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Economics of Fertility Management in Cotton Production in the United States

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ABSTRACT

Cotton is a high-value crop that requires the extensive use of costly fertilizers and chemicals. This paper provides a synthesis of the literature on the economics of fertilizer management in U.S. cotton production. The review identifies several production factors and nutrient application strategies based on published research including: 1) economically optimal N, P, and K management as affected by cotton lint and input prices, tillage practices, row-spacing, winter cover crops, and production risk (yield variability); 2) the trends in the adoption of precision farming technology to improve the efficiency of fertilizer and lime application in cotton production; and 3) the profitability of using precision technology for N, P, and K nutrient management in cotton production. Studies from peer-reviewed journals, Proceedings of the Annual Beltwide Cotton Conferences, and university publications were used to summarize current knowledge and suggest future avenues of research.

Keywords: nitrogen, optimal yield, phosphorus, potassium, precision farming, tillage

CONTENTS

INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is the single most important textile fiber in the world, accounting for nearly 40% of the total world fiber production (USDA ERS 2007). While cotton is biologically a perennial, herbaceous plant with tropical origins, it is typically grown as an annual crop. About 80 countries from around the globe grow cotton with China, the United States, and India providing over half of the world's cotton. The United States, while typically ranking second to China in production, is the leading exporter, accounting for over one-third of global trade in raw cotton (USDA ERS 2007).

Cotton farmers make extensive use of seed, fertilizers, and chemicals. For example, total operating and ownership costs for cotton grown in the United States averaged \$1,280 ha^{-1} compared with \$850 ha^{-1} for corn and \$340 ha^{-1} for soybeans (Brooks 2001; Forman and Livezey 2002; Forman 2006). Costs for seed, fertilizer, lime and chemical inputs comprised 42% of total operating expenses for cotton (Brooks 2001). Thus, the management of N, P, K, and lime has an important impact on the profitability of cotton production.

This article provides an overview of the economics of fertility management in U.S. cotton production research. It is organized around the following topics: 1) economically optimal N, P, and K management as affected by cotton lint yield response to those inputs, cotton lint prices, input prices, their interactions with other inputs such as tillage practices and winter cover crops, and production risk (yield variability); 2) the adoption rates by farmers and trends in the use of precision farming technology for N, P, and K nutrient management in cotton production, and 3) the profitability of using precision farming technology to improve the efficiency of N, P, and K nutrient management in cotton production. The article concludes with a discussion of future research needs to address the economics of nutrient management in cotton.

OPTIMAL N, P, AND K MANAGEMENT STUDIES

Management is a highly important factor in the success of any farming operation. Profit maximization is traditionally assumed to be the overriding goal in most management decisions (Shleifer and Vishny 1997). To achieve that goal, producers should understand the potential costs and returns of their farm operations, the profit equation, financial and production risks, as well as potential alternatives. To assist

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Invited Review

Fig. 1 Chemical application to cotton.

farm managers in this effort, enterprise budgets can be employed for both short- and long-term planning. Enterprise budgets estimate profitability for agricultural enterprises while documenting management practices and the resources and technology used. While many producers develop their own budgets, some producers choose to start with existing budgets (e.g., budgets developed by land-grant Extension personnel) and adjust them for their own enterprises. Budgets generally include variable operating costs, fixed ownership costs, and expected net returns. The economic viability of a crop production system depends on sound management decisions such as the selection of nutrient sources.

Many cotton economics studies have evaluated nutrient inputs to explain the relationship between production yield and profit. Increased uses of fertilizers, pesticides, and other chemicals have contributed toward the enhancement of agriculture's productivity over the past several decades (**Fig. 1**). Currently, production agriculture is facing significant challenges such as escalating costs of production, shortages of irrigation water, and increased public concern about the impacts of agricultural production on the environment (Yu *et al*. 1999).

N management in cotton

N management in cotton production is complex and involves a variety of factors including N source, timing, potential yield, soil type, weather, N fertilizer prices, lint prices, and other production practices such as winter cover crops or tillage (Gerik *et al*. 1998; Roberts *et al*. 1998; Larson *et al*. 2001a). N fertilization specifically influences the maturity, lint yield, and lint fiber quality of cotton. Inadequate or excessive N applications may reduce yields (Maples and Keogh 1971). A deficiency of N in the cotton crop causes premature senescence and reduces lint yields (McConnell *et al*. 1995). High N fertilization rates may cause excessive vegetative growth, thus delaying the maturation and harvest of the crop, which in turn may reduce lint yields in years with early frost or excessive rainfall during the fall (Hutchinson *et al*. 1995; McConnell 1995). The total amount of N available to the crop also affects fiber quality attributes such as fiber strength and micronaire (Bednarz *et al*. 2000; Bauer and Roof 2004; Boquet *et al*. 2004). Premiums and discounts for the various fiber characteristics of cotton lint can have an important impact on the profitability of cotton (Segarra *et al*. 1989; Ethridge and Hudson 1998).

Commercial fertilizer is the major source of N in U.S. cotton production. For example, about three-quarters (76%) of the cotton area in the United States received application of N fertilizer in 2001 (USDA NASS 2007). Winter legumes and animal manures are also potentially important sources of N for cotton production. Yield or profit maximizing N fertilizer rates vary depending on soil types, growing conditions, production practices and other factors. **Table 1** presents lint yield maximizing and profit maximizing N fertilization rates from selected cotton yield response studies published since 1993 (Bauer *et al*. 1993; Stevens *et al*. 1996; Roberts *et al*. 1999; Varco *et al*. 1999; Howard *et al*. 2001; Larson *et al*. 2001a; Fritschi *et al*. 2003; Bauer and Roof 2004; Boquet *et al*. 2004; Wiatrak *et al*. 2005; Cochran *et al*. 2007). The yield and profit maximizing N rates were calculated using the estimated yield response coefficients reported in the studies (**Fig. 2**). An N fertilizer price equivalent of \$0.75 kg^{-1} of N and a lint price of \$1.12 kg^{-1} were used to calculate the profit maximizing N fertilization rates for each study (Cochran *et al*. 2007).

Optimal N application rates calculated from the lint yield response functions varied considerably, ranging from 0 kg ha^{-1} to 224 kg ha^{-1} (**Table 1**). Besides differences in climate and soil type, an important factor contributing to the disparity in the yield and profit maximizing N fertilization rates reported in **Table 1**, was the use of legumes such as hairy vetch (*Vicia villosa* L.) and crimson clover (*Trifolium incarnatum* L.) to substitute for fertilizer N in cotton production (Bauer 1993; Varco *et al*. 1999; Larson *et al*. 2001a, 2001b; Boquet *et al*. 2004; Bauer and Roof 2004). The important general conclusions from these winter cover crop studies were as follows. First, when compared with cotton following no winter cover, the amount of N fertilizer required to maximize yields or profits was substantially less or was completely eliminated for cotton following a legume winter crop. The N fertilizer savings ranged from 21% (17 kg ha^{-1}) to 100% (73 kg ha^{-1}) with the vetch winter cover (**Table 1**). Second, cotton following hairy vetch provided similar or higher yield maximums to the cotton grown after no winter cover (Varco *et al*. 1999; Larson *et al*. 2001a). Third, cotton following vetch provided higher net revenues than cotton following a clover winter cover (Larson *et al*. 2001a; Cochran *et al*. 2007). Finally, weather and pests events may also increase yield and net revenue variability (risk) in the presence of a vetch winter cover crop and may impede farmer adoption of winter legumes to provide nitrogen to cotton (Varco *et al*. 1999; Larson *et al*. 2001b). On the other hand, yield risk due to drought may be reduced in the presence on non-legume winter cover crops such as winter wheat (Larson *et al*. 2001b).

The research results about the profitability of legume winter covers relative to no winter cover are mixed. The profit maximizing net revenues for cotton following a vetch cover were smaller than for cotton following no winter cover under a range of N fertilizer prices in the Larson *et al*. (2001a) and Cochran *et al*. (2007) studies. Yields for cotton after the two winter covers were similar but the N fertilizer savings were less than the expense of establishing the winter legume cover (Larson *et al*. 2001a; Cochran *et al*. 2007). By comparison, the profit maximizing net revenues for a vetch winter cover were higher than for no winter cover in the Varco *et al*. (1999) study. Lint yields for cotton following vetch were higher than for cotton following no winter cover in the Varco *et al*. (1999) study than in the Larson *et al*. (2001a) and Cochran *et al*. (2007) studies. The combination of higher lint yields and N fertilizer cost savings more than offset cost of establishing the winter cover in the Varco *et al*. (1999) study. The results from these studies indicate that a combination of nitrogen savings and yield gains are needed for vetch to be more profitable than cotton grown without a winter legume.

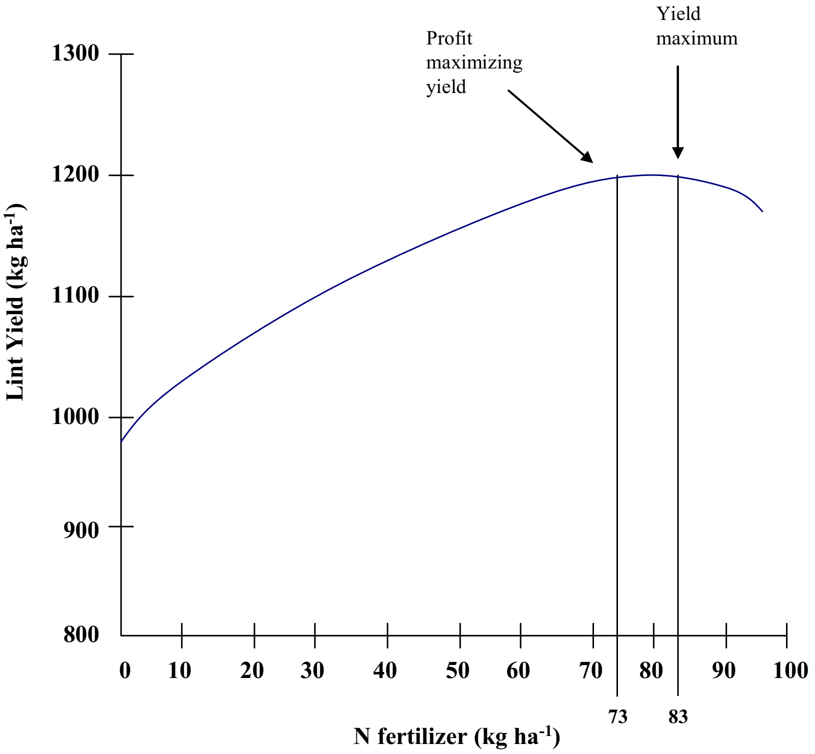
Another alternative source of N for cotton production is the use of animal manure or poultry litter. However, a study by Danforth *et al*. (1993) concluded that poultry litter may not be a cost effective alternative for supplying N to cotton unless the source is near the cotton field and transportation costs are low. As with vetch winter cover crops, poultry litter may be able to replace part or all of the fertilizer N in cotton production and provide similar yields (Reddy *et al*. 2004; Sistani *et al*. 2004; Mitchell and Tu 2005). Reddy *et al*. (2004) conducted field experiments from 1996 to 2001 with poultry litter applications of 100 and 200 kg ha^{-1}. Sistani *et al*. (2004) conducted field plot experiments during

Table 1 Lint yield maximizing and profit maximizing N fertilization rates from selected cotton yield response studies.

Study	State	Soil type	Cotton type	Data period	Winter cover crop	Tillage practice	Other practices	Applied N Rate†	
								Yield maximum	Profit maximum
								(kg N ha^{-1})	
Bauer *et al.* 1993	SC	Norfolk Loamy Sand	Upland	1989-01	Clover	Tillage		96	79
Bauer and Roof 2004	SC	Bonneau Loamy Sand	Upland	1998	Various	Tillage		83	74
Boquet *et al.* 2004	LA	Gigger Silt Loam	Upland	1995-01	None	Tillage	Irrigated	102	93
						No Till		112	106
					Wheat	Tillage		159	159
						No Till		128	120
					Vetch	Tillage		73	49
						No Till		5	0
Cochran *et al.* 2007	TN	Memphis Silt Loam	Upland	1996-01	None	Tillage	Full Lime	88	79
							Half Lime	89	81
						No Till	Full Lime	90	81
							Half Lime	92	83
					Wheat	Tillage	Full Lime	80	75
							Half Lime	79	74
						No Till	Full Lime	83	78
							Half Lime	83	78
					Vetch	Tillage	Full Lime	57	55
							Half Lime	65	64
						No Till	Full Lime	45	42
							Half Lime	52	51
					Clover	Tillage	Full Lime	0	0
							Half Lime	0	0
						No Till	Full Lime	0	0
							Half Lime	0	0
Fritschi *et al.* 2003	CA	Panoche Clay Loam	Acala	1998	None	Tillage	Irrigated	224	224
				1999				224	224
				2000				224	224
		Wasco Sandy Loam	Acala	1999	None	Tillage	Irrigated	224	224
				2000				224	224
		Panoche Clay Loam	Pima	1999	None	Tillage	Irrigated	180	172
				2000				188	176
Howard *et al.* 2001	TN	Loring Silt Loam	Upland	1994	None	No Till		107	101
				1995				73	66
				1996				112	106
				1997				141	133
		Memphis Silt Loam		1996-97	None	No Till		131	115
		Lexington Silt Loam		1996	Wheat	No Till		88	78
				1997				108	102
Larson *et al.* 2001	TN	Memphis Silt Loam	Upland	1981-99	None	Tillage		69	59
						No Till		83	73
					Wheat	Tillage		71	59
						No Till		97	86
					Vetch	Tillage		0	0
						No Till		0	0
					Clover	Tillage		0	0
						No Till		0	0
Roberts *et al.* 1999	TN	Loring Silt Loam	Upland	1994-97	None	No Till		116	108
		Memphis Silt Loam		1996-97	None			96	88
		Lexington Silt Loam		1996-97	Wheat			115	108
Stevens *et al.* 1996	MS		Upland		None			138	96
Vargo *et al.* 1999	MS	Caledonia loam	Upland	1989-92	None	No Till		98	75
					Rye			121	100
					Vetch			73	48
Wiatrak *et al.* 2005	FL	Dothan Silt Loam	Upland	1995	Wheat	Tillage	Irrigated	105	91
						Strip Till		0	0
				1996		Tillage		202	202
						Strip Till		202	202
				1997		Tillage		202	202
						Strip Till		202	202

†Yield and profit maximizing N rates were calculated using the estimated yield response function regression coefficients reported in each study. An N fertilizer price equivalent of \$0.75 kg^{-1} of N and a lint price of \$1.12 kg^{-1} were used to calculate the profit maximizing N fertilization rates for each study (Cochran et al. 2007). Estimates outside the range of N fertilization rates used in a study were set at either the lower or upper bound of the range of rates.

2000 to 2002 for three growing seasons with poultry litter applied at 2.24 Mg ha^{-1} (1 ton acre^{-1}). Mitchell and Tu (2005) applied broiler litter to supply total N rates of 134, 202, and 269 kg ha^{-1} at two research sites beginning in the 1990's (3- year study at the Tennessee Valley Research & Extension Center in Huntsville, AL and a 12- year study at the E.V. Smith Research Center in Central, AL). However, changes in soil physical properties were not documented in any of these studies. Therefore affects on management strategies were not reported. The only study that estimated a response function that could be used to evaluate profitability of different levels of litter was Mitchell and Tu (2005).



Profit Maximization

The profit from producing cotton can be represented by:

$$\pi = p \times y - r \times x \text{ and } y = \beta_0 + \beta_1 x - \beta_2 x^2,$$

where π is profit (\$ ha^{-1}), p is lint price (\$ kg^{-1}), y is lint yield (kg ha^{-1}), r is N fertilizer price (\$ kg^{-1}), x is the amount of N fertilizer applied (kg ha^{-1}), and β_i are parameters to be estimated using regression. The profit maximizing nitrogen rate is found by taking the first derivative of y with respect to x, setting the derivative equal to the ratio of N price to lint price, and solving for x such that

$$x = \frac{\beta_1 - (r/p)}{-2\beta_2}$$

Results for the production function where calculated using data from Larson *et al.* 2001.

Fig. 2 Profit maximization for a single input in cotton production.

However, Mitchell and Tu (2005) used a combination of N fertilizer and litter application rates to estimate their functions.

Fertilizer N can also influence the fiber quality attributes of cotton. A limited number of studies have evaluated lint fiber quality response to N fertilization. For example, Fritchi *et al.* (2003) and Bauer and Roof (2004) estimated quadratic response functions to evaluate micronaire response to N fertilization. Micronaire is a measure of fineness or thickness of the fiber and is important in the efficiency of the spinning and dyeing process of turning lint into a finished fabric product. The premium micronaire range is 3.5-4.9 (USDA, AMS 2006). Discounts are applied outside of the 3.5-4.9 micronaire range. Fritchi *et al.* (2003) found that N fertilization significantly impacted micronaire for Acala cotton grown on a Panoche clay loam [fine-loamy mixed (calcareous thermic Typic Torriorthents]. The N rates that maximized micronaire value in each year of the study were either in the base or premium range of the micronaire price difference schedule (USDA, AMS 2006). In addition, the profit maximizing N rates used for lint yields (**Table 1**) also produced micronaire values that were in the premium range. However, Fritchi *et al.* (2003) found that N fertilization did not significantly affect micronaire for Acala cotton grown on a Wasco sandy loam (coarse-loamy mixed, noacid, thermic Typic Torriorthents) or Pima (*G. barbadense* L.) cotton grown on a Panoche clay loam. The micronaire value maximizing N rate and the profit maximizing N rate used for lint yields (**Table 1**) also produced micronaire values that were in the premium range in the Bauer and Roof (2004) study. In addition, the estimated response function for fiber strength in the Bauer and Roof (2004) study produced fiber strength values that were in the premium range. Fiber strength is another important factor in the fiber spinning process. Thus far, there have been no studies that have explicitly included fiber quality in determining profit maximizing N fertilization rates for cotton.

The application of fertilizer N influences the variability (risk) of lint yields and net revenues from cotton production. Whether or not N is risk-increasing or risk-decreasing is an empirical issue. Roumasset *et al.* (1989) in a review of the literature reported that N fertilizer increases risk in some environments and decreased risk in other environments in crop production. A limited number of studies have evaluated yield risk for fertilizer in cotton. Farnsworth and Moffitt (1981) found that fertilizer was risk-reducing for the case of cotton in California's San Joaquin Valley. Lambert (1990) found that N fertilizer may decrease lint yield risk under ideal moisture conditions associated with irrigated production. By comparison, in a 14-year study Larson *et al.* (2001b) found that N fertilization for dryland cotton grown without a winter cover crop had no impact on lint yield risk. Larson *et al.* (2001b) did find that N fertilizer was risk-increasing for cotton grown after a hairy vetch or winter wheat (*Triticum aestivum* L.) cover crop. A subsequent study by Jaenicke *et al.* (2003) using the same dataset did not find that N fertilizer increases yield risk for cotton following a winter cover crop when production inefficiency was accounted for in the analysis. Results from the limited studies evaluating the effect of N fertilizer on yield risk suggest that N from fertilizer or legume sources may not increase yield risk in cotton production.

Cotton production systems based on less tillage and fewer trips across fields have stimulated grower interest in fertilizer N management including sources and methods of application. While cotton has traditionally been grown under conventional-tillage methods, more growers are utilizing reduced-tillage or no-tillage methods in an effort to lower equipment and labor expenses (York and Culpepper 2001). The amount of crop residue left on the surface after planting the current crop is typically used to define different tillage systems (Sandretto 2001). No-tillage is generally defined as not having any tillage operations before planting and may leave 30% or more of the previous crop's residue on the soil surface after planting (**Box 1**). Reduced-tillage may have between 15 and 30% of the previous crop's residue on the surface at planting. In the past, the inability to incorporate herbicides or to conduct between-row cultivation reduced weed control options; however, the introduction of transgenic technologies and reduced-tillage cultivators has helped growers achieve season-long weed control in reduced-tillage operations (Wilcut *et al.* 1995). Contemporary studies that have evaluated N rates for both conventional-tillage and no-tillage (e.g., **Fig. 3**) in the same experiment have generally not found consistent differences in the N rate to maximize yield or profit for both tillage systems

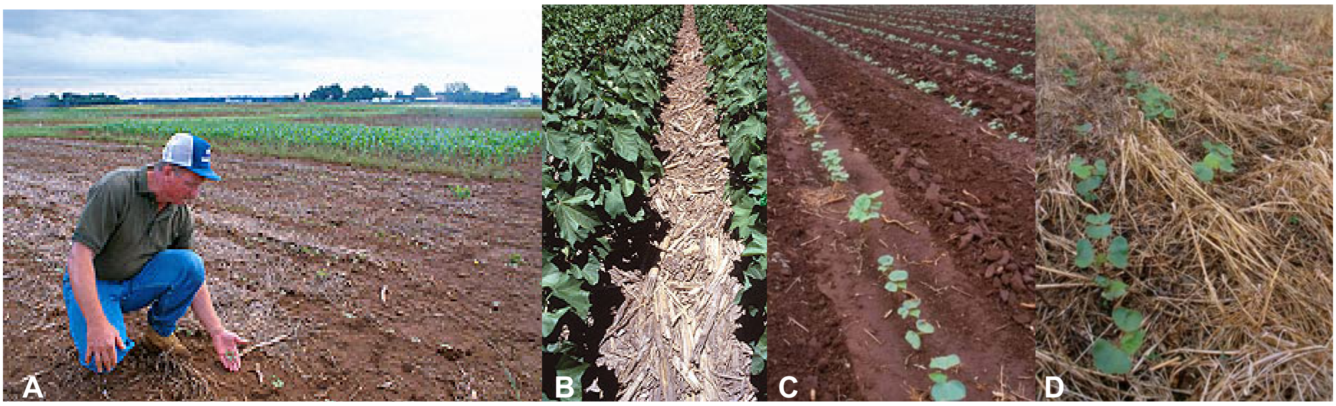


Fig. 3 Tillage practices in cotton production. Conventional-tillage (**A**), No-tillage (**B**), Conventional tillage leaves soil vulnerable to erosion (**C**) and No-tillage in ultra-narrow rows with a winter cover crop protects it (**D**).

Box 1 Tillage Definitions

Conservation tillage: Any tillage and planting system that covers 30 percent or more of the soil surface with crop residue, after planting, to reduce soil erosion by water. Where soil erosion by wind is the primary concern, any system that maintains at least 454 kg ha^{-1} (1,000 lb acre^{-1}) of flat, small grain residue equivalent on the surface throughout the critical wind erosion period. Two key factors influencing crop residue are (1) the type of crop, which establishes the initial residue amount and its fragility, and (2) the type of tillage operations prior to and including planting.

Tillage systems include:

No-till: The soil is left undisturbed from harvest to planting except for nutrient injection. Planting or drilling is accomplished in a narrow seedbed or slot created by coulters, row cleaners, disk openers, in-row chisels, or roto-tillers. Weed control is accomplished primarily with herbicides. Cultivation may be used for emergency weed control.

Ridge-till: The soil is left undisturbed from harvest to planting except for nutrient injection. Planting is completed in a seedbed prepared on ridges with sweeps, disk openers, coulters, or row cleaners. Residue is left on the surface between ridges. Weed control is accomplished with herbicides and/or cultivation. Ridges are rebuilt during cultivation.

Mulch-till: The soil is disturbed prior to planting. Tillage tools such as chisels, field cultivators, disks, sweeps, or blades are used. Weed control is accomplished with herbicides and/or cultivation.

Reduced tillage (15-30% residue): Tillage types that leave 15-30% residue cover after planting, or 227-454 kg ha^{-1} (500-1,000 lb acre^{-1}) of small grain residue equivalent throughout the critical wind erosion period. Weed control is accomplished with herbicides and/or cultivation.

Conventional tillage (less than 15% residue): Tillage types that leave less than 15% residue cover after planting, or less than 227 kg ha^{-1} (500 lb acre^{-1}) of small grain residue equivalent throughout the critical wind erosion period. Generally includes plowing or other intensive tillage. Weed control is accomplished with herbicides and/or cultivation.

Source: United States Department of Agriculture, Economic Research Service 2007.

(**Table 1**). Another conservation tillage system that incorporates no tillage is ultra-narrow-row cotton (UNRC). UNRC is defined as having a row-spacing of between 19.1 to 38.1 cm (7.5 to 15 inches) (Parvin *et al.* 2002). Another characteristic of UNRC is the use of high plant densities, relative to wide-row cotton (Delaney *et al.* 2002). The limited studies that have evaluated N fertilization for UNRC suggest that the yield maximizing N rates for UNRC and wide-row cotton may not be different from each other (Boquet 2005; Clawson *et al.* 2006). Thus, the profit maximizing N rates may also not be different from wide-row cotton but would need to be quantified through further research.

Although several researchers have studied N sources and application methods for conventional-tillage cotton systems, less research has dealt with N sources and application methods in no-till production systems. Research by Roberts *et al.* (1999) studied the economically optimal N rates for alternative application methods for no-tillage cotton systems. Yield response functions were estimated for broadcast and injected N and tested for significant differences in the response function among application methods and locations. Their results showed that the broadcast and injected yield response functions were not significantly different from one another. Thus, the profit maximizing N-fertilizer rates were not different across nitrogen sources.

Bednarz *et al.* (2000) studied the impact of various starter fertilizer sources on cotton production. Their study focused on total shoot N and Ca increases with starter fertilizers while taking into account plant height, leaf area index, and shoot dry weight. With the exception of micronaire, starter fertilizers did not significantly influence the fiber properties investigated. However, they found that differences in fiber properties did result in small differences in cotton price premiums or discounts. Additionally, lint yields were significantly increased with starter fertilizers at two field sites when the crop was exposed to an extended period of cool weather immediately after planting. The most appropriate cotton starter fertilizer appeared to depend on soil type.

With increased environmental pressures, cotton producers may need to improve the efficiency of N fertilization. Including foliar applications in a cotton fertility program can improve N efficiency through improved application timing and flexibility. Roberts *et al.* (2006) compared yields and economic returns from four soil and foliar N fertilization programs utilizing data from experiments conducted in 11 southern states in the United States in 2001 and 2002. Results from their analysis showed that lint yield were highest for Foliar CoRoN, which was significantly different from Foliar Urea with 2/3 Soil N but not Full Soil N. Foliar CoRoN had the highest cost and net revenue, and its net revenue was significantly different from 2/3 Soil N only. Foliar CoRoN maintained its positive economic advantage over other treatments under large (100%) changes in N prices and foliar application costs. Applying soil N at 2/3 the recommended rate followed by foliar N applications uses N more efficiently than applying the full recommended rate to the soil, provides at least as much net revenue, and has the added flexibility of correcting N deficiencies during a critical stage of boll development.

P and K management in cotton

P is a fairly immobile element in the soil, and is not lost rapidly in the same way as N. Instead, mobility to the roots

Box 2 Mycorrhizae Definitions.

Definitions of **Mycorrhizae** on the Web:

- The symbiotic association of beneficial fungi with the small roots of some plants, including pines. Mycorrhizae may improve the water and nutrient uptake of trees, especially of immobile nutrients such as phosphorus. www.sfrc.ufl.edu/Extension/ssfor11.htm
- Modified roots consisting of a mutually beneficial relationship between plant roots and fungi. Plants support fungi by providing sugar and a hospitable environment. Fungi support plants by providing increased surface area for water uptake and by selectively absorbing essential minerals. Syn: fungus roots www.nps.gov/plants/restore/library/glossary.htm

is the prime limitation to uptake. Because of the low mobility of P, root interception is the prime method of uptake, regardless of soil pH (Busman *et al*. 1998). Cotton roots are aided in their interception of soil P by mycorrhizal fungi (Liu 1995). These fungi grow in the small feeder roots and surrounding soil. They derive food from the plant and in return increase uptake of immobile nutrients by enhanced interception. Cotton is highly dependent on mycorrhizae (e.g., **Box 2**) for P uptake (Gasoni and de Gurfinkel 1997).

P is tightly bound in the soil, especially at either low or high pH, which reduces its solubility (Busman *et al*. 1998). Cold soils further decrease P uptake due to slow root growth and reduced solubility of P in cold water. Despite cotton's peak consumption of P during the summer months, deficiencies often occur in seedling cotton, when the plant outgrows the stored P in the seed (Bassett *et al*. 1970; Halevy 1976).

Commercial fertilizer is also an important source of P and K in cotton production. The percentage of cotton area on which P and K fertilizers were applied in the United States in 2001 was 48 percent and 41 percent, respectively (USDA, NASS, 2007). In a study conducted by Howard *et al*. (1997), the critical fertilizer P rate estimated to achieve 95% of the maximum cotton yield was 108 kg P_2O_5 ha^{-1} for the disk-till system and 90 kg ha^{-1} for the no-till system. In a similar study by Cox and Barnes (2002), the authors suggested an economically critical Mehlich 3-P level of 33 parts per million (ppm) or about 90 kg ha^{-1} for a disk-till system. They reported that about 16.78 kg of P_2O_5 ha^{-1} $year^{-1}$ would be needed just to maintain the soil test P level in the optimum range. Optimum soil P fertility on this soil resulted in cotton lint yields of 840 kg ha^{-1}.

Because of the strong influence of soil temperature on P uptake, winter crops such as small grains generally require a higher level of soil P than do warm-season crops such as cotton (Smith and Roncadori 1986). P fertilizer is often applied to these rotation crops and cotton benefits from residual carry-over. Where carry-over P is not available, such as with continuous cotton, applications are made to provide P during the "cold soil" periods, often as a starter fertilizer mixed in the surface soil. Subsoils can become deficient in P due to its poor mobility, which restricts root growth and water uptake from the subsoil (Morel and Fardeau 1990).

Of all the nutrients, K is the only one that comes close to being specific to a plant part. All nutrients (including K) are needed during the plants' entire growth cycle, but the need for K rises dramatically when bolls are set on the plant (Abaye 1996). Bolls are major sinks for K, and high concentrations of K are required to maintain sufficient water pressure for fiber elongation. K is also involved in enzyme activation and pH balance in the cell, which is important for plant health and disease suppression (Hake *et al*. 1991).

K mobility in soils is intermediate between N and P, but is not easily leached because it has a positive charge (K^+) which causes it to be attracted to negatively charged soil colloids (Mullins and Burmester 1990). Roots have to grow near the source of K, but mycorrhizae are not required for K uptake (Rosolem and Mikkelsen 1991). Like N, K is stored in leaves for reuse later by developing bolls. The peak need for K is during boll filling, and to be available at this time K must be in solution where late-season roots are inactive (Mullins and Burmester 1991). When fruit retention is low, crop demand for K is less. Foliar K has been successfully used in some areas to partially satisfy K demand for high yield conditions, but soil applications should be the best way to supply all fertilizer nutrients, including K (Cassman *et al*. 1989; Pettigrew 2003; Pettigrew *et al*. 2005).

Research on optimal K rates was studied by Roberts *et al*. (1999). Their study specifically investigated the application of an adjuvant with foliar potassium nitrate (KNO_3) on medium-to-high-K soils to determine the economic benefit to cotton producers. Foliar applying K to cotton plants at or shortly after bloom had been shown to correct late season K deficiencies and enhance lint yields in low-K soils (Roberts *et al*. 1997; Howard *et al*. 1998). Yields from cotton produced on high-K soils had not responded as well to foliar K treatments (Howard *et al*. 1997).

Results from Roberts *et al*. (1999) suggest that farmers producing cotton on these medium-to-high-K soils who were already applying foliar KNO_3 could increase their net revenue substantially by adding the adjuvant to the foliar fertilizer. On the other hand, a decrease in net revenue for the foliar KNO_3 treatment without the adjuvant compared with the check suggests that farmers of these medium-to-high-K soils would simply incur economic losses by foliar applying KNO_3 without the adjuvant. The high break-even cotton lint prices for conventional-tillage cotton produced at Jackson, Tennessee and for conventional- and no-tillage cotton produced at Milan, Tennessee (\$1.03 kg^{-1}, \$0.61 kg^{-1}, and \$1.03 kg^{-1}, respectively) suggest that applying foliar KNO_3 without the adjuvant would be unprofitable across a wide range of prices expected to prevail in the near future.

Research on an adjuvant with foliar-applied K was followed by research on using an adjuvant with foliar-applied Boron (B) (Roberts *et al*. 2000). As a micronutrient, B plays an essential role in plant cell formation and in converting N and carbohydrates into protein. Roberts *et al*. (2000) found that foliar-applying B four times at a rate of 0.11 kg ha^{-1} per application was more profitable than foliar-applying B four times at double that rate. Foliar-applying B at 0.11 kg ha^{-1} per application and soil-applying B at the currently recommended rate of 0.56 kg ha^{-1} provided about the same net returns. Both application rates and methods were economically superior to not applying B. Applying agricultural limestone did not reduce B availability to the crop. Foliar-applying B with an adjuvant was economically superior to both soil and foliar applications without the adjuvant.

Fertility management interactions with other inputs

Producers and researchers are evaluating plant growth regulators and starter fertilizers applied in-furrow to determine whether they improve cotton yields. Existing research on these products for cotton is limited and often conflicting. In addition, little economic analysis exists for this area. Research conducted by Cochran *et al*. (2001) evaluated the profitability of in-furrow applications of 11-16-0, Asset, Asset RTU (ready to use), and PGR-IV (Plant Growth Regulator-IV) applied at planting and foliar applications at pinhead square and repeated after seven days for cotton that was produced in disk-till and no-till production systems. Asset contains 2% water-soluble Mg derived from magnesium ammonium carboxylate (Helena Chemical Co., 1997a). Asset RTU is a pre-mixed 6-20-5 plant nutrient solution that also contains 0.02% B, 0.05% Cu, 0.10% chelated Fe, 0.05% chelated Mn, 0.0005% Mo, and 0.05% chelated Zn (Helena Chemical Co., 1997b). PGR-IV is a solution containing 0.0028% indolebutyric acid and 0.003% gibberellic acid (Micro Flo Co. 1997).

Results from their study revealed that, for the disk-till system, Asset RTU applied at 2.33 L ha^{-1} produced higher lint yield and net revenue than all other treatments except Asset RTU applied at 1.75 L ha^{-1}. Asset applied at 2.33 L ha^{-1} produced higher lint yield and net revenue than the PGR-IV treatment and the check for the no-till system. The RPG-IV treatment was not economically superior to the other treatments for either tillage system because of higher material costs without offsetting increases in yield. Sensitivity analysis revealed that the ranking of these treatments by profit maximizing farmers would not change under any reasonable future price or input cost scenario. These results can help cotton producers make decisions about starter fertilizers, fertilizer additives, and plant growth regulators for their tillage systems.

In a field study by Cochran *et al.* (2007), cotton lint yield response functions for no cover, winter wheat, and hairy vetch winter cover alternatives were estimated for various N fertilization rates and the full University of Tennessee Extension recommended rate of lime and half the recommended rate. Rates of N fertilizer applied to the experimental plots were 0, 34, 67, and 101 kg ha^{-1} (0, 30, 60, and 90 lb $acre^{1}$). Lime rates were 3.4, 4.5, 5.6, 6.7, and 7.8 Mg ha^{-1} (1.5, 2, 2.5, 3, and 3.5 ton $acre^{1}$) for the full recommended rate and 1.7, 2.2, 2.8, 3.4, and 3.9 Mg ha^{-1} (0.75, 1, 1.25, 1.5, and 1.75 ton $acre^{1}$) for half the recommended rate. Water pH and buffer values were used to assign the full recommended rate of lime as suggested by Savoy and Joines (2001). Results indicated that cotton lint yields and net revenues achieved with one-half the recommended rate of lime were either comparable or greater than the full rate of lime regardless of tillage or winter cover crop regime. Based on the findings of this study, cotton farmers may find it more profitable to apply one-half the recommended rate of lime without reducing the efficiency of N fertilizer in cotton production.

PRECISION FARMING TECHNOLOGY AND FERTILITY MANAGEMENT

Technological innovations have had a significant impact on cotton production, ranging from mechanical pickers to precision agriculture. In the push to mechanize agriculture in the 20th century, there was strong economic pressure to use uniform input application rates over large areas to maximize returns per worker (Lambert and Lowenberg de Boer 2000). Traditionally, optimal fertilizer input use in agriculture has assumed spatial and temporal field homogeneity with respect to soil fertility, pest populations, and crop characteristics. That is, optimal fertilizer input decision rules did not account for these differences within fields. With the introduction of precision farming (PF) technologies (also known as “Site Specific Farming”, “Precision Agriculture”, and “Target Farming”), farmers gained a labor-effective method to monitor crop needs at the sub-field level and apply inputs based on the varying needs of the crop throughout the field. PF technology recognizes the variability of soil, pest, and crop factors within fields and seeks to optimize variable input use under these conditions. Roberts *et al.* (2004) state that PF is an advanced information-technology-based agricultural management system designed to identify, analyze, and manage spatial and temporal variability within fields for optimum profitability, sustainability, and protection of the environment. The suite of PF technologies includes electronic applications such as global positioning systems, yield monitors, geographic information systems, remote sensing, and variable rate technologies (VRT) that use controllers on application equipment to vary input amounts across a farm field. Combining these VRT innovations and site-specific information systems has energized PF research in cotton production. The information systems developed and used by researchers have led to improved optimal decision rules for better management of agricultural practices and inputs.

Adoption of precision farming technology for fertility management

Farmers often use yield monitors as an entry point into precision farming (Lowenberg de Boer 1999). One of the impediments to the adoption of PF technologies by cotton growers was the lack of a reliable cotton yield monitor before 2000 (Larson *et al.* 2005). Seed cotton is much more difficult to measure as it flows through the harvester than grains or oilseeds. Cotton yield monitors were first marketed to farmers in 1997 and had poor accuracy, sensors that were apt to become blocked by dust and other materials, and had problems maintaining calibration (Durrence *et al.* 1999; Wolak *et al.* 1999; Roades *et al.* 2000). Subsequent cotton yield monitor technologies introduced in 2000 appeared to be much more reliable (Perry *et al.* 2001).

Thus, the lack of reliable yield monitors and other technologies that could take advantage of the unique growth and development characteristics of cotton impeded the adoption of PF in U.S. cotton production. In 2000, data from the Agricultural Resource and Management Surveys (ARMS) conducted by the U.S. Department of Agriculture indicated that only 1.3% of cotton area in the United States was yield monitored compared with 34.2% of corn area (USDA ERS 2005). By 2003, the yields measured spatially using yield monitors rose slightly to 1.7% of cotton area. A 2001 mail survey of cotton growers in six southern states in the United States indicated that 2.8% of 1,373 survey respondents used cotton yield monitors (Roberts *et al.* 2002).

Early adoption of PF technology in cotton production focused on fertility and pH management using geo-referenced soil maps, grid soil sampling, management zone soil sampling, and variable rate technology (VRT) for application of fertilizers and lime (Roberts *et al.* 2004). Roberts *et al.* (2004) reported that 17% of 1373 cotton farmers in six southern U.S. states in 2001 used grid or management zone soil sampling to identify fertility and pH needs in cotton fields. This is comparable to the 2000 ARMS data which indicated that geo-referenced soil maps were used on 14.2% of planted cotton area (USDA 2005). However, the cotton area on which cotton farmers were using geo-referenced soil maps had dropped to 4.8% by 2003 (USDA 2005). The drop in map usage between 2003 and 2005 may be partially explained by how farmers were asked about map usage. The 2003 ARMS survey asked if the had ever used a geo-referenced soil map. For the 2005 ARMS survey, farmers were asked about geo-referencing in the current and previous year. Farmers likely do not need to create a new soil map in each year which may explain some of the drop in map usage. The adoption of VRT for application of fertilizers in cotton was also low relative to other crops and was used on only 3.7% of planted cotton area in 2003 (USDA ERS 2005). Low cotton lint prices for this period may also explain the low adoption of PF technology in cotton production.

A limited set of studies have evaluated the factors that have influenced cotton farmers to adopt VRT application of fertilizer and lime. Roberts *et al.* (2004) used probit models to identify factors influencing adoption of PF fertilizer technologies by Southeastern U.S. cotton farmers. They found that younger, more educated farmers who operated larger farms were most likely to adopt site-specific information technology. The probability of adopting VRT was higher for younger farmers who operated larger farms, owned more of the land they farmed, were more informed about the costs and benefits of PF, and were optimistic about the future of PF.

Besides improved profitability, VRT application of fertilizer and lime may result in environmental improvements for farmers. Larkin *et al.* (2005) used a logit model to identify the factors that influenced whether farmers in the Southeastern United States perceived an improvement in environmental quality from adopting PF. Farmers with larger farms or higher yields were more likely to believe they observed positive environmental benefits with PF. Farmers who found PF profitable or who believed input reduction was important had higher probabilities of reporting environmental benefits. Farmers with higher incomes or who were more dependent on farm income were less likely to perceive environmental benefits.

Knowing the factors that influence cotton farmers' perceptions of the importance of PF technologies for improving the efficiency of fertilizer applications can help determine why different groups of farmers adopt such technologies (Torbett *et al.* 2007). Such information can help target specific groups of farmers for the adoption of such technologies to increase fertilizer efficiency in meeting crop needs and reducing the negative environmental impacts of crop fertilization. Torbett *et al.* (2007) found that precision farmers who used grid or management zone soil sampling and on-the-go sensing placed the highest importance on PF technologies while those who used geospatial mapping and remote sensing found PF technologies least important for improving the efficiency of fertilizer applications. Older precision farmers who rented a larger proportion of their land and used a computer for farm management placed greater importance on PF technologies for improving the efficiency of fertilizer applications than other cotton precision farmers.

Profitability of precision farming technology

There was little or no published research on the profitability of PF technology for nutrient management in cotton production before 2000 (Lambert and Lowenberg de Boer 2000). Several studies have subsequently examined the profitability of using PF to manage N, P, K, and lime inputs in cotton production. Larson *et al.* (2005) evaluated investment in a yield monitoring system and VRT to manage fertilizer and lime inputs in cotton production. The example farm was located in the Mississippi Delta region of the United States and had 809 ha (2,000 acres) of cotton and 607 ha (1,500 acres) of other crops. Breakeven yield gains to payback the investment in information technology and VRT were evaluated for N, P, K and lime input savings scenarios that ranged from 25 percent below to 25 percent above uniform rate technology (URT) application rates. Results indicated that a yield gain of 6% more than whole field management yield was required to payback the investment in PF for fertilizer and lime management.

Yu *et al.* (1998) derived spatially optimal N fertilization levels and net revenues for irrigated cotton production and found that VRT application of N fertilizer would result in a 2.29% increase in yield over URT practices. More efficient spatial application of N fertilizer translated into an increase in net revenue of 1.69%. In another VRT N management study, Velandia *et al.* (2006) evaluated using management zones for the application of N fertilizer on irrigated cotton in the High Plains region of Texas in the United States. Their results indicated that delineating N management zones in fields based on potential yield differences throughout the field would result in higher net revenues relative to URT application. The higher net revenues for VRT N fertilization were achieved by more efficiently utilizing N for the whole field. Bronson *et al.* (2006) also found that VRT N fertilization resulted in more consistent lint yield response relative to zero-N plots in all 3 years. However, net returns to fertilizer were significantly greater with VRT N fertilization than URT N fertilization in only 1 of 3 years.

Research by Intarapapong *et al.* (2002) revealed that more than 80% of cotton fields in the Delta region of the United States contain a high level of P (P-level). At a high P-level, P fertilizer is not recommended. Intarapapong, *et al.* (2002) used the Environmental Policy Integrated Climate (EPIC) simulation model to estimate the impact of high P-levels on cotton yields with VRT and URT application of P. Model results showed no change in yields between the recommended VRT and URT application scenario for cotton. However, nitrate runoff and P loss in sediment declined by 4.3% and 3.39%, respectively, with VRT application. Economic net returns increased about \$12.26 ha^{-1} as a result of decreased input costs with VRT.

Roberts *et al.* (2006) examined how applying multiple inputs in fields with multiple management zones using VRT versus URT management influences profitability of cotton. They specifically evaluated N and irrigation water applied to cotton fields with three management zones in the United States using VRT and URT management. Results indicated that the optimal VRT rate of N or irrigation water increased when VRT was used to manage one input and URT was used to manage the other input. Thus, if interactions exist among inputs, single-input VRT may provide sub-optimal net revenues unless URT rates for other inputs are also adjusted. Roberts *et al.* (2006) conclude that the economic viability of single- or multiple-input VRT varies from field to field depending on interactions among inputs, as well as spatial variability and yield response variability among management zones. Thus, no general rule exists for determining whether single- or multiple-input VRT is more profitable than URT application of all inputs because each field is different.

FUTURE RESEARCH DIRECTIONS IN COTTON FERTILITY MANAGEMENT

Soil fertility is the single highest input investment for cotton producers (Bednarz and Ethridge 1990). Good soil-fertility management ensures proper availability of nutrients for maximum production. More than any other nutrient, N can increase or decrease yields of cotton. Excessive application of N not only increases production costs but may also cause rank growth, delay maturity, make defoliation more difficult, and negatively impact yields (Pettigrew and Adamczyk 2006). Rising input costs and static or declining acreage and commodity prices have put pressure to find yield improvements as well as production practices that reduce or control costs to sustain the potential for profitability.

The introduction of legumes into the cotton production system is an area that requires additional research. Vetch crops grown in the fallows of traditional systems have not been fully investigated in cotton production. Maintaining and building soil fertility through soil N and soil organic matter reserves with legumes may reduce reliance on chemical fertilizers, but additional research is needed to determine the impact on cotton growth, yield and overall profit. Benefits of cover crops are not always found in short-term or factorial experiments as they involved long-term and cascading effects on crop and pest communities (Snapp *et al.* 2005). Therefore environmental benefits and costs need to be fully investigated under various conditions.

In addition to the economic soil fertility research presented in this article, a number of new practices, or old practices being used under new conditions, need to be addressed. A significant portion of cotton is currently being grown using conservation-tillage practices. These production practices create unique challenges for soil sampling and fertilization that need to be investigated. Due to recent increases in landfill costs, more and more by-products are becoming available for land application. These materials may be from the agricultural, municipal or industrial sectors and may have value as fertilizer, lime or soil amendments for cotton. The soil fertility aspect of precision farming is certainly an important and popular topic that will continue to require attention, especially since an accurate cotton yield monitor has only recently become available.

Since the late 1990s, seed companies have been bringing new cotton varieties to the market at a rapid rate, but recommended fertilization rates of N, P and K have not kept pace. Biotechnology has only recently been introduced into cotton production on a commercial scale. These innovations have generally taken the form of insect resistance and herbicide tolerance. The adoption of these technologies by producers has been rapid. Widespread adoption of biotechnology and precision agriculture technologies holds tremendous promise of additional benefits. These benefits go beyond the environmental benefits of reduced pesticides and extend to the potential for reducing soil loss and contributing to more sustainable production agriculture. However, more economic research is needed to determine if fertilizer savings are consistent enough to offset the greater costs of variable-rate fertilization.

Finally, profitable cotton production has resulted in the development of a great number of nontraditional growth regulator and nutritional in-furrow and foliar treatment products. These products need to be tested under randomized, replicated, and unbiased experimental conditions to verify their effectiveness. Estimates of the cost reductions induced by the introduction of new technologies are crucial and are often difficult to measure accurately. Emphasis on cotton fertility management has changed from simply "farming by soil" (Robert 1999), through variable-rate technologies, to vehicle guidance systems, and evolved to product quality and environmental management. Thus, cotton production has become more challenging. At various places throughout the world the degree of development varies, and so does the focus on technological innovation. When PF technologies are first introduced into a country, or for use in producing a crop, yield mapping and variable-rate application of inputs are generally adopted to save costs while, in time, product quality and the environment come more into focus. The development of proper decision-support systems for implementing precision decisions remains a major area for economic research. Other critical research issues are insufficient recognition of temporal variation, lack of whole-farm focus, crop quality assessment methods, and product tracking and environmental auditing.

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