's "Old Rotation". p. 30-35. *In* E. van Santen (ed.), *Making Conservation Tillage Conventional: Building a Future on 25 Years of Research*. Proc. of 25th Annual Southern Conservation Tillage Conference for Sustainable Agriculture. Auburn, AL 24-26 June 2002. Special Report No. 1. Alabama Agric. Expt. Stn. and Auburn University, AL.
- Nelson, W.N., B.A. Krantz, C.D. Welch, and N.S. Hall. 1949. Utilization of phosphorus as affected by placement: II. Cotton and corn in North Carolina. *Soil Sci.* 68:137-144.
- Parvin, D., J.J. Varco, and S.W. Martin. 2003. Managing nitrogen for maximum profitability in no-till cotton production. Research Report 2003-005. Department of Agricultural economics. Mississippi State University.
- Sabbe, W.E. and D.B. Marx. 1987. Soil sampling: spatial and temporal variability. p. 1-14. *In* J.E. Brwon (ed.), *Soil Testing: Sampling, Correlation, Calibration, and Interpretation*. SSSA Special Publication Number 21. SSSA. Madison, WI.
- Savoy, H.J., Jr. 1999. Use of Soil Tests for Nitrate-Nitrogen in the South. SERA-IEG-6 Southern Regional Fact Sheet. (URL - <http://www.clemson.edu/agrsrvlb/sera6/southernfactsheet.htm>).
- Scharf, P.C., N.R. Kitchen, K.A. Sudduth, J.G. Davis, V.C. Hubbard, and J.A. Lory. 2005. Field-scale variability in optimal nitrogen fertilizer rate for corn. *Agron. J.* 97:452–461.
- Scharf, P.C. and J.A. Lory. 2002. Calibrating corn color from aerial photographs to predict sidedress nitrogen need. *Agron. J.* 94:397-404.
- Schlegel, A.J., K.C. Dhuyvetter, and J.L. Havlin. 1996. Economic and environmental impacts of long-term nitrogen and phosphorus fertilization. *J. Prod. Agric.* 9: 114-118
- Snyder, C.S. 1998. Plant tissue analysis—a valuable nutrient management tool. *News & Views*. Potash & Phosphate Institute. Norcross, GA.
- Snyder, C.S. 1999. Vegetative filter strips reduce runoff losses and help protect water quality. *News & Views*. Potash & Phosphate Institute. Norcross, GA.
- Stewart, W.M. 2001. Balanced fertilization increases water use efficiency. *News & Views*. Potash & Phosphate Institute. Norcross, GA (URL: [http://www.ppi-ppic.org/ppiweb/ppinews.nsf/\\$webcontents/736A94E12DC4646D85256A0300522826/\\$file/Water+Use+Efficiency.pdf](http://www.ppi-ppic.org/ppiweb/ppinews.nsf/$webcontents/736A94E12DC4646D85256A0300522826/$file/Water+Use+Efficiency.pdf) ).
- Tarkalson, D.D. and R.L. Mikkelsen. Runoff phosphorus losses as related to phosphorus source, application method, and application rate on a Piedmont soil. *J. Environ. Qual.* 33:1424-1430.
- Wiatrick, P.J., D.L. Wright, J. Pudelko, and W. Kozlars. 2002. Influence of nitrogen and tillage on cotton. p. 131-135. *In* E. van Santen (ed.) *Making Conservation Tillage Conventional: Building a Future on 25 Years of Research*. Proc. of 25th Annual Southern Conservation Tillage Conference for Sustainable Agriculture. Auburn, AL 24-26 June 2002. Special Report No. 1. Alabama Agric. Expt. Stn. and Auburn University, AL.