MAINTAINING SOIL PRODUCTIVITY IN IRRIGATED COTTON PRODUCTION IN THE TEXAS HIGH PLAINS

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Abstract

The retention of soil productivity is a genuine facet of sustainable agriculture and an essential issue for producers and land owners. The objective of this study was to evaluate the sensitivity of the optimal decision rules for nitrogen fertilizer application and the impact on net returns for irrigated cotton production in the High Plains of Texas when provisions are included requiring maintenance of soil productivity. Results indicate that as the desired level of soil productivity maintenance increased, additional nitrogen applications were required, net present value of returns were reduced, and the annual payment required to offset these economic losses increased across a series of nine production scenarios.

Introduction

Modern agriculture is undergoing a shift in emphasis from a primary goal of maximizing production and profit for the short term, to an enlarged perspective that also considers the ability to maintain production over the long run. This sustainable perspective carries with it important implications for resource allocation and land tenure relationships. A further development has been the increased popularity of land leasing agreements in the United States, which has enlarged the separation between ownership and operation. This structural phenomenon has renewed interest in the possible trade-offs between the traditional goals of maximizing production and profit and the desire to optimize sustainability.

Land represents over 70 percent of the value of assets in agriculture, and access to land is typically gained either through ownership or leasing. Recently released data from the 1992 Census of Agriculture show that farmers operated 405 million acres under lease, through 2.1 million rental arrangements (USDA, 1995). Nationally, farmers leased 43 percent of the farm land operated in 1992, the highest proportion since 1940. In Texas, 49.3 percent of the total land acreage in farms was rented either by tenants or part owners. The proportions of owned and rented land in farms have implications for decision making in production, the level of capital available to the industry, major land use changes, and the extent of participation in and benefits received from agricultural policies.

This study is a continuation of on-going efforts to analyze optimal decision rules for nitrogen fertilizer application for irrigated cotton production in the High Plains of Texas. The prominence of leasing agreements in production agriculture and continued concerns related to economically and environmentally beneficial production systems have motivated this study. This research extends previous research by Segarra et al. (1989) by incorporating the influences of maintaining soil productivity on the derivation of dynamic optimal nitrogen application patterns. The aforementioned study found that dynamic optimal nitrogen applications critically relied on initial nitrate-nitrogen levels and nitrogen-to-cotton price ratios. In addition, single-year optimization lead to suboptimal nitrogen applications, which helped to explain long-term cotton yield declines in the High Plains of Texas; however, single-year optimization did not significantly impact the net present value of returns from irrigated cotton operations.

For the purposes of this study, the term "production environment" will refer to a particular nitrogen-cotton price ratio, and the term "soil productivity" will be used to describe the nitrate-nitrogen content of the soil as an appropriate proxy for the productive characteristics of the soil resource base. Soil productivity is a critical issue for landlords who will ultimately regain control of their land at the termination of a leasing agreement as well as for the traditional family-farm operator who will eventually deed the land to following generations. The inability of agricultural producers to influence output or input prices accentuates the importance of sound production practices and efficient resource use as key components for profitability and survival.

The primary objective of this study was to evaluate the sensitivity of optimal decision rules for nitrogen fertilizer application and the impact on net returns for irrigated cotton production in the High Plains of Texas when provisions are included requiring maintenance of soil productivity. In particular, a dynamic optimization model of nitrogen utilization which incorporates an intertemporal nitrate-nitrogen residual carry-over function and restrictions related to various cotton prices, nitrogen prices and soil productivity maintenance levels is presented.

The Study Area and Soil Resource Base

This study assumes typical conditions related to irrigated cotton production on the High Plains of Texas. Texas is the leading producer of cotton in the United States (24 percent of domestic supplies), and 57.7 percent of Texas cotton production is produced in the Texas High Plains (Texas Agricultural Statistics Service, 1993). This area encompasses 39 counties with over 3 million planted acres of cotton.

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Three major soil resource areas are prevalent in the region. Hardlands account for 54 percent of this area and are characterized by fine-textured clays and clay loams. Mixedlands represent 23 percent of the region and are primarily medium-textured loams and loamy sands. Sandylands account for 23 percent of the area and are predominantly coarse-textured sands.

The Dynamic Optimization Model

Contemporary studies that have addressed the impacts of nitrogen fertilizer applications and residual nitrate-nitrogen levels on crop yields (Segarra, 1989; Segarra et al., 1989; Glover, 1994; Schnitkey and Miranda, 1993; and Cochran and Govindasamy, 1994) reveal that the accumulation of residual nitrate-nitrogen in sufficient quantities affects crop yields. They also indicate that total nitrogen available to plants at a given time is a function of previous nitrogen levels and previous levels of residual nitrate-nitrogen. This would imply that optimal decision rules for nitrogen use must account for these dynamic relationships.

The deterministic specification of the empirical dynamic optimization model formulated to derive optimal decision rules for nitrogen fertilizer follows that of Kennedy (1986), and Segarra et al. (1989):

$$(1)\ \text{MAX}\ \underset{[Na_t]}{Z} = \sum_{T=0}^{n} \left[P_t - Y_t (NT_t) - CN_t - Na_t \right] - (1 + r)^{-t}$$

subject to:

$$(2)\ Nt_t \cdot NA_t \cdot NR_{Tt}$$

$$(3)\ NR_{t-L} = \int_t \left[NA_t \cdot NR_t \right],$$

$$(4)\ NA_{t-1} - Na_t,$$

$$(5)\ NR_0 \cdot NR(0),$$

and

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

where Z is the per-acre net present value ($) of returns to land, irrigation water, overhead, risk, and management from cotton production; n is the length of the planning horizon in years; P is the cotton price ($/lb.); Y is the cotton yield function (lbs./acre); NT is the nitrogen available to the cotton plants (lbs./acre); CN is the price of nitrogen ($/lb.); NA is the nitrogen applied (lbs./acre); r is the discount rate; and NR is the nitrate-nitrogen residual (lbs./acre). In addition, the subscript t denotes the specific year within the planning horizon.

Equation (1) represents the objective function of the dynamic optimization model. Equation (2) is an equality constraint which accounts for the total quantity of nitrogen available to the crop by adding up the applied nitrogen and the nitrate-nitrogen residual. Equation (3) is the equation of motion in the model which updates the nitrate-nitrogen residual necessary for consideration in equation (2). That is, residual nitrate-nitrogen at a particular point in time is, in turn, a function of previous nitrogen applications and previous levels of nitrate-nitrogen. Equation (4) places a restriction of equal nitrogen applications throughout the planning horizon. The justification for this restriction is that nitrogen and cotton prices vary year to year and thus a "rolling horizon" dynamic optimal decision rule subject to input and output price variability is desired. Following Segarra et al. (1989), this restriction provides for a more stable optimal decision rule to simplify management implementation. Finally, equation (5) is an initial condition on the nitrate-nitrogen residual.

The yield response function, Y_t in equation (1) was taken from findings previously reported by Segarra et al. (1989). These authors estimated the yield response as a function of the total nitrogen available to the plants, accumulated daily heat units, inches of water received during the growth period, row spacing, cotton variety, soil moisture deficiency, and soil type using logarithmic, Mitscherlich-Spillman, and quadratic functional forms to capture diminishing marginal returns. The nitrate-nitrogen residual function, equation (3), was taken from previous research by Sunderman, (1976), and Sunderman et al., (1972).

For illustrative purposes, consider the production environment for the Dunn 56-C cotton variety produced on mixedland soils. Following Segarra et al. (1989), the appropriate formulation of the cotton yield function for this scenario is:

$$(6)\ Y_t = 497.14 + 15.03 \ln (NT),$$

where ln denotes the natural logarithm of total nitrogen available to the cotton plants. Equation (6) provides the yield function used to solve the optimization model in equation (1).

The optimization model depicted in equations (1 - 5) was solved for the mixedland soil resource area and the Dunn 56-C cotton variety assuming: (a) a ten-year planning horizon; (b) three alternative levels of cotton price (0.55, 0.60, and 0.65 dollars per pound); (c) three alternative levels of nitrogen price (0.20, 0.25, and 0.30 dollars per pound); (d) a discount rate of 5 percent; (e) an initial condition of the nitrate-nitrogen residual of 30.0 pounds per acre; and (f) four alternative soil productivity maintenance restrictions that specified the level of the nitrate-nitrogen at the end of the planning horizon (0, 18, 24, and 30 lbs./acre).

Empirical Results

Solutions to the 36 optimization models (corresponding to four soil productivity maintenance restrictions, three cotton prices and three nitrogen prices) were obtained using

GAMS (Brooke et al., 1988). Table 1 illustrates the per-acre dynamic optimal levels of applied nitrogen, associated net present value of returns for alternative cotton-nitrogen prices, and soil productivity remaining at the end of the terminal period when there was no restriction on the condition of land at the end of the planning horizon. Notice that as the nitrogen-cotton price ratio decreased, more nitrogen was applied in the dynamic optimal solutions. Dynamic optimal levels of nitrogen application ranged from 10.17 lbs./acre/year for a production environment with a nitrogen-cotton price ratio of 0.545 to 30.68 lbs./acre/year for a nitrogen-cotton price ratio of 0.308. The reduced nitrogen-cotton price ratio also resulted in a higher net present value of returns and higher levels of soil productivity remaining at the end of the terminal period. The optimal residual nitrate-nitrogen level at the end of the planning horizon ranged from 10.82 lbs./acre (at a nitrogen-cotton price ratio of 0.545) to 14.38 lbs./acre (at a nitrogen-cotton price ratio of 0.308) when there was no restriction on the level of soil productivity to be maintained. This range of terminal residual nitrate-nitrogen levels is equivalent to stating that the land at the end of the planning horizon retained only 36.06 percent and 47.93 percent of the original soil productivity, respectively, when compared to the initial residual nitrate-nitrogen level of 30 lbs./acre.

In order to examine the impacts of a soil productivity maintenance restriction, an additional constraint was imposed on the model to fix the terminal residual nitrate-nitrogen level to a desired level. Table 2 presents a comparative situation to the optimal solutions reported in Table 1 by detailing the impacts of a 60 percent soil productivity maintenance restriction. This restriction is equivalent to fixing the minimum level of residual nitrate-nitrogen at 18 lbs./acre at the end of the terminal period. The dynamic optimal nitrogen application was completely insensitive to the production environment with this restriction. That is, dynamic optimal nitrogen applications for the 60 percent soil productivity maintenance scenario remained at 51.34 lbs./acre/year regardless of the nitrogen-cotton price
ratio. However, incorporating this restriction directly affects the additional nitrogen applications necessary for compliance, net present value of returns, and soil productivity remaining at the end of the terminal period for each of the nine production environments considered.

Additional nitrogen applications required to meet the 60 percent soil productivity maintenance restriction ranged from 41.17 lbs./acre/year (for a nitrogen-cotton price ratio of 0.545) to 20.66 lbs./acre/year (for a nitrogen-cotton price ratio of 0.308). The associated reduction in net present value of returns ranged from $38.07/acre to $5.46/acre across production environ-ments. Additional soil productivity remaining at the end of the terminal period ranged from 23.94 percent to 12.07 percent across production environments versus that of the optimal solutions for identical production environments without a soil productivity maintenance restriction (Table 1).

The final component of Table 2 identifies the value of an annual payment (annuity) to a lessee required to exactly offset the economic losses which evolve due to compliance with the soil productivity maintenance restriction. These reported values acknowledge two distinct facets of the losses from maintaining soil productivity. The first aspect is the time value of money -- i.e., values reported refer to an annuity payment with a discount rate of 5 percent and a 10-year planning horizon. The second aspect recognizes the basis for the annuity as 75 percent of the reduction in the net present value of returns (this accounts for the fact that the typical landlord in the Texas High Plains assumes 25 percent of fertilization costs). The value of the annuity required to offset the economic losses which evolves due to compliance with the 60 percent soil productivity maintenance restriction ranged from $3.70/acre/year to $0.53/acre/year across production environments.

Table 3 presents a comparative situation to the optimal solutions reported in table 1 by detailing the impacts of an 80 percent soil productivity maintenance restriction. This restriction is equivalent to fixing the minimum level of the residual nitrate-nitrogen level at 24 lbs./acre at the end of the terminal period. Once again, this restriction further influences the dynamic optimal nitrogen applications, net present value of returns, and soil productivity remaining at the end of the terminal period for each of the nine production environments considered. The dynamic optimal nitrogen application levels were again insensitive to the production environment. That is, optimal nitrogen applications for the 80 percent soil productivity maintenance scenario remained at 86.09 lbs./acre/year regardless of the nitrogen-cotton price ratio.

Additional nitrogen applications required to meet the 80 percent soil productivity maintenance restriction ranged from 75.92 lbs./acre/year (for a nitrogen-cotton price ratio of 0.545) to 55.41 lbs./acre/year (for a nitrogen-cotton price ratio of 0.308). The associated reduction in net present value of returns ranged from $92.55/acre to $28.61/acre across production environ-ments. Additional soil productivity remaining at the end of the terminal period ranged from 43.94 percent to 32.07 percent across production environ-ments versus that of the optimal solutions for identical production environ-ments without a soil productivity maintenance restriction (table 1). Finally, the value of the annuity required to offset the economic losses related to com-pliance with the 80 percent soil productivity maintenance restriction ranged from $8.99/acre/year to $2.78/acre/year across production environments.

The constraint governing the terminal residual nitrate-nitrogen level was then modified to impose a 100 percent soil productivity maintenance restriction. This restriction is equivalent to fixing the minimum level of the residual nitrate-nitrogen level at 30 lbs./acre at the end of the terminal period (equal to the initial residual nitrate-nitrogen level). Table 4 presents a comparative situation to the optimal solutions reported in Table 1 by detailing the impacts of this type of agreement. The dynamic optimal nitrogen application level to ensure 100 percent soil productivity maintenance across production environments was found to be 120.65 lbs./acre/year. This restriction has relatively dramatic impacts on additional optimal nitrogen applications and net present value of returns, as well as the soil productivity remaining at the end of the terminal period for each of the nine production environments considered.

Additional nitrogen applications required to meet the 100 percent soil productivity maintenance restriction ranged from 110.48 lbs./acre/year (for a nitrogen-cotton price ratio of 0.545) to 89.97 lbs./acre/year (for a nitrogen-cotton price ratio of 0.308). The associated reduction in net present value of returns ranged from $154.43/acre to $60.49/acre across production environments. Additional soil productivity remaining at the end of the terminal period ranged from 63.94 percent to 52.07 percent across production environments versus that of the optimal solutions for identical production environments without a soil productivity maintenance restriction. This addition to soil productivity reflects the replenishing of the entire initial residual nitrate-nitrogen levels that were present at the time that cotton production was initiated. Finally, the value of the annuity required to offset the economic losses which evolve due to compliance with the 100 percent soil productivity maintenance restriction ranged from $15.00/acre/year to $5.88/acre/year across production environments.

Conclusions and Implications

The objective of this paper was to evaluate the sensitivity of the optimal decision rules for nitrogen fertilizer application and the impact on net returns for irrigated cotton producers in the High Plains of Texas when provisions are included requiring maintenance of soil productivity. As the desired level of soil productivity maintenance increased, additional nitrogen applications were required, net present value of returns were reduced, and the annual payment required to offset these economic losses increased across a series of nine production environments (nitrogen-cotton price ratios) considered. While exact estimates of these categories were reported for irrigated cotton producers in the High Plains of Texas, soil productivity maintenance restrictions like those examined in this study have more widespread consequences.

Current land tenure agreements make no allowance regarding the condition of the land (i.e. soil productivity) either at the initiation or at the conclusion of the lessor-lessee relationship. However, substantial evidence exists which supports the premise that residual nitrate-nitrogen levels play a vital role in the productive capabilities of land in future periods.

Actions devoted to maintaining soil productivity carries with them a number of corresponding ramifications. Maintenance of soil productivity implies the annual application of (in some cases) substantial amounts of additional nitrogen. This may be viewed as contradictory to recent environmental concerns which have concentrated on production systems which emphasize lower levels of input use in agriculture. Also, the additional nitrogen applications (over those otherwise deemed optimal) effectively reduce the net present value of returns. If a landlord desires to implement this type of soil productivity maintenance restriction, it will most likely only be acceptable to the lessee if it were accompanied by an annual payment (or reduction in land rent) to offset the economic losses of compliance.

It can be argued that because many, if not most, farmers do follow recommended nitrogen application rates, they are accounting for the nutrient stores in soil organic matter and nutrient carryover because such credits are built into these recommendations. Nevertheless, simple management alertness can result in more nutrient efficiencies in current production systems, over and above the benefits of using rotations. However, these increased efficiencies will require more intensive management as they succumb to the pressures of economics and environmental regulation.

Research designed to develop feasible sustainable agricultural practices must incorporate both economic and environmental concerns in order to be considered a viable alternative. A research focus in agriculture that takes advantage of this knowledge and experience permits exploration of the multiple bases upon which sustainability rests. Further research is needed to evaluate the impacts of adopting the dynamic optimization nitrogen applications derived in this study. The functional form of the yield response function employed in this study did not allow for the possibility of nitrogen "burn out" resulting from excessive nitrogen applications. In addition, alternative means for maintaining soil productivity (other than simply applying additional nitrogen) represent another potential approach for preserving productivity.

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Table 1. Per-Acre Dynamic Optimal Levels of Applied Nitrogen, Associated Net Present Value of Returns for Alternative Cotton-Nitrogen Prices, and Soil Productivity Remaining at the End of the Terminal Period, Assuming 30 lbs./acre Initial Condition of Land at the End of the Planning Horizon.[1,2]

	Cotton Price ($/lb.)		
Nitrogen Price ($/lb.)	0.55	0.60	0.65
	Nitrogen Application (lbs./acre/year)		
0.30	10.17	12.53	14.90
0.25	15.38	18.26	21.16
0.20	23.35	27.00	30.68
	Net Present Value of Returns ($/acre, 10-year Planning Horizon)		
0.30	2306.38	2518.93	2730.94
0.25	2311.25	2524.30	2737.83
0.20	2318.60	2532.91	2747.69
	Soil Productivity Remaining at the End of the Terminal Period[3] (% of Initial Nitrate-Nitrogen Level)		
0.30	36.06	37.43	38.80
0.25	39.08	40.75	42.42
0.20	43.69	45.80	47.93

[1] Mixedlands soil resource area of the Texas High Plains.

[2] Results are reported for the Dunn 56-C cotton variety.

[3] Exact nitrate-nitrogen levels may be determined by multiplying the soil productivity remaining (percentage reported above) by the initial nitrate-nitrogen residual level (30 lbs./acre).

Table 2. Additional Nitrogen Application; Reduction in Net Present Value of Returns; Additional Soil Productivity Remaining at the End of the Terminal Period; and Annual Payment Required to Offset Losses due to a Restriction Requiring 60% Soil Productivity Maintenance. [1]

	Cotton Price ($/lb.)		
Nitrogen Price ($/lb.)	0.55	0.60	0.65
	Additional Nitrogen Application (lbs./acre/year)		
0.30	41.17	38.81	36.44
0.25	35.96	33.08	30.18
0.20	27.99	24.34	20.66
	Reduction in Net Present Value of Returns ($/acre, 10-year Planning Horizon)		
0.30	38.07	33.55	28.50
0.25	23.04	19.03	15.49
0.20	10.49	7.74	5.46
	Additional Soil Productivity Remaining at the End of the Terminal Period (% of Initial Nitrate-Nitrogen Level)		
0.30	23.94	22.57	21.20
0.25	20.92	19.25	17.58
0.20	16.31	14.20	12.07
	Annual Payment Required to Offset Losses from Maintaining Soil Productivity[2] ($/acre/year)		
0.30	3.70	3.26	2.77
0.25	2.24	1.85	1.50
0.20	1.02	0.75	0.53

[1] Results reported represent a comparative situation to that in which no restriction governing soil productivity exists (Table 1).

[2] Calculated as an annuity payment equivalent to 75% of the reduction in the net present value of returns.

Table 3. Additional Nitrogen Application; Reduction in Net Present Value of Returns; Additional Soil Productivity Remaining at the End of the Terminal Period; and Annual Payment Required to Offset Losses due to a Restriction Requiring 80% Soil Productivity Maintenance. [1]

	Cotton Price ($/lb.)		
Nitrogen Price ($/lb.)	0.55	0.60	0.65
	Additional Nitrogen Application (lbs./acre/year)		
0.30	75.92	73.56	71.19
0.25	70.71	67.83	64.93
0.20	62.74	59.09	55.41
	Reduction in Net Present Value of Returns ($/acre, 10-year Planning Horizon)		
0.30	92.55	85.71	78.34
0.25	64.18	57.85	51.99
0.20	38.29	33.22	28.61
	Additional Soil Productivity Remaining at the End of the Terminal Period (% of Initial Nitrate-Nitrogen Level)		
0.30	43.94	42.57	41.20
0.25	40.92	39.25	37.58
0.20	36.31	34.20	32.07
	Annual Payment Required to Offset Losses from Maintaining Soil Productivity[2] ($/acre/year)		
0.30	8.99	8.32	7.61
0.25	6.23	5.62	5.05
0.20	3.72	3.23	2.78

[1] Results reported represent a comparative situation to that in which no restriction governing soil productivity exists (Table 1).

[2] Calculated as an annuity payment equivalent to 75% of the reduction in the net present value of returns.

Table 4. Additional Nitrogen Application; Reduction in Net Present Value of Returns; Additional Soil Productivity Remaining at the End of the Terminal Period; and Annual Payment Required to Offset Losses due to a Restriction Requiring 100% Soil Productivity Maintenance. [1]

	Cotton Price ($/lb.)		
Nitrogen Price ($/lb.)	0.55	0.60	0.65
	Additional Nitrogen Application (lbs./acre/year)		
0.30	110.48	108.12	105.75
0.25	105.27	102.39	99.49
0.20	97.30	93.65	89.97
	Reduction in Net Present Value of Returns ($/acre, 10-year Planning Horizon)		
0.30	154.43	145.94	136.91
0.25	112.72	104.73	97.22
0.20	73.48	66.75	60.49
	Additional Soil Productivity Remaining at the End of the Terminal Period (% of Initial Nitrate-Nitrogen Level)		
0.30	63.94	62.57	61.20
0.25	60.92	59.25	57.58
0.20	56.31	54.20	52.07
	Annual Payment Required to Offset Losses from Maintaining Soil Productivity[2] ($/acre/year)		
0.30	15.00	14.18	13.30
0.25	10.95	10.17	9.44
0.20	7.14	6.48	5.88

[1] Results reported represent a comparative situation to that in which no restriction governing soil productivity exists (Table 1).

[2] Calculated as an annuity payment equivalent to 75% of the reduction in the net present value of returns.