The *Journal of Cotton Science 20:18–25 (2016)*
http://journal.cotton.org, © The Cotton Foundation 2016

AGRONOMY AND SOILS

Changing Optimal Nitrogen Levels in Cotton

Frederic B. Ouédraogo*, B. Wade Brorsen, and D. Brian Arnall

ABSTRACT

Cotton (*Gossypium hirsutum L.*) yield has gone up while nitrogen recommendations per bale has trended down. This study seeks to explain why nitrogen recommendations have changed by determining the changes in the production function for cotton. The gain in productivity has several likely explanations including but not limited to successful efforts in plant genetics and improved pest management. The changes in the yield function suggest the sources of increased yields and nitrogen efficiency in cotton. A linear stochastic plateau response function was fit with long-term experimental data from the Altus (Oklahoma) experimental station. The experiment was a randomized complete block design with a combination of nitrogen (N), phosphorus (P), and potassium (K). Only yields of plots where P and K are kept at a constant rate of 59 kg ha^{-1} and 75 kg ha^{-1} were used. Data were collected during the period 1972 to 2010. The maximum likelihood method was used to estimate the parameters of each response function. Because some varieties were only observed in a short period of time (less than three years of observations), the response function could not be estimated for all varieties individually. Data from the first two varieties (Stoneville 213 and Lankart LX-571) and those from the last two varieties (Paymaster 2280 BG RR and Delta Pine 0924 B2RF) were pooled together. The results indicate an increase in the slope that is synonymous with an increased efficiency in nitrogen utilization. The plateau has also shown an increase, which implies improvements in yield potential. The intercept, which represents yield with no nitrogen applied, has increased, but not as much as the slope or plateau. The economically optimal rate of nitrogen was determined for each variety group and the results indicate that optimal nitrogen level ranged between 33 kg ha^{-1} and 85 kg ha^{-1}.

Cotton (*Gossypium hirsutum L.*) lint yields in the United States (U.S.) have trended up since 1925 while the nitrogen (N) per bale recommendation has dropped (Mitchell and Phillips, 2010; Arnall and Boman, 2012). This gain in productivity has several likely explanations including, but not limited to, successful efforts in plant genetics and improved pest management. Several scientists have agreed upon the important role of breeding in cotton yield improvement (Meredith and Bridge, 1972; Davis, 1978; Meredith, 1984; Basu, 1995). Cotton has also benefited from improved pest management, highlighted by eradication of the boll weevil (*Anthonomus grandis Boheman*). Integrated pest management, such as destroying host plant materials and selective use of insecticides, helps keep insects below acceptable damage threshold levels (Alabama Cooperative Extension System, 2014). Insecticides that preserve beneficial insects and more effective herbicides are also major contributors to this increase in yield.

In this study, lint yield response functions were estimated for cotton variety groups to determine changes in parameters of cotton production functions. The stochastic plateau response function was used to estimate cotton lint yield response to N fertilizer. The linear plateau model was adapted from the von Liebig "law of the minimum," which relates yields linearly to the limiting nutrient up to the von Liebig point, where another nutrient becomes limiting. The plateau-type response function therefore consists of two parts: a first part in which yield increases with the amount of nutrient added, and a second part that remains constant or plateaus. The plateau can be assumed deterministic or stochastic. Agronomic studies, such as Girma et al. (2007), now commonly use a quadratic plateau model that is not stochastic. Even though the stochastic plateau model is linear, it yields an expected yield function that is similar to the quadratic plateau model. The considerable advantage of the linear stochastic plateau model over the quadratic non-stochastic plateau model for the purpose of this study is that interpretation is more intuitive.

F.B. Ouédraogo and B.W. Brorsen, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74075; and D.B. Arnall, Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74075
*Corresponding author: frederic.ouedraogo@okstate.edu

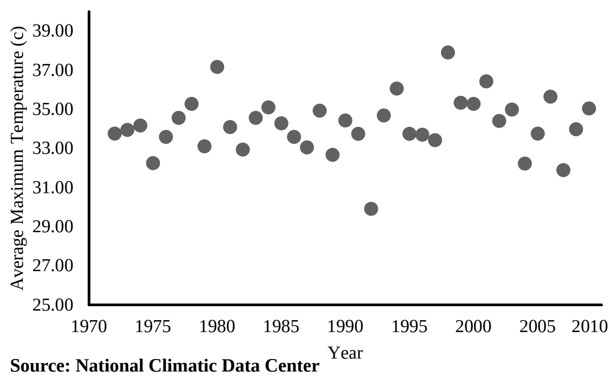
An increase in the intercept of the linear model for instance indicates that yields have gone up over the years even if no N is applied. Such an improvement in lint yield can be credited to improvement in pest management (IPM), cultural practices, and environmental factors (good weather conditions). For example, Oklahoma, like many other states, was severely hit by the boll weevil, until 1998, when the boll weevil eradication program was initiated (Grefenstette and El-Lissy, 2010). Similarly, a difference in the slope coefficients among varieties indicates a difference in nitrogen utilization. Excessive application of nitrogen may be more beneficial to seed yield than lint yield (Egelkraut et al., 2004). One way to use nitrogen efficiently is to lower the seed weight per bale and this has accomplished by plant geneticists. Average seed size has declined over the last three decades (Main et al., 2014), which may explain lower optimal nitrogen recommendations. The plateau reflects the average lint yield potential for each variety. An increase in the yield potential likely indicates an improvement in plant genetics or breeding, but could also be influenced by an improvement in pest management as well as other factors. The results of this study can help determine the relative importance of possible sources of increased yield and the possible factors that have led to increased nitrogen efficiency in cotton production.

MATERIALS AND METHODS

Long-term (38 years) experimental data on cotton varieties were used from the Altus experiment station. A history of this experiment is accessible via Oklahoma State University web site http://nue.okstate.edu/Long_Term_Experiments/E439.htm. The experimental field has Tillman clay loam soil and has been previously and continuously used for cotton production. Planting, fertilizing, and harvesting dates, seeding rates and frequency of irrigation, herbicide application, and insecticide application are reported in Table 1. The planting, fertilization, and harvesting dates have become slightly earlier over time. There was some variation in fertilization dates, which could also add some variation to the results.

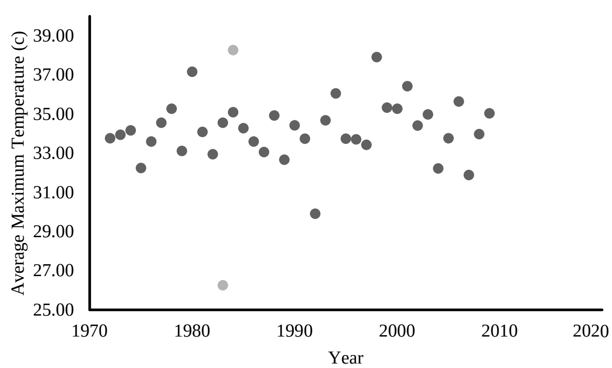
The experiment was a randomized complete block design (RCBD) with four replicates and six treatment (nitrogen) levels. An incomplete factorial combination of nitrogen (N), phosphorus (P), and potassium (K) was applied to different plots during 1972 to 2010. Girma et al. (2007) used data from this experiment for the time period 1989-2004. Only cotton yield response to nitrogen was investigated so that only plots in which P and K were kept at a constant rate of 59 kg ha^{-1} and 75 kg ha^{-1} were used. Fertilizers were broadcast on the surface of the field prior to planting. The six nitrogen treatments included a control (N = 0), 45, 90, 135, 180, and 225 kg ha^{-1}. The nitrogen was surface broadcast and incorporated prior to planting. In early years, ammonium nitrate was used (Oklahoma State University Undated), but urea has been used in more recent years. No nitrification inhibitors were ever used. Because lint yield decreased at the highest level of nitrogen, only the first five nitrogen levels were used.

Each plot was 18.3 meters long with six 1.02 m spaced rows. Cotton was produced using furrow irrigation. Due to limits on available irrigation water and rainfall variability, the number of irrigation events per year varied from one to eight times. The annual averages of water received per irrigation varied from 76 to 101 mm of water. The amount of water received by the plants was a function of the frequency of irrigation. Figure 1 and Figure 2 show average maximum temperature and total rainfall, respectively, for a nearby station (Altus DAM, Oklahoma). Data were retrieved from the National Climatic Data Center.



Source: National Climatic Data Center

Figure 1. Average Maximum Temperature from June to July at Altus DAM, Oklahoma



Source: National Climatic Data Center

Figure 2. Average Rainfall Received in Altus DAM Station from June to August

Eight cultivars: *Stoneville 213* (1972-1974), *Lankart LX-571* (1975-1977), *Westburn M* (1978-88), *Paymaster 145* (1989-94), *Paymaster HS26* (1995-00), *Paymaster 2326 BG RR* (2001-05), *Paymaster 2280 BG RR* (2006-08), and *Delta Pine 0924 B2RF* (2009-10) were grown. Data from the first two varieties (*Stoneville 213* and *Lankart LX-571*) and those from the last two varieties (*Paymaster 2280 BG RR* and *Delta Pine 0924 B2RF*) were pooled due to a limited number of observations. The cultural practices consistently followed the practices used by neighboring farmers. The number of pesticide and herbicide applications is shown in Table 1. The new varieties have reduced the number of insecticide applications. The number of herbicide applications has not decreased, but presumably herbicides have become more effective. Harvesting was mechanical and only the middle rows of each plot are collected for the purpose of the experiment.

Stochastic Plateau Response Functions. The stochastic plateau response function used here was developed by Tembo et al. (2008) and can be mathematically expressed as:

$$y_{it} = \min(\alpha_0 + \alpha_1 n_i, \varpi + u_t) + v_t + \varepsilon_{it} \quad (1)$$

where y_{it} is cotton yield for the *i*th treatment in year *t*, n_i is the amount of nitrogen used on the *i*th treatment, ϖ is the average yield potential, α_0 and α_1 are parameters of the model to be estimated, $u_t \sim N\left(0,\sigma_u^2\right)$, $v_t \sim N\left(0,\sigma_v^2\right)$, and $\varepsilon_{it} \sim N\left(0,\sigma_\varepsilon^2\right)$ are the plateau random effect, the intercept year random effect, and the random error term, respectively, with all three error terms being independent.

The response function (1) was estimated separately for each of the five groups. The intercept year random effect $\left(u_t\right)$ reflects a shift of the whole yield function up or down. The plateau random effect, $\left(v_t\right)$ allows year-to-year variation of the expected yield potential. This might be mainly due to favorable or severe environmental conditions such as rainfall, heat, or irrigation. Even though the cotton was irrigated, rainfall would also be beneficial. High temperature may lead to significant decrease in lint yield as a result of high respiration (Arevalo et al., 2003). Reddy et al. (1992) analyzed lint yield under different heat scenarios in Mississippi and found that maximum yield was achieved at a mean temperature between 25° and 28°C. Since weather is unpredictable at the time of the fertilization decision, weather was modeled as part of the error terms.

Optimization Problem. Assuming risk neutrality, the optimization problem is to select the level of nitrogen that maximizes expected net returns:

$$\max_n E(\pi \mid n) = pE(y \mid n) - rn \quad (2)$$

such that $y = \min(\alpha_0 + \alpha_1 n, \varpi + u)$ and $n \geq 0$ where $E\left(\pi \middle| n\right)$ is the expected net returns conditional on the amount of nitrogen applied, *p* is the price of a kilogram of cotton and *r* the price of a kilogram of nitrogen. Since agricultural commodity and input prices are volatile, a sensitivity analysis was conducted over the output and nitrogen prices. Cotton price was the average price received by the farmers during the last five years (2010 – 2014). Price data were retrieved from the National Cotton Council (NCC) monthly price reports. The five-year average price was $1.72 per kilogram. Two additional prices corresponding to 20% below and above the average price were also considered. The three input price scenarios were $0.66 per kilogram, $1.10 per kilogram, and $1.43 per kilogram.

Optimal nitrogen was determined as in Tembo et al. (2008):

$$n^* = \left(\frac{Z_\alpha \sqrt{\sigma_u^2}}{\alpha_1} + \frac{\left(\varpi - \alpha_0\right)}{\alpha_1} \right) \quad (3)$$

where $Z_\alpha = \left(\alpha_0 + \alpha_1 n - \varpi\right)\sigma_u^{-1}$ was a quantile of a standard normal distribution and *n** represented the profit maximizing level of nitrogen.

RESULTS AND DISCUSSION

As shown in Fig.4, average lint yield was relatively higher for the new varieties as compared to Stoneville, Lankart, and Westburn. At the control level of nitrogen, varieties grown before 1996 produced on average between 336 and 560 kg ha^{-1} whereas the newest varieties yielded more than 672 kg ha^{-1}. Lint yields have doubled and tripled since 1996. The most recent four varieties showed a jump in yield even with no nitrogen applied, which might reflect improved pest resistance, but could also reflect genetic changes such as reduced seed size.

Yield Response Functions. A likelihood ratio test was conducted to test the joint null hypothesis that the parameters for each variety were the same and thus the data could be pooled. The test consists of estimating the restricted model (the pooled data) and obtaining the log-likelihood. Then estimating the response function for each individual variety and computing the unrestricted model log-likelihood by summing up the log-likelihood obtained for each variety. The likelihood ratio statistic $-2\ln\left[(R)/(U)\right] = 9705.2 - 9383.9 = 321.3$, where (R) and (U) are the likelihood of the restricted model and the unrestricted model, respectively, is greater than $\chi^2_{.05(30)} = 43.8$, so the pooled model could be rejected.

Table 1. Annual Details on Experiment 439

Year	Variety	Seeding Rates	Frequency			Dates of		
			Irrigation	Herb	Insect	Fertilizing	Planting	Harvesting
1972	ST 213	22	3	1	-	5/15/1972	5/31/1972	12/22/1972
1974	ST 213	22	2	1	-	5/10/1974	5/30/1974	12/18/1974
1975	LKT LX	21	1	1	-	5/19/1975	5/16/1975	12/3/1975
1976	LKT LX	20	5	1	-	5/12/1976	5/18/1976	11/19/1976
1977	LKT LX	21	2	1	-	4/8/1977	5/17/1977	11/18/1977
1978	WEST	21	4	1	-	8/7/1978	5/10/1978	12/7/1978
1979	WEST	21	1	2	-	5/17/1979	5/31/1979	12/7/1979
1980	WEST	21	6	1	-	7/24/1980	5/22/1980	12/2/1980
1981	WEST	20	1	2	-	7/16/1981	5/23/1981	12/2/1981
1982	WEST	21	4	1	-	5/19/1982	5/20/1982	1/11/1983
1983	WEST	21	7	2	-	5/11/1983	6/1/1983	12/9/1983
1984	WEST	21	5	1	-	4/26/1984	5/24/1984	1/1/1985
1985	WEST	21	4	1	-	5/17/1985	5/17/1985	12/21/1985
1986	WEST	18	3	1	-	5/10/1986	5/23/1986	1/6/1987
1987	WEST	18	4	2	1	5/11/1987	5/13/1987	12/2/1987
1988	WEST	18	6	1	2	5/4/1988	6/21/1988	11/30/1988
1989	PM 145	16	3	3	4	4/27/1989	5/23/1989	11/8/1989
1990	PM 145	21	2	3	2	5/14/1990	5/15/1990	11/2/1990
1991	PM 145	21	4	3	4	3/11/1991	5/28/1991	12/5/1991
1992	PM 145	17.8	1	2	6	5/5/1992	7/1/1992	2/1/1993
1993	PM 145	17.6	5	2	9	3/25/1993	5/27/1993	11/30/1993
1994	PM 145	18.4	5	3	3	4/21/1994	5/10/1994	10/4/1994
1996	PM HS26	17.2	3	2	7	4/25/1996	5/9/1996	11/7/1996
1997	PM HS26	17.2	2	3	11	4/22/1997	5/14/1997	10/31/1997
1998	PM HS26	17.2	7	3	14	4/23/1998	5/19/1998	10/9/1998
1999	PM HS26	17.2	5	2	7	5/14/1999	5/19/1999	10/21/1999
2000	PM 2326	17.2	4	5	6	-	-	-
2001	PM 2326	16.2	4	5	4	4/10/2001	5/23/2001	10/31/2001
2002	PM 2326	16.2	5	4	2	3/28/2002	5/14/2002	10/4/2002
2003	PM 2326	16.2	5	5	3	4/10/2003	5/22/2003	11/21/2003
2004	PM 2326	16.2	4	3	3	4/15/2004	5/15/2004	11/11/2004
2005	PM 2326	16.2	4	4	1	4/27/2005	5/9/2005	11/7/2005
2006	PM 2280	15.2	5	5	3	4/20/2006	5/15/2006	11/3/2006
2007	PM 2280	15.2	5	4	3	4/26/2007	5/19/2007	10/25/2007
2008	PM 2280	15.2	6	5	2	4/28/2008	5/13/2008	11/5/2008
2009	DP 0924	15.2	8	6	2	3/6/2009	5/20/2009	11/13/2009
2010	DP 0924	15.2	7	3	2	3/23/2010	5/5/2010	10/19/2010

Note: ST 213 = Stoneville 213, LKT LX = Lankart LX, WEST = Westburn M, PM = Paymaster, DP = Delta Pine. Insecticide treatments for 1972-1986 were as needed, but data are unavailable. In the early years, tillage was used in addition to herbicides.

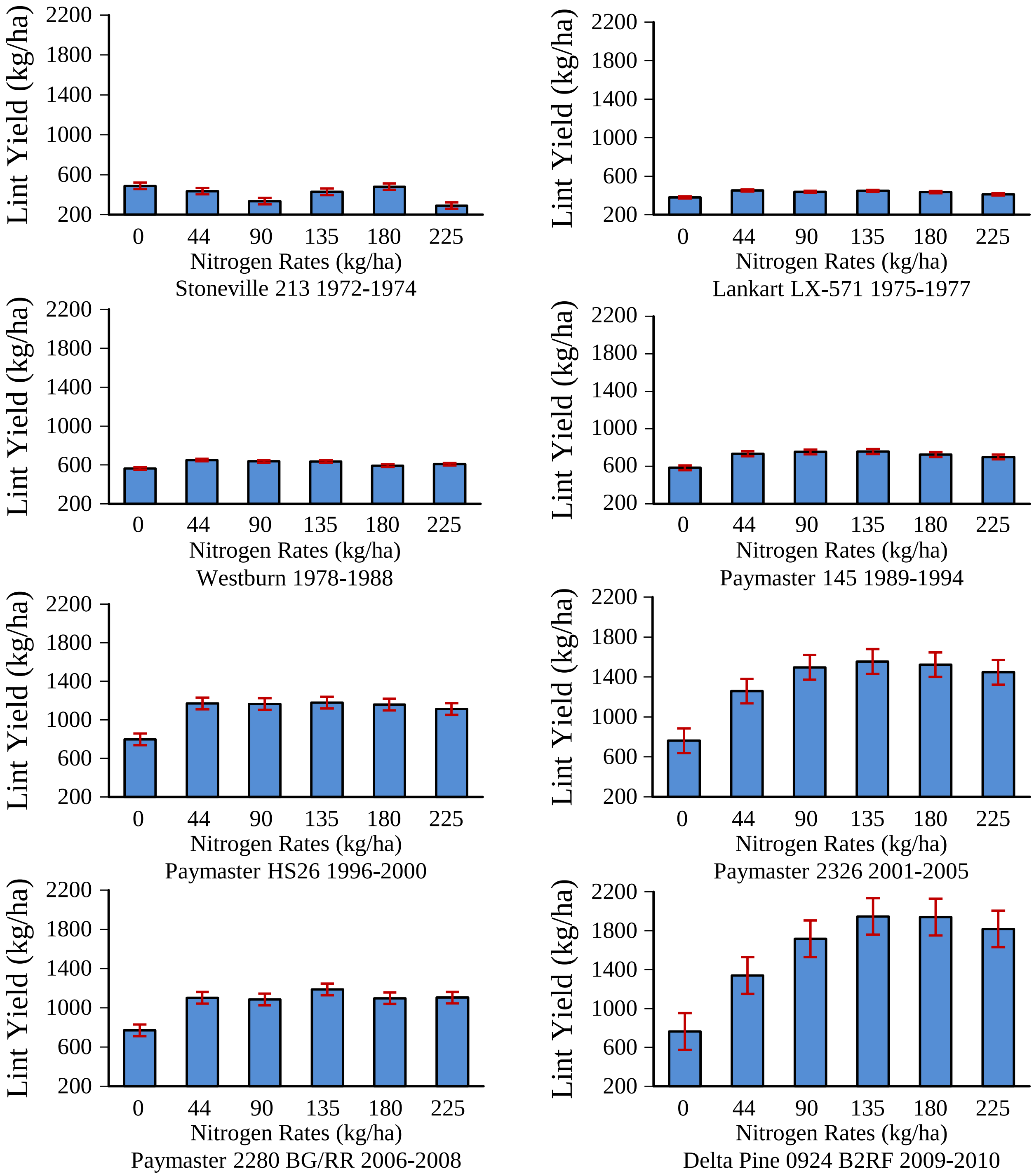


Figure 3. Lint Yield Response to Nitrogen Fertilizer for each Cotton Variety

The maximum likelihood estimates of the yield response functions for each variety group are presented in Table 2. All parameters except those of the Stoneville variety group were statistically significant with a p-value <0.0001. The intercept ranged from 463 kg ha^{-1} to 849 kg ha^{-1}. The newest varieties had the highest intercepts. A smaller seed size could allow cotton to produce more lint with the same amount of nitrogen. Insect damage would reduce yield at all levels of nitrogen and so the pest resistance and insect eradication efforts could also explain the increase in intercept. Compared to the two other parameters of interest, the intercept did not change as much between the old variety groups and the new variety groups.

Table 2. Maximum Likelihood Estimates of Cotton Lint Yield Response to Nitrogen per Variety Group

Parameter	Stoneville 213[Z]	Westburn M	Paymaster 145	Paymaster HS26	Paymaster 2326	Paymaster 2280 BG/RR[Z]	All Cotton
Intercept	463.58[Y] (27.69)	643.02[Y] (22.84)	689.98[Y] (26.37)	690.12[Y] (22.58)	790.30[Y] (40.61)	849.01[Y] (43.60)	642.93[Y] (14.36)
Slope	3.14 (361.76)	6.27† (1.38)	11.38† (1.31)	13.11† (1.08)	11.37† (1.10)	12.76† (1.01)	12.19† (0.56)
Plateau	506.00† (15.06)	784.65† (10.05)	909.11† (11.81)	965.64† (14.01)	1480.58† (38.24)	1422.22† (24.66)	961.76† (7.36)
Variance of the plateau error	36912.00† (9769.87)	25104.00† (2675.60)	21407.00† (2970.99)	12352.00† (2105.00)	14075.00† (3386.73)	70472.00† (6287.28)	43220.00† (1428.00)
Variance of the intercept error	16054.00† (4035.93)	5680.00† (983.10)	12870.00† (2744.93)	16906.00† (2117.01)	3104.57† (3014.04)	18018.00† (4313.73)	20431.00† (1396.93)
Variance of the error term	11365.00† (1608.48)	10110.00† (975.61)	10396.00† (1349.02)	7615.73† (1080.89)	20781.00† (3134.91)	31650.00† (4571.12)	16619.00† (810.59)
-Log Likelihood	617.00	1357.00	752.35	604.40	649.00	683.40	4819.50

[Z] Stoneville 213 = Stoneville 213 and Lankart LX. Paymaster 2280 BG/RR = Paymaster 2280 and Delta Pine.

[Y] P-value not significant.

† P-value <0.001 implies that the estimated parameter is statistically different than zero at any conventional significance level Values in parentheses represent the standard errors of the parameter estimates.

The slope, reflecting the productivity in response to increasing nitrogen rate increased sharply, but leveled off with recent varieties. Paymaster HS26 was the most responsive to nitrogen with a response rate of 14 kg ha^{-1}. This response rate of the Paymaster HS26 was more than three times the response rate of the older varieties (Stoneville 213, Lankart LX, and Westburn M). The slope was insignificant for the earliest variety, which suggested that nitrogen was not the limiting factor even when no nitrogen was applied. The reduced nitrogen per bale recommendations (Mitchell and Phillips, 2010; Arnall and Boman, 2012) were consistent with the increase in slope. Pests may act to reduce yield proportionally rather than as a limiting factor and the increased slope could be explained by pest reductions as well as genetics.

In terms of average yield potential, the two newest varieties were the leading varieties. The increase in the average expected plateau was consistent with an improvement in plant genetics. The duration of maturity of the new varieties was relatively shorter than that for the previous specimen as reflected in the earlier harvest dates shown in Table 1. The earlier maturity reduced the effect of late rainfall stress and heat on yields. The expected yield plateau was below 1,000 kg ha^{-1} for the conventional varieties and up to 1,480 kg ha^{-1} for Paymaster 2326 BG/RR. The improvements in genetics and pest control have made it possible to apply nitrogen at higher levels before it is no longer the limiting factor.

Among the three estimated parameters, the expected plateau and the slope had the highest increase from one variety to the next.

Economically Optimal Levels of Nitrogen. Optimization results are presented in Table 3. The profit maximizing rates of N ranged from 33 kg ha^{-1} to 85 kg ha^{-1}. The newest varieties, Delta Pine and Paymaster 2280, benefited from a relatively high level of nitrogen (74 to 85 kg ha^{-1}). The response function of the Stoneville 213 did not yield statistically significant parameter estimates, therefore the nitrogen requirement for this variety should be interpreted with caution.

At the input-output price of $1.43 per kilogram of nitrogen and $1.72 per kilogram of cotton, Westburn and Paymaster 145 required 50 kg ha^{-1} and 38 kg ha^{-1}, respectively. This is at least 6 kg ha^{-1} lower than the official recommended rates issued by the Oklahoma State University extension program. For Paymaster 2326, optimal nitrogen was higher than the official rate, but given the high yield potential of this variety, it is worth applying such an amount of nitrogen. Note that conditions on an experiment station may be more ideal than on farmers' fields, so the results do not necessarily mean that the extension recommendations are wrong. Paymaster HS26 at any price scenario required less nitrogen than 56 kg ha^{-1} as recommended by the Oklahoma State extension service. The low nitrogen recommendation for Paymaster HS26 is primarily due to it having a large slope parameter. When the price of cotton reaches a peak at $2.00 per kilogram and the nitrogen price is down to $0.66 per kilogram, an expected-profit-maximizing producer would apply 85 kilogram per hectare of Paymaster 2280.

Table 3. Optimal Nitrogen Rates as Variety, Nitrogen Price and Cotton Price Change

	Price of cotton: $1.38/kg								
	Price of nitrogen: $0.66/kg			Price of nitrogen: $1.10/kg			Price of nitrogen: $1.43/kg		
	RatesZ	Std. ErrY	Rates/bale	Rates	Std. Err	Rates/bale	Rates	Std. Err	Rates/bale
Stoneville 213	76.3	4236.0	28	54.0	637.5	19	40.4	1771.8	16
Westburn M	58.7	8.8	16	51.4	7.1	14	47.2	6.2	13
Paymaster 145	41.5	3.9	10	38.2	3.6	9	36.4	3.4	9
Paymaster HS26	36.2	2.3	8	34.1	2.5	8	33.0	2.4	8
Paymaster 2326	78.8	6.4	12	76.1	6.1	11	74.6	5.9	11
Paymaster 2280	81.9	5.0	13	76.8	4.6	12	74.0	4.4	11
All cotton	56.1	2.1	13	51.9	1.9	12	49.5	1.8	11
	Price of cotton: $1.72/kg								
Stoneville 213	84.8	5513.1	25	64.2	2323.8	22	52.0	284.6	19
Westburn M	61.6	9.5	17	54.7	7.9	15	50.7	7.0	14
Paymaster 145	43.3	4.1	10	39.7	3.7	10	37.9	3.5	9
Paymaster HS26	37.0	2.8	8	35.0	2.6	8	33.9	2.5	8
Paymaster 2326	79.8	6.5	12	77.3	6.2	11	75.9	6.1	11
Paymaster 2280	84.0	5.2	13	79.1	4.8	12	76.4	4.6	12
All cotton	57.8	2.2	13	53.8	2.0	12	51.5	1.9	12
	Price of cotton: $2.06/kg								
Stoneville 213	91.2	6474.2	26	71.9	3545.4	23	60.5	1724.4	21
Westburn M	63.9	10.0	18	57.2	8.5	16	53.5	7.6	15
Paymaster 145	43.8	4.1	11	40.8	3.8	10	39.1	3.7	9
Paymaster HS26	37.7	2.8	9	35.8	2.6	8	34.7	2.5	8
Paymaster 2326	80.6	6.6	12	78.2	6.3	12	76.9	6.2	11
Paymaster 2280	85.6	5.3	13	80.9	5.0	12	78.3	4.8	12
All cotton	59.2	2.2	13	55.3	2.0	13	53.1	1.9	12

Z The optimal N levels are the expected profit maximizing levels calculated following Tembo et al. (2008).

Z The standard errors are calculated using the delta rule.

CONCLUSIONS

Long-term experimental cotton data from the Altus, OK experimental station were used to determine the changes in parameters that explain increased cotton lint yield and improved efficiency in nitrogen use. Five cotton variety groups were used and a stochastic plateau model was fit to each variety group's yield data. The yield plateau was assigned a stochastic error component, which allowed the plateau to vary across years.

A preliminary data analysis was conducted to ensure that different varieties yielded unequal lint quantity. The analysis of variance showed that the newest varieties (those grown after 1996) were more productive than the older varieties. Variations of the parameters of interest (intercept, slope, and plateau) were used to explain the improvement in cotton lint yield.

Results indicated substantial increases in both the slope and the plateau parameters. This yield improvement can be explained by factors such as improved plant genetics and increased pest management efforts, but we cannot rule out other factors. Intercepts did not show as much increase as the other two parameters, but they also showed that the new varieties perform better than the older varieties. The optimization results indicated that optimal nitrogen level ranges between 33 kg ha^{-1} and 85 kg ha^{-1}. In terms of kilogram per bale, the newest varieties required 11 to 12 kg N for each bale produced.

ACKNOWLEDGEMENTS

This research benefited from financial support from the Oklahoma Agricultural Experiment Station, USDA National Institute of Food and Agriculture Hatch Project number OKL02939, the A.J. and Susan Jacques Chair, and the Nutrients for Life Foundation Professorship of Soil & Food Crop Nutrition. We also want to thank the many people who made the research possible by collecting the data over the years. Some of these people are Billy Tucker, who started the experiment, Robert Westerman, William Raun, Randy Boman, and current station superintendent Rocky Thacker.

REFERENCES

Alabama Cooperative Extension System. 2014. Insect, disease, nematode, and weed control recommendations for 2014. Extension System, IPM-0415.

Arevalo, L.S., D.M. Oosterhuis, D. Coker, and R.S. Brown. 2008. Physiological response of cotton to high night temperature. American Journal of Plant Sciences and Biotechnology 2:63-68.

Arnall, B., and R. Boman. 2012. Cotton yield goal – nitrogen rate recommendation.

Oklahoma Cooperative Extension Service PSS-2158.

Basu, A.K. 1995. Hybrid cotton results and prospects. p. 335–341. In G.A. Constable and N.W. Forester (ed.) Challenging the Future. Proc. World Cotton Res. Conf., Brisbane, Australia. 14–17 Feb. 1994. CSIRO, Australia.

Davis, D.D.1978. Hybrid cotton: special problems and potentials. Advances in Agronomy 30:129-147.

Egelkraut, T.M, D.E. Kissel, M.L. Cabrera, G.J. Gascho, and W. Adkins. 2004. Nitrogen concentration in cottonseed as an indicator of N availability. Nutrient Cycling in Agroecosystems 68:235-242.

Girma, K., R.K. Teal, K.W. Freeman, R.K. Boman, and W.R. Raun. 2007. Cotton lint yield and quality as affected by applications of N, P and K fertilizers. Journal of Cotton Science 11:12–19.

Grefenstette, B., and O. El-Lissy. 2010. Boll Weevil eradication update. Beltwide Cotton Conferences, Nashville, TN.

Main, L.C., L.T. Barber, R.K. Boman, K. Chapman, D.M. Dodds, S. Duncan, K.L. Edmisten, P. Horn, M.A. Jones, G.D. Morgan, E. R. Norton, S. Osborne, J.R. Whitaker, R.L. Nichols, and K.F. Bronson. 2014. Effects of nitrogen and planting seed size on cotton growth, development and yield. Agronomy Journal 105(6):1853-1859.

Meredith, W.R., Jr., and R.R. Bridge. 1972. Heterosis and gene action in cotton, *gossypium hirsutum L.* Crop Sci. 12:304–310.

Meredith, W.R., Jr. 1984. Quantitative genetics. p. 131–150. In R.J. Kohel and C.F. Lewis (ed.) Cotton. Agron. Monogr. 24. ASA, CSSA, and SSSA, Madison, WI.

Mitchell, C.C., and S. Phillips. 2010. "Nitrogen recommendations." p. 9-17. In Research-Based Soil Testing and Recommendations for Cotton on Coastal Plain Soils. Southern Cooperative Series Bulletin No. 410.

National Cotton Council (NCC). http://www.cotton.org/econ/prices/monthly.cfm.

Oklahoma State University. Undated. "Experiment 439: Long-Term Application of N, P, and K in continuous Cotton, 1965-2000." Accessed October 2015. Available at http://nue.okstate.edu/Long_Term_Experiments/E439.htm.

Reddy, K.R., H.F. Hodges, and V.R. Reddy. 1992. Temperature effect on Pima cotton growth and development." Agronomy Journal 84:26-30.

Tembo, G., B.W. Brorsen, F.M. Epplin, and E. Tostão. 2008. Crop input response functions with stochastic plateaus. American Journal of Agricultural Economics 90:424-34.