Nitrogen Carry-over Impacts in Irrigated Cotton Production, Southern High Plains of Texas

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A dynamic optimization model which introduces an intertemporal nitrate-nitrogen residual function is used to derive and evaluate nitrogen fertilizer optimal decision rules for irrigated cotton production in the Southern High Plains of Texas. Results indicate that optimal nitrogen applications critically depend on initial nitrate-nitrogen levels and nitrogen-to-cotton price ratios. Also, the results indicate that single-year optimization leads to suboptimal nitrogen applications, which helps explain long-term cotton yield declines in the Southern High Plains of Texas; but single-year optimization does not significantly impact the net present value of returns of irrigated cotton operations.

Key words: dynamic optimization, nitrogen carry-over, production efficiency.

The agricultural sector's economic and political environment coupled with producers' inability to influence either output or input prices highlight the importance of input use efficiency in production as a key component for profitability and survival. In this study, efficiency in irrigated cotton production stemming from optimal nitrogen fertilizer applications is addressed.

The primary objective of this study is to empirically derive and evaluate nitrogen fertilizer optimal decision rules for irrigated cotton in the Southern High Plains of Texas. In particular, a dynamic optimization model of nitrogen utilization which introduces an intertemporal nitrate-nitrogen carry-over function in the optimization procedure is presented.

The Study Area

The Southern High Plains of Texas (SHPT) is a semiarid region located in the western part of the state, encompassing some 22 million acres (35,000 square miles) in 42 counties. Three major soil resource areas can be identified in the SHPT: hardlands, composed of fine-textured clays and clay loams, comprising 54% of the area; mixedlands, composed primarily of medium-textured loams and loamy sands, representing 23% of the area; and sandylands, composed of coarse-textured sands, also representing 23% of the area (Lee).

The major crops produced in the area are cotton, wheat, and grain sorghum. Cotton's relative importance increased from 35% of the planted acreage during the 1971–82 period to 59% in 1985 (Texas Agricultural Statistics Service). The fact that cotton is the most important crop in the SHPT coupled with evidence of declining profit margins in recent years (Eth-

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ridge and Bowman) stimulated this study focusing on optimization of nitrogen fertilizer applications in irrigated cotton production.

The Optimization Model

Contemporary studies addressing the impacts of nitrogen fertilizer applications and nitrate-nitrogen residual on crop yields (Carter, Jensen, and Bosma; Hooker, Gwin, and Gallagher; Onken and Sunderman; Onken, Matheson, and Nesmith; Roberts, Weaver, and Helps) have revealed that accumulation of residual nitrate-nitrogen in sufficient quantities affects crop yields. That is, total nitrogen available to plants at a given time is a function of applied nitrogen and residual nitrate-nitrogen at that time. Further, residual nitrate-nitrogen at a particular point in time is, in turn, a function of previous nitrogen applications and previous levels of residual nitrate-nitrogen. Therefore, in deriving optimal decision rules for nitrogen fertilizer applications, a dynamic model which accounts for such relationships must be used. Previous studies addressing both deterministic and stochastic derivation of optimal fertilization decision rules which introduce carry-over functions include Godden and Helyar; Kennedy (1980, 1986a, b); Kennedy et al.; Stauber, Burt, and Linse; and Taylor.

The deterministic specification of the empirical dynamic optimization model formulated in this study to derive nitrogen fertilizer optimal decision rules follows that of Kennedy et al.:

$$(1)\quad \underset{\{NA_t\}}{\mathrm{Max}}\ Z = \sum_{t=0}^{n} \{[P_t \cdot Y_t(NT_t) - CN_t \cdot NA_t] \cdot (1 + r)^{-t}\}$$

subject to:

$$(2)\quad NT_t = NA_t + NR_t,$$
$$(3)\quad NR_{t+1} = f_t[NA_t, NR_t],$$
$$(4)\quad NR_0 = NR(0),$$

and

$$NA_t, NR_t, NT_t \geq 0 \qquad \text{for all } t,$$

where, Z is the per-acre present value ($) of returns to land, irrigation water, overhead, risk, and management from cotton production; n is the length of the planning horizon, in years, of the decision maker (the farmer in this case); P_t is the cotton price ($/lb.) in year t; Y_t is the cotton yield function (lbs./acre) in year t; NT_t is the nitrogen available to the cotton plants (lbs./acre) in year t; CN_t is the price of nitrogen ($/lb.) in year t; NA_t is the nitrogen applied (lbs./acre) in year t; r is the discount rate; and NR_t is the nitrate-nitrogen residual (lbs./acre) in year t.

Equation (1) represents the objective function, or performance measure, of the optimization model. Equation (2) is an equality constraint which adds up the applied nitrogen and nitrate-nitrogen residual at time t, and is used as a variable in equation (1) to compute the current cotton yield. Equation (3) is the equation of motion of the model which updates the nitrate-nitrogen residual necessary for equation (2). Equation (4) is an initial condition on nitrate-nitrogen residual. Finally, the nonnegativity constraints on the decision and state variables of the model are specified.

The yield response function, Y_t in equation (1), and the nitrate-nitrogen residual function, equation (3), were estimated using data from three experimental sites in the SHPT over a three-year period (Sunderman; Sunderman, Onken, and Jones). Additional data on irrigation, rainfall, temperature, residual nitrogen, and soil moisture conditions were obtained from experimental records at the Texas Agricultural Experiment Station at Lubbock, Texas, and the National Oceanic and Atmospheric Administration (U.S. Department of Commerce).

Variables directly under the farmer's control and which influence irrigated cotton yields include the level of fertilization, level of irrigation, row spacing, seed variety, and planting data. Other factors not directly under the farmer's control influencing irrigated cotton yields include soil type, level of rainfall, and temperature. Alternative model specifications and explanatory variables, using logarithmic, Mitscherlich-Spillman, and quadratic functional forms to capture diminishing marginal returns, of the yield response function were estimated using linear and nonlinear regression techniques. The best function obtained in the process was:

$$(5)\quad \begin{aligned} Y_t = {} & \underset{(.69)}{177.84} + \underset{(2.64)}{15.03}[\ln(NT_t \cdot HU_t)] \\ & + \underset{(1.61)}{38.15}[\ln(W_t \cdot HU_t)] + \underset{(3.70)}{18.33}\, RWSP \\ & + \underset{(3.61)}{39.10}\, VAR - \underset{(-8.29)}{51.28}\, MDEF_t \\ & - \underset{(-12.27)}{203.48}\, ST1 - \underset{(-2.14)}{32.89}\, ST2 \qquad R^2 = .367, \end{aligned}$$

where, Y_t and NT_t are as defined previously; HU_t, the accumulated daily heat units received during the cotton-growing season in year t in degrees Fahrenheit (daily heat units are computed as [(daily high temperature + daily low temperature)/2] − 60); W_t, the inches of water received during the growth period in year t; $RWSP$, the number of rows per 40-inch bed; VAR, a dummy variable to indicate cotton variety, $VAR = 0$ for Paymaster Dwarf and $VAR = 1$ for Dunn 56-C; $MDEF_t$, the cumulative soil moisture deficiency measured as in inches of water needed to fill the soil profile during the cotton-growing season in year t; $ST1$ and $ST2$, dummy variables to indicate soil resource area where $ST1 = ST2 = 0$ indicates mixedlands, $ST1 = 1$ indicates hardlands, and $ST2 = 1$ indicates sandylands; and ln denotes the natural logarithm of the variable.

The values in parenthesis below the estimated parameters in equation (5) are their associated t-values. Each of the estimated parameters was significant at the .05 level with the exceptions of the intercept, which was significant at the .21 level, and the parameter of the $\ln(W_t{*}HU_t)$ variable, which was significant at the .10 level.

Based on prior information with respect to the specification of the adequate functional form of the residual nitrate-nitrogen carry-over function for irrigated cotton production in the top six inches of the soil profile for the mixedlands soil resource area by Sunderman and by Sunderman, Onken, and Jones, the estimated carry-over function was:

$$(6)\quad \underset{}{NR_{t+1}} = \underset{(-2.12)}{-2.167} + \underset{(6.07)}{.0199}\, NA_t + \underset{(14.77)}{.9922}\, NR_t$$

$$R^2 = .86,$$

where the variables are defined as before and parameter t-values are reported as before. Estimated parameters in equation (6) were significant at the .01 level except for the intercept, which was significant at the .05 level.

To derive optimal decision rules with respect to nitrogen applications, cotton production experts were consulted to specify representative appropriate levels of all variables in equation (5) except for the nitrogen variable (Lyle; Onken; Supak). That is, representative levels for HU, W, $RWSP$, and $MDEF$ in equation (5) for irrigated cotton production were substituted to derive six cotton yield functions, corresponding to two cotton varieties and the three alternative soil resource areas for the SHPT. Values substituted in equation (5) were: $W_t = 6.50$, $MDEF_t = 4.30$, $RWSP_t = 1$, and $HU_t = 2{,}271$. These substitutions and appropriate substitution of the dummy variables in equation (5) provided the following general functional form of the cotton yield function:

$$(7)\qquad Y_t = I_v^s + 15.03 \ln(NT_t),$$

where I_v^s corresponds to the intercept of the yield function for a given soil resource area and cotton variety combination. In particular, the intercepts were: 293.66 pounds for the Dunn variety and 254.56 pounds for the Paymaster variety grown in the hardlands, 497.14 pounds for the Dunn variety and 458.04 pounds for the Paymaster variety grown in the mixedlands, and 464.25 pounds for the Dunn variety and 425.15 pounds for the Paymaster variety grown in the sandylands. Equation (7) provided the yield functions used to solve the optimization model in equation (1).

Results

The optimization model depicted in equations (1)–(4) was solved for the mixedlands soil resource area (MSRA) and the Dunn 56-C cotton variety combination assuming: (*a*) a ten-year planning horizon; (*b*) five alternative levels of cotton price (.40, .45, .50, .55, .60 dollars per pound); (*c*) five alternative levels of nitrogen price (.10, .15, .20, .25, .30 dollars per pound); and (*d*) two alternative initial conditions of nitrate-nitrogen residual in pounds per acre (16.3 and 30.0). Also, alternative discount rates were used, but the results reported here correspond to those with a 5% discount rate ($r = .05$).

As expected, optimal decision rules for applied nitrogen varied across periods for a given nitrogen and cotton price combination at a given nitrate-nitrogen initial condition. However, because a more stable optimal decision rule was desired to simplify management implementation, for a given nitrogen and cotton price combination and initial residual nitrogen condition, an additional constraint equating nitrogen applications across periods was introduced. Another justification for the introduction of this additional constraint is the fact that nitrogen and cotton prices vary year to year,

Table 1. Per-Acre Dynamic Optimal Levels of Applied Nitrogen and Associated Net Present Value of Returns for Alternative Cotton-Nitrogen Prices, Assuming 16.3 lbs./acre Initial Condition on Nitrate-Nitrogen, MSRA[a] of the SHPT[b]

Nitrogen Price ($/lb.)	Cotton Price ($/lb.)				
	.40	.45	.50	.55	.60
			Nitrogen Application (lbs./acre/year)		
.30	15.06	17.36	19.70	22.07	24.46
.25	18.76	21.59	24.46	27.35	30.26
.20	24.46	28.08	31.72	35.39	39.07
.15	34.16	39.07	43.99	48.93	53.88
.10	53.88	61.33	68.79	76.25	83.73
			Net Present Value of Returns ($/acre, 10-year planning horizon)		
.30	1,727.74	1,948.62	2,170.13	2,392.22	2,614.83
.25	1,734.55	1,956.46	2,179.02	2,402.17	2,625.85
.20	1,743.22	1,966.43	2,190.30	2,414.76	2,639.77
.15	1,754.91	1,979.83	2,205.41	2,431.59	2,658.32
.10	1,772.21	1,999.56	2,227.59	2,456.22	2,685.40

[a] Mixedlands soil resource area.
[b] Southern High Plains of Texas.

and thus a "rolling horizon" dynamic optimal decision rule subject to input and output prices variability is desired. The overall effect of this constraint was that the per-acre present value of returns, Z in equation (1), decreased but by less than one-twentieth of 1% in all cases. Therefore, this trade-off in revenue was considered adequate in exchange for a simple decision rule.

Solutions of the 50 optimization models (corresponding to two nitrate-nitrogen residual levels, five cotton prices and five nitrogen prices) were obtained using GAMS (General Algebraic Mathematical System), a mathematical system developed by the World Bank, and are presented in tables 1 and 2. The top portion of each table depicts the optimal levels of nitrogen applications for the alternative cotton-nitrogen price combinations. The bottom portion of each table depicts their associated per-acre present value of returns.

Because the optimization model solves for specific, discrete combinations of nitrogen and cotton prices which may vary substantially, it

Table 2. Per-Acre Dynamic Optimal Levels of Applied Nitrogen and Associated Net Present Value of Returns for Alternative Cotton-Nitrogen Prices, Assuming 30 lbs./acre Initial Condition on Nitrate-Nitrogen, MSRA[a] of the SHPT[b]

Nitrogen Price ($/lb.)	Cotton Price ($/lb.)				
	.40	.45	.50	.55	.60
			Nitrogen Application (lbs./acre/year)		
.30	3.31	5.55	7.84	10.16	12.52
.25	6.91	9.70	12.52	15.38	18.26
.20	12.52	16.00	19.71	23.34	27.00
.15	22.13	27.00	31.90	36.82	41.75
.10	41.75	49.17	56.61	64.07	71.53
			Net Present Value of Returns ($/acre, 10-year planning horizon)		
.30	1,757.02	1,977.98	2,199.56	2,421.69	2,644.35
.25	1,759.05	1,981.02	2,203.62	2,426.80	2,650.51
.20	1,762.90	1,986.15	2,210.04	2,434.53	2,659.55
.15	1,769.73	1,994.66	2,220.26	2,446.46	2,673.20
.10	1,782.13	2,009.49	2,237.52	2,466.16	2,695.34

[a] Mixedlands soil resource area.
[b] Southern High Plains of Texas.

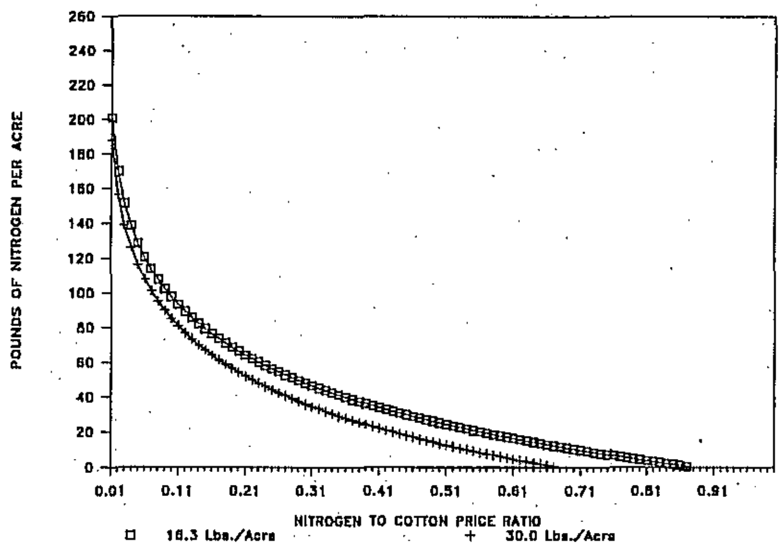

Figure 1. Continuous form of the optimal decision rules of applied nitrogen for the 16.3 and 30 lbs./acre levels of initial nitrate-nitrogen

was recognized that a generalized relationship based on relative rather than on absolute prices could be useful. Consequently, a generalization of the optimal nitrogen application decision rules was derived for the two levels of initial conditions on nitrate-nitrogen. The procedure was to regress the optimal nitrogen application against the nitrogen-cotton price ratios. For each given level of initial condition on nitrate-nitrogen residual, the 25 optimal decision rules of nitrogen application were listed along with their associated nitrogen-to-cotton price ratios; five of those were eliminated since five alternative cotton-nitrogen price combinations for which the optimization model was solved had the same price ratios and thus the same optimal decision rule. A functional form of the following type was then fitted to the remaining 20 points of optimal decision rules of nitrogen applications and nitrogen-to-cotton price ratios:

(8) $$e^{NA} = A * R^{\beta} * \epsilon,$$

where e is the mathematical constant whose

Table 3. Per-Acre Single-Year Optimization Levels of Applied Nitrogen and Associated Net Present Value of Returns for Alternative Cotton-Nitrogen Prices, Assuming 16.3 lbs./acre Initial Condition on Nitrate-Nitrogen, MSRA[a] of the SHPT[b]

Nitrogen Price ($/lb.)	Cotton Price ($/lb.)				
	.40	.45	.50	.55	.60
	Nitrogen Application (lbs./acre/year)				
.30	3.74	6.47	8.75	11.53	13.76
.25	7.74	11.02	13.76	17.10	20.35
.20	13.76	17.85	21.27	25.45	29.24
.15	23.78	29.24	33.80	39.36	43.82
.10	43.82	52.01	58.85	67.20	77.63
	Net Present Value of Returns ($/acre, 10-year planning horizon)				
.30	1,706.64	1,936.55	2,160.41	2,384.81	2,608.16
.25	1,725.58	1,950.04	2,173.47	2,397.82	2,622.28
.20	1,738.77	1,963.08	2,187.26	2,412.37	2,637.67
.15	1,752.85	1,978.25	2,203.91	2,430.42	2,657.15
.10	1,771.43	1,998.98	2,227.00	2,455.78	2,685.22

[a] Mixedlands soil resource area.
[b] Southern High Plains of Texas.

Table 4. Per-Acre Single-Year Optimization Levels of Applied Nitrogen and Associated Net Present Value of Returns for Alternative Cotton-Nitrogen Prices, Assuming 30.0 lbs./acre Initial Condition on Nitrate-Nitrogen, MSRA[a] of the SHPT[b]

Nitrogen Price ($/lb.)	Cotton Price ($/lb.) .40	.45	.50	.55	.60
	Nitrogen Application (lbs./acre/year)				
.30	0.00	0.00	0.00	0.00	0.06
.25	0.00	0.00	0.06	3.40	6.65
.20	0.06	4.15	7.57	11.75	15.54
.15	10.08	15.54	20.10	25.66	30.12
.10	30.12	38.31	45.15	53.50	63.93
	Net Present Value of Returns ($/acre, 10-year planning horizon)				
.30	1,756.14	1,975.66	2,195.17	2,414.69	2,634.34
.25	1,756.14	1,975.66	2,195.28	2,420.38	2,645.31
.20	1,756.22	1,981.22	2,205.69	2,431.11	2,656.58
.15	1,766.80	1,992.44	2,218.19	2,444.83	2,671.88
.10	1,781.06	2,008.69	2,236.72	2,465.55	2,695.07

[a] Mixedlands soil resource area.
[b] Southern High Plains of Texas.

natural logarithm is equal to one; R is the nitrogen-to-cotton price ratio; NA is the optimal level of applied nitrogen; A and β are the parameters to be estimated; and ϵ is the error term. Regression results from the linearized form of equation (8) for both nitrate-nitrogen initial conditions were:

(9) (16.3 lbs./acre)

$$NA = -5.9109 - 44.942 \ln(R)$$
$$(-2.378) \quad (-19.721) \qquad R^2 = .9558,$$

(10) (30.0 lbs./acre)

$$NA = -17.654 - 44.663 \ln(R)$$
$$(-7.054) \quad (-19.475) \qquad R^2 = .9547,$$

where the variables are defined as above and the values in parenthesis below the estimated parameters represent their associated t-values. All parameter estimates were significant at the .01 level with the exception of the intercept for the 16.3 lbs./acre initial condition in nitrate-nitrogen, which was significant at the .05 level. It is important to stress the fact that equations (9) and (10) were estimated to find an approximation of the continuous form of the nitrogen fertilizer optimal decision rules rather than to test the significance of the optimal decision rules obtained by solving the optimization model in equations (1)–(4).

Equations (9) and (10) are presented graphically in figure 1. As expected, given a nitrogen-to-cotton price ratio, the higher the initial condition on nitrate-nitrogen, the lower the optimal level of applied nitrogen. Also, given the initial condition on nitrate-nitrogen, the higher the nitrogen-to-cotton price ratio, the lower the optimal level of applied nitrogen. Information contained in figure 1 can also be presented to farmers in table form. As pointed out implicitly by Onken, Matheson, and Nesmith, this is important because "[the] Use of fertilizers in a crop production system is an economic investment. Insufficient applications of fertilizers are costly in [terms of] lost yields and over-application results in unwarranted production costs" (p. 134).

To address that point, the model in equations (1)–(4) was solved to derive nitrogen application optimal decision rules for a single-year planning horizon. This is representative of the common practice in which decision makers have soil tests performed on their land and decide how much nitrogen to apply without regard to future residual nutrient considerations. Thus, this represents a short-run optimization in which an annual decision is made which implicitly ignores the dynamic nature of nitrogen applications through nitrate-nitrogen carry-over effects. Discrete results of this single-year type of decision at alternative nitrogen and cotton prices for the two alternative levels of nitrate-nitrogen existing in the soil at the time the decision is made are presented in tables 3 and 4 along with their associated net present value of returns. Also, the continuous form of the nitrogen applications under this single-year type decision are presented in figures 2 and 3 along with the corresponding op-

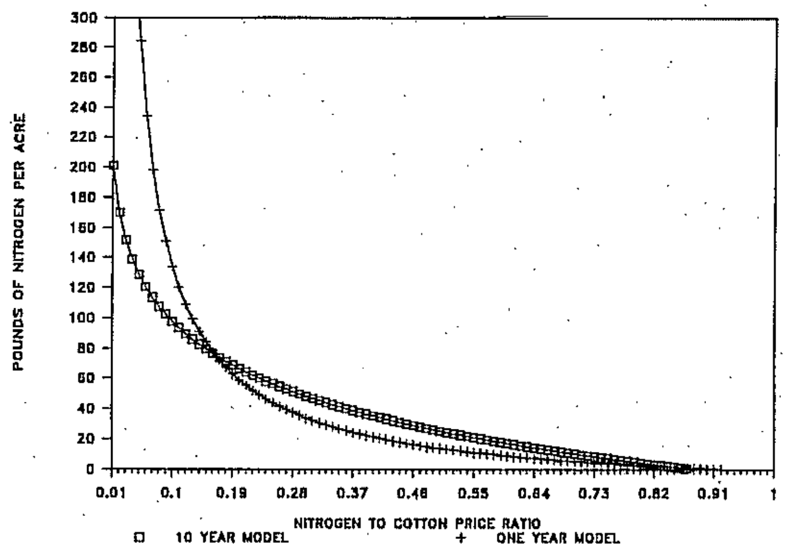

Figure 2. Short-run versus long-run optimal decision rules of applied nitrogen for the 16.3 lbs./acre level of initial nitrate-nitrogen

timal decisions of the 10-year dynamic optimization model.

Comparisons of the results within a nitrate-nitrogen initial condition reveal that, depending on the level of the nitrogen-to-cotton price ratio, the single-year optimization model overfertilizes or underfertilizes relative to the long-run (10-year) dynamic optimization model (figs. 2, 3). That is, the single-year model tends to overshoot optimal levels of nitrogen applications at relatively low nitrogen prices and undershoot optimal levels of nitrogen applications at relatively normal nitrogen prices. Notice in tables 1–4, that for all discrete combinations of nitrogen and cotton prices, nitrogen applications under the single-year model are lower than those of the dynamic model. Furthermore, in the SHPT the average ratio of nitrogen/cotton prices ranged from .39 to .45 between 1976 and 1985, depending on the form of nitrogen applied (Texas Agricultural Statistics Service). At these historical nitrogen-

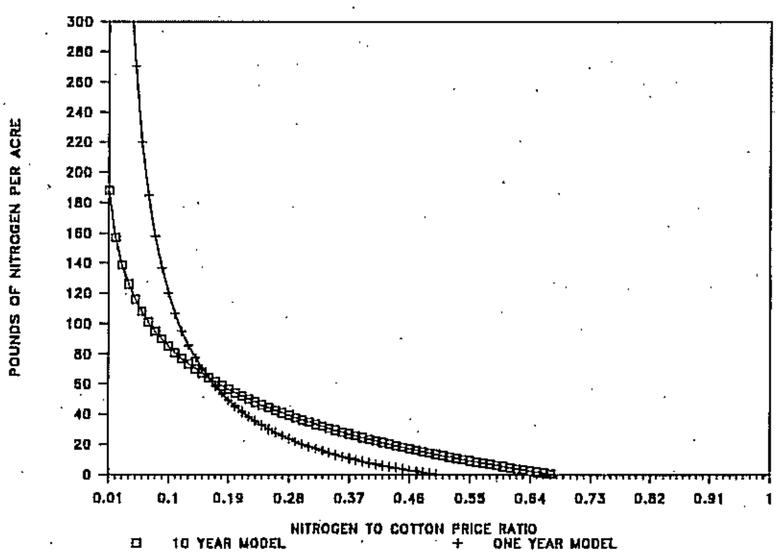

Figure 3. Short-run versus long-run optimal decision rules of applied nitrogen for the 30 lbs./acre level of initial nitrate-nitrogen

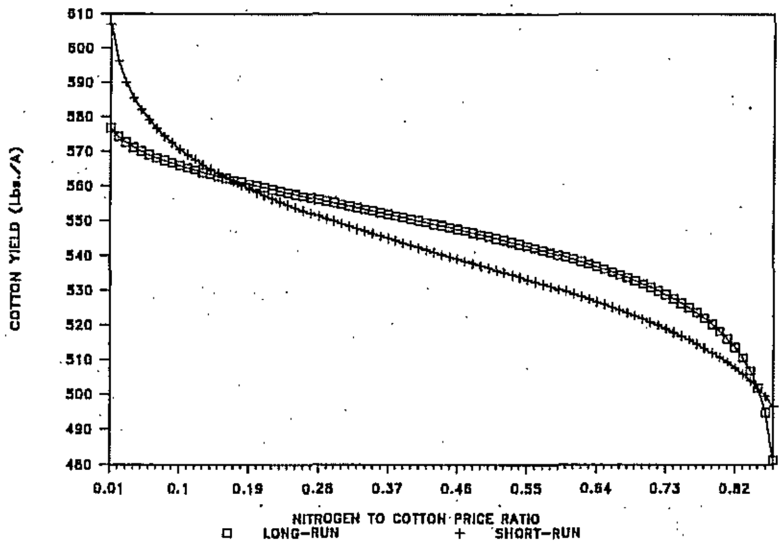

Figure 4. Dunn variety cotton yields associated with the short-run and long-run optimal levels of applied nitrogen, assuming a 16.4 lbs./acre level of initial nitrate-nitrogen residual

to-cotton price ratios, the optimum nitrogen application rates are always below those derived from the dynamic 10-year planning horizon model. This suggests that the single-year planning model yields suboptimal or inefficient levels of nitrogen applications, implying lower irrigated cotton yields than optimal.

In figure 4, the Dunn variety irrigated cotton yields associated with the single-year (short-run) and 10-year (long-run) models for the mixedlands soil resource area, assuming 16.3 lbs./acre initial level on nitrate-nitrogen, across nitrogen-to-cotton price ratios are presented. As can be seen in that figure, given the historical nitrogen-to-cotton price ratios, the irrigated cotton yields corresponding to the single-year model are lower than those of the 10-year model. This finding supports Neal and Ethridge's econometric finding that nitrogen fertilizer prices, which in turn affect nitrogen application rates, consistently explain more of the declining cotton yield trends in the SHPT than any other factor.

In particular, Neal and Ethridge point out that: "Since 1966, annual cotton yields in the Texas High Plains have declined at a rate of about 10 pounds per acre per year" (p. 27). Cotton yield differentials between the long-run and short-run models (figure 5) show that at historical nitrogen-to-cotton price ratios, cotton yields derived from the series of single-year decision models are 7.5 to 8.5 lbs./acre below long-run optimum. This suggests that short-term planning, perhaps induced by financial restrictions, may explain as much as 75% of the yield declines in the SHPT. It also suggests that if nitrogen-to-cotton price ratios remain near the historical levels, and if decision makers followed the nitrogen application optimal decision rules derived with the long-run model, cotton yields would increase and operations would be more efficient. However, it is important to point out that by following the dynamic optimal decision rules, implying higher levels of nitrogen use, net present value of returns would increase but not significantly (compare net returns in tables 1 and 3 and tables 2 and 4). Kennedy (1986b) reports similar findings in that, for certain types of response functions, the gains from adopting the optimal multiperiod rule over the single-period rule can be quite low.

Concluding Remarks

The objective of this paper was to derive nitrogen application optimal decision rules, considering the dynamic nitrate-nitrogen residual impacts of nitrogen applications, for irrigated cotton production in the Southern High Plains of Texas. It was shown that single-year derivation of optimal decision rules of nitrogen applications for cotton which ignores the dynamic nature of the problem leads to suboptimal nitrogen application levels, implying

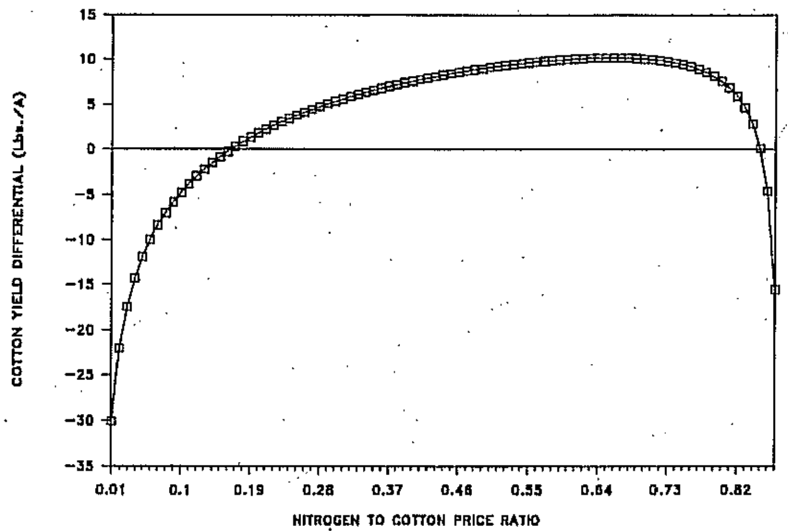

Figure 5. Dunn variety cotton yield differential between the long-run and short-run optimal levels of applied nitrogen, assuming a 16.3 lbs./acre level of initial nitrate-nitrogen residual

inefficiencies in irrigated cotton production. It was also shown, however, that adoption of multiperiod optimal decision rules of nitrogen utilization would not significantly increase net present value of returns. The optimal decision rules derived from the dynamic model which considered the nitrate-nitrogen residual impacts were found to be critically influenced by both the initial condition on nitrate-nitrogen and cotton and nitrogen price ratios.

The results derived in this study can be used and easily interpreted by decision makers to evaluate the efficiency of their cotton operations. This is important because input use efficiency in production is a key component for profitability and survival. It is recognized that the results stemming from this study are not applicable to other areas since information requirements are quite specific. In particular, critical elements in the derivation of comparable results for other areas and crops would be both adequate functional form and estimation of the nitrate-nitrogen carry-over function. However, the methods used to derive nitrogen application optimal decision rules in this study are applicable to other areas of the country to evaluate efficiency and profitability of agricultural reproduction not only with respect to nitrogen utilization but other production inputs as well.

Further research is needed to evaluate nitrate-nitrogen carry-over under sequential cropping (crop rotations) and anticipated advances in nitrogen fixation biotechnologies, because they would impact optimal nitrogen levels. Also, research addressing the variability of the marginal rate of substitution between nitrate-nitrogen residual and applied nitrogen is needed as evidence of its existence is provided by Onken, Matheson, and Nesmith. For those interested readers, a documented copy of the GAMS optimization model used in this study is available from the authors.

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