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STAFF PAPER

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DECEMBER 1993
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Contribution No. 94-272-D from the Kansas Agricultural Experiment Station, Kansas State University, Manhattan, KS 66506.

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Factor Input Demand Subject to Economic and Environmental Risk: The Case of Nitrogen Fertilizer in Corn Production

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December 1993

Presented at the 1994 Annual Meetings of the

Southern Agricultural Economics Association,

Nashville TN, February 5-9, 1994

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Contribution No. 94-272-D from the Kansas Agricultural Experiment Station.

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Abstract

Nitrogen (N) fertilizer demand in relation to economic and environmental risks associated with N-fertilizer management are examined. Both nominal and environmental damage-adjusted net returns distributions are evaluated using stochastic dominance analysis. Results suggest that, in the absence of environmental risk, N demand becomes more elastic as farmers become more risk averse. When environmental risk is introduced to the decision-making process, N demand becomes even more elastic.

Key Words: environmental damage, factor input demand, nitrogen fertilizer management, risk, stochastic dominance

Factor Input Demand Subject to Economic and Environmental Risk:

The Case of Nitrogen Fertilizer in Corn Production

The purpose of this paper is to examine how factor input demand is affected when economic and environmental risks are simultaneously taken into account. The demand for N fertilizer in the production of dryland corn in northeast Kansas is used as an example. Numerous studies evaluate the economics of fertilizer management, the economics of crop rotations to reduce commercial fertilizer use, and/or the costs of nutrient pollution (Ayer et al.; Jacobs and Casler; Jordan et al.; Lambert; Papendick et al.; SriRamaratnam et al.; Stoecker and Onken; Taylor and Frohberg; Walker and Hoehn; Williams et al.). Similarly, several studies evaluate the tools (input restrictions, standards, taxes, and charges) often considered for mediating nonpoint source pollution (Horner; Jacobs and Casler; Lambert; Sharp and Bromley; Shortle and Dunn). Although several of these studies address economic risk associated with the management strategies and mediating tools, none of them account for both economic and environmental uncertainty as recommended by Shortle and Dunn.

Nonpoint-source water pollution from agriculture has long been identified as a major contributor to water resource contamination. Crutchfield et al. note that most studies in the past have focused on water pollution caused by soil erosion and sedimentation; the contribution of agrichemicals to water resource contamination has not been considered appropriately. Pesticide and nitrate contamination of water resources recently has received much public attention because of associated health risks (Hallberg; Johnson et al.; P.F. Pratt; U.S. Environmental Protection Agency 1990, 1992). The severity of potential agricultural-source nitrate contamination of water resources is discussed widely in the literature (Koelliker et al.; Lee and Nielson; Miranowski; Nielson and Lee). A major concern is the increase in fertilizer applications; the U.S. per-acre application rate doubled between 1965 and 1984 (Lee and Nielsen). Corn production accounts for nearly 44% of all fertilizers used in agriculture (U.S. Department of Agriculture). Two important factors influence groundwater contamination from nitrates: the rate of N application and the soil leaching potential (Anderson et al; Neeteson et al.; Peterson and Frye). Because modifying soil leaching potential is a long-term process, the first line of action is modifying N-fertilizer applications and use rates.

Theory and Methods

Often, regulatory or tax incentives are suggested as the appropriate tools to "internalize" externalities and modify the profit maximization decision of the farmer in regard to optimal input use. However, much of the environmental damage from many production practices concentrates at the production site, thereby posing immediate potential health risks to the producer and, as such, is not external to the producer. The same health risks are generalized to society only after sustained use of the practices over a longer period. Therefore, it is reasonable to consider the farmer's decision process as more multi-faceted than profit-driven alone; rather, it should be considered as a process in which the manager considers both economic gains and environmental quality if adequate information about both exists. When provided with the necessary information on the environmental impacts of production practices, the farmer will choose input combinations that may be different from those chosen if profit maximization were the sole motivation. This is a fairly straight-forward application of the LeChatelier Principle to factor input demand; a comparable hypothesis relating environmental risk to product demand is discussed by John et al. The LeChatelier Principle states that "the slopes of demand functions do not decrease (usually increase) *in absolute value* as constraints are added to the optimization problem" (Beattie and Taylor, p. 132); similarly, the slopes of demand functions do not increase (usually decrease) *in absolute value* as constraints are removed from the optimization problem. An example of the LeChatelier effect applied to input demand and externalities is provided in figure 1 where $x^d(w_x \mid e^0)$ is the constrained factor demand schedule (potential environmental damage is unknown or priced at zero) and $x^d(w_x, e)$ is the unconstrained factor demand schedule (potential environmental damage is known, priced greater than zero, and included in all production decisions). At factor cost w_x^0, input level x_0^0 is chosen to maximize profit in the short and long run (constrained and unconstrained input demand, respectively). However, if the factor cost is increased to w_x^1, the profit-maximizing input level is x_0^1 in the constrained case, where there is limited or no knowledge of environmental damage, and x_1^1 in the unconstrained case.

The problem arises of how to incorporate environmental costs appropriately into a model of the producer's decision process. Four points must be recognized. First, maximizing profits or minimizing costs per unit of environmental damage overlooks the costs associated with that damage. Second, pollution externalities from agricultural sources often can be mediated by adjusting the mix of variable inputs (e.g., altering the method of and/or reducing the level of N-fertilizer applied). Third, external costs arise due to excess factor inputs; in other words, often because of uncontrollable factors, a divergence occurs between the level of a factor input into the production process and the level of the factor actually used in the production process. Finally, quantifying the actual costs of external effects is very difficult; however, one method of representing external costs is on a relative scale (Hoag and Hornsby). The last two points present a unique modelling opportunity. To arrive at the "full environmental" cost of a particular strategy, the external costs are estimated on a relative scale in proportion to the costs of the damage-causing factor(s) and added to the "nominal" costs of the strategy.

A graphical representation of this hypothesis is presented in Figure 2. Under the standard assumption of full input usage (i.e., there is no divergence between the level of a factor input into the production process and the level of the factor actually used in the production process) the marginal value product for the amount of input applied is equal to the marginal value product of input utilized in the production process (i.e., $MVP_a = MVP_u$). However, sometimes due to forces both within and beyond the control of the producer, MVP_a and MVP_u diverge. When $MVP_a = MVP_u$, the optimal input level, $x_a = x_u$, is decided by equating MVP with private marginal factor cost, MFC^P. However, when $MVP_a \neq MVP_u$,[1] the producer still optimizes by equating MVP_a with MFC^P, however the level of input applied, x_a, exceeds x_u by x_e. When $x_e > 0$, the social marginal factor cost (MFC^S) and MFC^P diverge and a deadweight loss phenomenon occurs. Because the producer has already paid w_x^P for x_e, the external cost of the excess factor input is represented by the shaded triangular area, which is approximately equal to $\frac{1}{2}(w_x^S - w_x^P)(x_a - x_u) = \frac{1}{2}(w_x^S - w_x^P)x_e$. The full environmental cost ("real costs") of a production strategy can be approximated by estimating the area of this triangle and adding it to the out-of-pocket costs already incurred by the producer. As long as x_e is relatively small compared to x_a, the easiest way to approximate w_x^S is by linear interpolation, $w_x^S \approx (x_a/x_u)w_x^P$. Interpolating w_x^S as such is comparable to the Hoag and Hornsby relative cost scheme.

Thus, the "nominal" or private net returns (π_n; which do not include environmental costs) from a production strategy, calculated by netting total costs and total revenues, are

(1) $$\pi_n = py - (w_x^P x_a + w_2 x_2 + \ldots + w_n x_n) - FC ,$$

where p is product price, y is output, w_i is the cost of input x_i, and FC is fixed costs. Alternatively, the "real" or social net returns (π_r; which account for environmental costs) are calculated as

(2) $$\pi_r = py - (w_x^P x_a + w_2 x_2 + \ldots + w_n x_n) - \frac{1}{2}(w_x^S - w_x^P)x_e - FC ,$$

where x_e is the excess factor input causing the environmental damage, and all other variables are as defined in equation (1). The attractive feature of this method is that the "real" or social net returns distribution reflects the environmental damage distribution (and therefore the risk of environmental damage) without making *a priori* assumptions about the dollar costs of the external effects such as in Carriker and Huang and Lantin. Additionally, conventional risk analysis techniques (e.g., stochastic dominance analysis) can be applied to these distributions.

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[1] Note that $MVP_a \geq MVP_u$ and that $x_a \geq x_u$.

Data

The CERES-Maize corn growth simulation model (Jones and Kiniry) and the WGEN weather simulation model (Richardson and Wright) were used to generate 50 individual-year per-acre corn yield distributions at six different N-fertilizer rates (50, 75, 100, 125, 150, and 175 pounds per acre) and two fertilizer treatments (single application and split application) on a Marshall silt-loam soil in northeast Kansas. Both simulation models have been validated for northeast Kansas (Carriker and Williams).

A N-budget approach (Power and Broadbent; Schepers and Fox), used to define potential nitrate loading, is based on the nutrient balance equation

(3) $$RN_{tn} = \sum^{tn} (AP_t + AR_{\Delta t} - RM_{\Delta t} - L_{\Delta t}) ,$$

where RN_{tn} is soil organic and inorganic nutrients remaining at time tn, AP_t is soil organic and inorganic nutrients present at time t, $AR_{\Delta t}$ is organic and inorganic nutrients added or returned to the soil during the time interval Δt, $RM_{\Delta t}$ is plant nutrients removed with the harvested crop during the time interval Δt, $L_{\Delta t}$ is organic and inorganic nutrients lost during time interval Δt, t is the beginning time, tn is the ending time, and Δt is the time interval between t and tn (Miller and Larson, p. 555). Assuming a one-year soil nutrient management scheme in which the objective is to maintain, rather than deplete or enrich, the soil nutrient pool (i.e., $RN_{tn} = AP_t$) and rearranging equation (3) results in

(4) $$L_{\Delta t} = AR_{\Delta t} - RM_{\Delta t} ,$$

where $L_{\Delta t}$ is redefined as the surplus of organic and inorganic nutrients exceeding the needs of the crop and potentially lost to the environment. In this study, the definition of potential surplus N is defined, following Huang and Lantin, as the difference between the amount of mineral N applied and the amount of N removed when the grain is harvested; the crop stover is returned to the soil. Though this method measures only "potential" environmental loading, it is consistent with the concept of fertilizer use efficiency.

A summary of the twelve per-acre yield and surplus N distributions is presented in table 1. The highest mean yields occur at the 175 lbs. N/acre level[2] under both the single and split application treatments. Though the coefficients of variation for yields are nearly the same at all N levels within a treatment, the relative variabilities of yields at the extreme N levels are greater than at the intermediate N levels; this is consistent with the findings of SriRamaratnam et al. and Williams et al. The lowest mean surplus N occurs at the 50 lbs. N/acre level under both treatments; the largest coefficients of variation for surplus N also occur at this N level. Surplus N is lower for a split application than for the corresponding single application at each N level.[3]

Per-acre net return (over total costs) distributions, with and without commodity program participation, are calculated for the twelve N management strategies based on enterprise budgets for northeast Kansas dryland corn (Vandeveer) and the 1991 provisions of the Food, Agriculture, Conservation, and Trade Act of 1990 (table 2). The resulting 24 strategies comprise six N application levels using two treatments, a single pre-plant application of anhydrous ammonia and a split treatment comprised of a pre-plant application of 50% of the fertilizer as anhydrous ammonia and a pre-tassel stage application of 50% of the fertilizer as urea, with and without participation in the government commodity program. It is assumed, for the commodity program participation, that corn is grown on flex acres and that the surplus N level is 92.5% of the non-participation level (7.5% of base acres, allocated to ARP, are not fertilized).

The environmentally-nominal and environmentally-real net return distributions are summarized in table 3. Mean nominal net returns range from -$27.32/acre for the strategy of a single application of 50 lbs. N without participation in the government program to $157.97/acre for the strategy of a single application of 175 lbs. N with participation in the government program. Mean real net returns range from -$27.42/acre for the strategy of a single application of 50 lbs. N

[2] All N-fertilizer levels and costs are stated in units of mineral N.

[3] The surplus N distributions were truncated at zero (i.e., no negative surplus N levels). Of the 1,200 surplus N calculations, only 11 were negative.

without participation in the government program to \$155.71/acre for the strategy of a single application of 175 lbs. N with participation in the government program. Note that at all fertilizer levels, the strategy with the highest mean nominal net return is under program participation and, for the lower three N rates, under the split application treatment. This relationship remains the same when the environmentally real net returns are compared.

Procedures

Production agriculture involves numerous risks. These risks, which influence the decision-making process, arise from the variability of yields and input and output prices. Yield and output price variability are considered in this analysis. Stochastic dominance with respect to a function (SDRF) analysis of net return distributions is employed to identify the risk efficient set of strategies from among the alternatives. The risk preference categories used are based on whole-farm risk aversion coefficients (J.W. Pratt) adjusted to evaluate per-acre net returns (Raskin and Cochran; Williams et al.). The SDRF analysis is conducted using a microcomputer program developed by Cochran and Raskin. Initially, SDRF analysis is used to compare the nominal net return distributions for the 24 strategies; the real net return distributions for the 24 strategies are then compared. Finally, after identifying the dominant distribution(s), the incremental value of N-fertilizer to the producer is estimated separately for both the nominal and real net return distributions, thus providing the needed information to approximate N-fertilizer demand schedules. This last step is achieved by calculating, for each risk attitude category, the premium that the producer would be willing to pay to use the dominant strategy (Mjelde and Cochran), rather than be forced to use an alternative strategy, then dividing by the fertilizer level of the alternative (dominated) strategy. The upper bound of the premium, which we use, is equivalent to the minimum parallel shift in the cumulative distribution of the dominant strategy that results in the dominant distribution being dominated by the comparison distribution. By plotting the incremental values obtained for the nominal distributions (constrained environmental damage information) and the real distributions (unconstrained environmental damage information) in an N-Price/N-quantity space, approximate constrained and unconstrained N-fertilizer demand schedules may be compared.

Results

In the absence of both economic and environmental risks, the preferred strategy would be identified on the basis of expected net returns (table 3); in this case, the strategy with a single application of 175 lbs./acre of N with program participation is preferred with mean net returns of \$157.97/base acre and expected surplus N of 59.2 lbs./base acre ($64.0 \times 0.925 = 59.2$ lbs./base acre). The same is true when environmentally-real net returns are considered.

The results of the SDRF analysis are summarized in table 4. When environmental damage is not included in the decision-making process, the SDRF analysis identifies the 175 lbs./acre N, single application with program participation strategy (175/P1) as the dominant strategy for producers with strongly risk preferring to strongly risk averse risk attitudes. This preferred strategy fails to differ from that chosen based solely on expected net returns and does not enforce the importance of risk in the decision-making process (Fleisher).

When environmental damage is incorporated into the decision-making process, only one strategy is identified as dominant for the strongly risk preferring to moderately risk averse risk attitude categories. Because environmental damage deflates net returns (inflates the variable costs) for the less environmentally-sound strategies, strongly risk averse producers are indifferent between the 150/P1 strategy (150 lbs. N, single application, with program participation) and the 175/P1 strategy.

For each risk attitude category, the incremental values of N to the producer were calculated for the nominal and real net return distributions. These values then were plotted in N-price/N-quantity space for each risk attitude category and informal regression lines (not forced through the point representing the preferred strategy) fitted to the data (figure 3). To save space, not all results of this process are presented. The two panels in figure 3 present the results for the extreme risk attitudes. As might be expected (Robison and Barry), N demand becomes more elastic as risk aversion increases. However, and more importantly, the unconstrained N demand is more elastic, though only slightly, than the constrained N demand in all cases, which is just as hypothesized.

Summary and Conclusions

Factor input demand should be affected when both economic and environmental risks are simultaneously taken into account in the producers decision-making process. N fertilizer demand in corn production was used as an example to test this direct application of the LeChatelier Principle. Weather and corn growth simulation models were used to generate 50-year dryland corn yield distributions at six different N-fertilizer levels and two different application treatments. A distribution of potential environmental damage, surplus N, also was calculated for each of the 12 strategies. Net returns were then calculated for each strategy under participation and non-participation in the 1991 government commodity program; the resulting 24 net return distributions were considered environmentally "nominal". In order to account for environmental damage and risk in the decision-making process, environmental costs were approximated and incorporated into the calculations of "environmentally real" net returns for each observation. The result was 24 "nominal" and 24 "real" net return distributions. Stochastic dominance with respect to a function (SDRF) analysis was employed to identify the dominant strategy set from the "nominal" distributions; the same was done with the "real" distributions. The incremental values of N-fertilizer for each of the dominated strategies then were calculated from the SDRF results and plotted as informal N demand schedules in N-price/N-quantity space.

The results indicate that, regardless of the inclusion or exclusion of environmental risk information in the decision-making process, N demand is more elastic as risk attitudes become more risk averse. More importantly, the results show that N demand is even more elastic when environmental damages are included in the decision process (unconstrained factor demand) than when such information is excluded (or limited) from the decision process (constrained factor demand) regardless of risk attitude. The latter finding suggests that by better educating producers about the potential environmental damage, and therefore localized health risks, caused by particular production strategies, they would choose more environmentally sound production strategies.

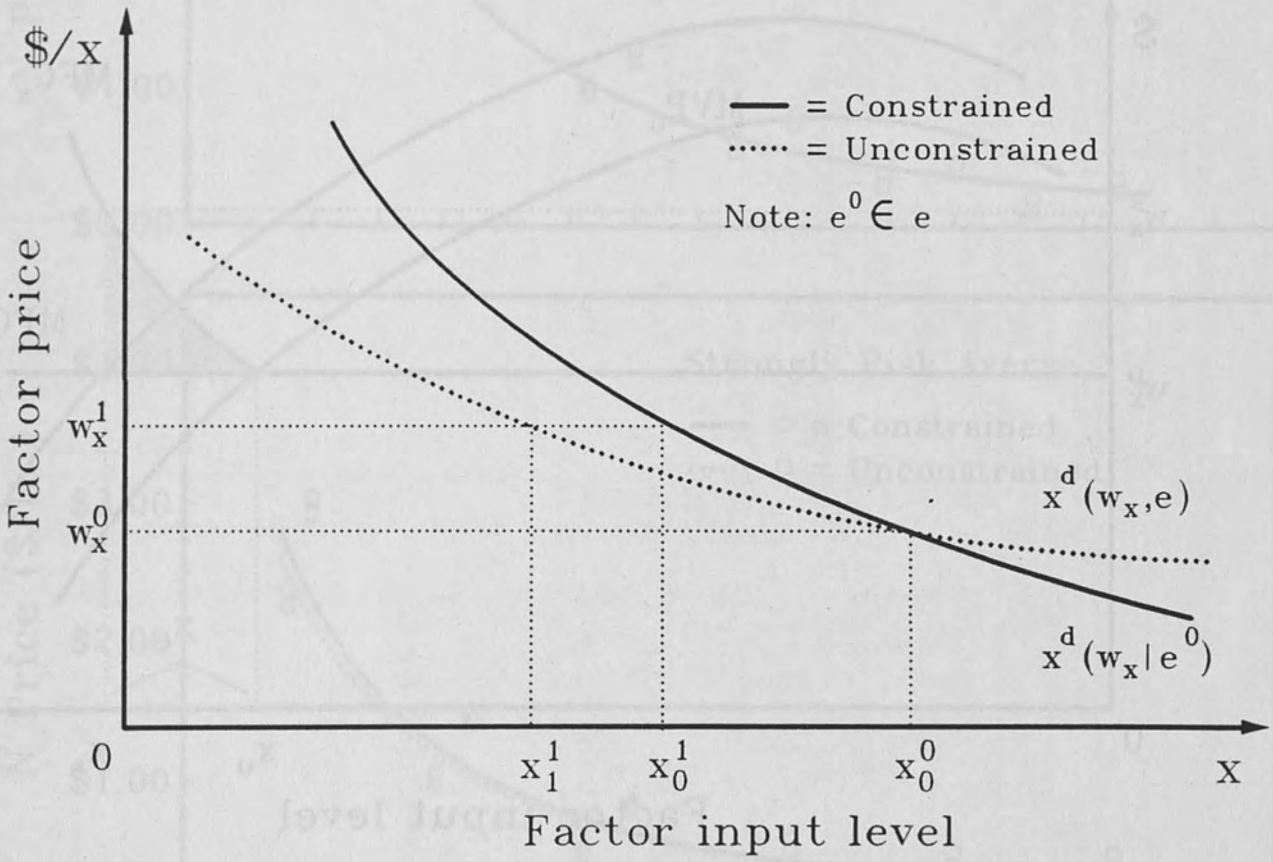

Figure 1. Constrained and unconstrained factor input demand schedules

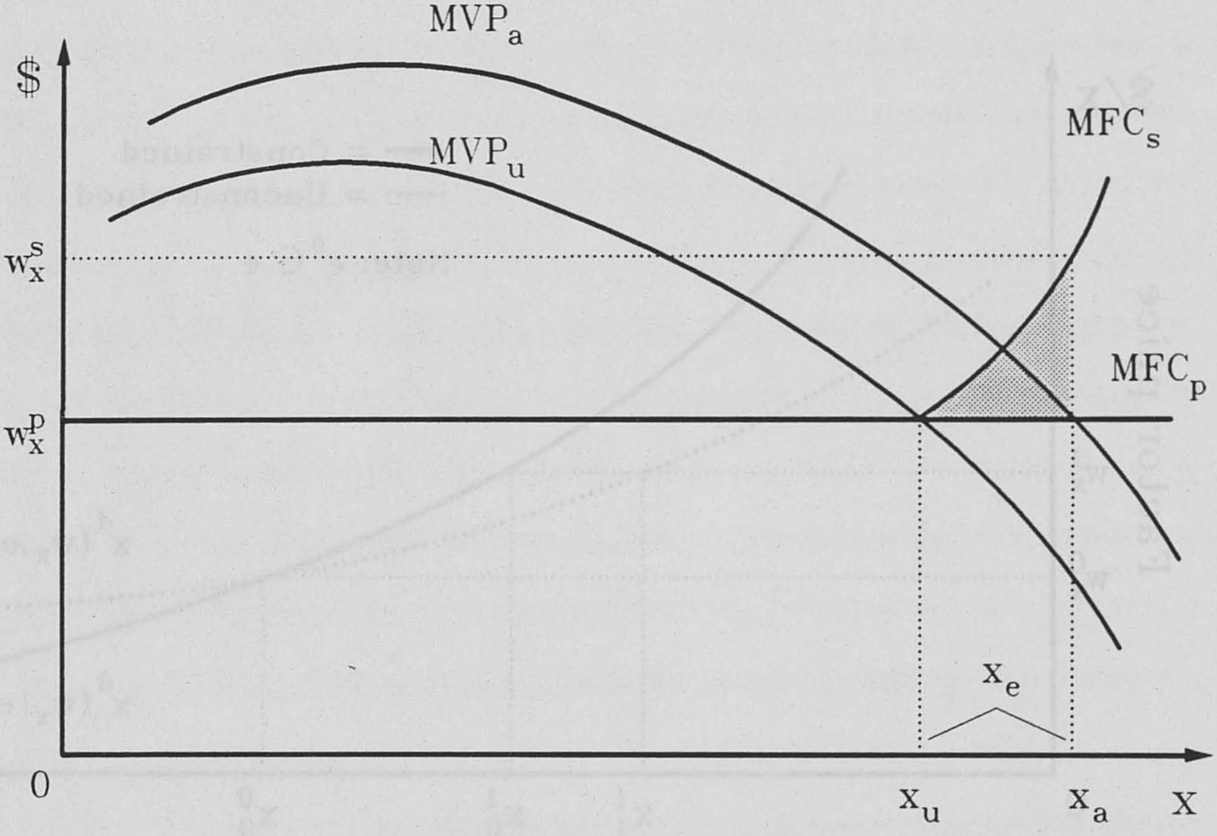

Figure 2. Divergence between private and social marginal factor cost and between applied and used marginal value product schedules

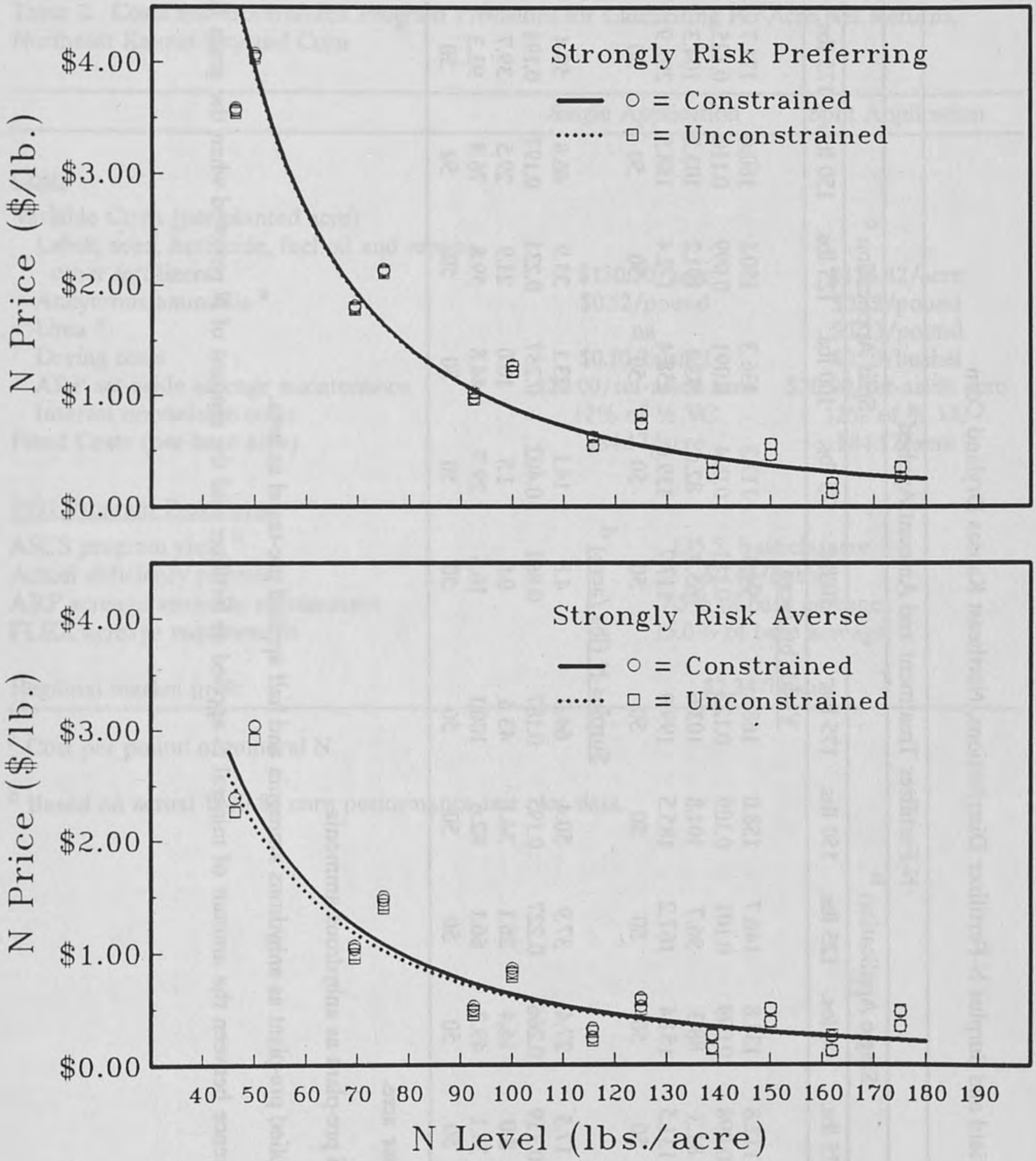

Figure 3. Approximate N-fertilizer demand schedules

Table 1. Summary of Yield and Surplus N-Fertilizer Distributions, Northeast Kansas Dryland Corn

	N-Fertilizer Treatment and Amount Applied [a]											
	Single Application [b]						Split Application [c]					
Statistic	50 lbs.	75 lbs.	100 lbs.	125 lbs.	150 lbs.	175 lbs.	50 lbs.	75 lbs.	100 lbs.	125 lbs.	150 lbs.	175 lbs.
	Yield (bu./acre)											
Mean	90.4	112.8	131.8	146.7	158.0	168.1	94.4	117.3	136.3	150.1	160.6	171.7
C.V.	0.114	0.098	0.099	0.101	0.109	0.122	0.111	0.094	0.091	0.099	0.110	0.125
Minimum	61.5	81.3	88.3	96.7	101.8	103.6	65.3	82.6	93.4	101.2	103.2	104.3
Maximum	112.1	131.5	151.4	167.2	185.5	199.0	117.7	139.6	158.4	172.4	188.5	202.9
# of Obs.	50	50	50	50	50	50	50	50	50	50	50	50
	Surplus N (lbs./acre) [d]											
Mean	6.9	17.5	27.4	37.9	50.4	64.0	4.8	14.1	23.1	33.9	46.8	59.4
C.V.	0.633	0.319	0.266	0.227	0.195	0.187	0.861	0.402	0.287	0.231	0.197	0.194
Minimum	0.0	8.0	16.4	26.1	34.1	43.6	0.0	1.5	10.0	21.9	29.5	39.7
Maximum	18.5	31.1	49.2	66.1	82.6	100.1	16.5	29.7	44.8	59.8	76.8	93.3
# of Obs.	50	50	50	50	50	50	50	50	50	50	50	50

[a] Pounds of mineral N per acre.

[b] All N-fertilizer applied pre-plant as anhydrous ammonia.

[c] Half of N-fertilizer applied pre-plant as anhydrous ammonia and half applied pre-tassel as urea.

[d] Surplus N is the difference between the amount of mineral N applied as fertilizer and the amount of N removed when the grain is harvested.

Table 2. Costs and Government Program Provisions for Calculating Per-Acre Net Returns, Northeast Kansas Dryland Corn

	Single Application	Split Application
Costs		
Variable Costs (per planted acre)		
Labor, seed, herbicide, fuel oil and repairs, other fertilizers	$130.30/acre	$133.42/acre
Anhydrous ammonia [a]	$0.12/pound	$0.12/pound
Urea [a]	na	$0.23/pound
Drying costs	$0.10/bushel	$0.10/bushel
ARP set-aside acreage maintenance	$20.00/set-aside acre	$20.00/set-aside acre
Interest on variable costs	12% of ½ VC	12% of ½ VC
Fixed Costs (per base acre)	$84.17/acre	$84.17/acre
1991 Program Provisions		
ASCS program yield [b]	135.5 bushels/acre	
Actual deficiency payment	$0.43/bushel	
ARP acreage set-aside requirement	7.5% of base acreage	
FLEX acreage requirement	15.0% of base acreage	
Regional market price	$2.34/bushel	

[a] Cost per pound of mineral N.

[b] Based on actual 1980-84 corn performance test plot data.

Table 3. Summary of Net Returns Per Base Acre, Northeast Kansas Dryland Corn

Cost Scheme	Fertilizer Treatment [b]	N-Fertilizer Level and Commodity Program Strategy [a]											
		50 lbs./Acre		75 lbs./Acre		100 lbs./Acre		125 lbs./Acre		150 lbs./Acre		175 lbs./Acre	
		N	P	N	P	N	P	N	P	N	P	N	P
		Mean Net Returns Over Total Costs ($/Acre) [c]											
Nominal	Single	-27.32	11.94	19.57	55.32	58.99	91.77	88.99	119.53	111.02	139.91	130.55	157.97
		(-0.84)	(1.78)	(1.26)	(0.41)	(0.49)	(0.29)	(0.37)	(0.26)	(0.35)	(0.25)	(0.35)	(0.27)
	Split	-24.60	14.45	22.04	57.60	59.77	92.50	86.05	116.81	104.83	134.18	124.97	152.81
		(-0.95)	(1.49)	(1.12)	(0.40)	(0.46)	(0.28)	(0.38)	(0.26)	(0.38)	(0.27)	(0.38)	(0.29)
Real [d]	Single	-27.42	11.85	19.19	54.97	58.27	91.12	87.88	118.50	109.33	138.34	128.11	155.71
		(-0.84)	(1.81)	(1.30)	(0.42)	(0.51)	(0.30)	(0.38)	(0.26)	(0.36)	(0.26)	(0.37)	(0.28)
	Split	-24.69	14.37	21.68	57.27	59.07	91.85	84.82	115.67	102.79	132.29	122.03	150.09
		(-0.95)	(1.51)	(1.15)	(0.40)	(0.48)	(0.28)	(0.40)	(0.27)	(0.40)	(0.29)	(0.41)	(0.31)

[a] "N" indicates non-participation in the government commodity program; "P" indicates participation in the government commodity program.

[b] "Single" application indicates all N-fertilizer applied pre-plant as anhydrous ammonia; "Split" indicates half of N-fertilizer applied pre-plant as anhydrous ammonia and half applied pre-tassel as urea.

[c] Coefficient of variation statistics are in parentheses.

[d] Refer to text for definition of "real net returns."

Table 4. Results from Stochastic Dominance Analysis of Net Return Distributions

Approximate Risk Attitude	Pratt-Arrow Risk Aversion Coefficients	Nominal Net Returns	Real Net Returns [a]
		- - - - - - - - Efficient Set Strategies [b] - - - - - - - -	
Strongly Risk Preferring	-0.0640 to -0.0320	175/P1	175/P1
Moderately Risk Preferring	-0.0320 to -0.0064	175/P1	175/P1
Slightly Risk Preferring	-0.0064 to 0.0000	175/P1	175/P1
Risk Neutral	-0.0064 to 0.0064	175/P1	175/P1
Slightly Risk Averse	0.0000 to 0.0064	175/P1	175/P1
Moderately Risk Averse	0.0064 to 0.0320	175/P1	175/P1
Strongly Risk Averse	0.0320 to 0.0640	175/P1	150/P1, 175/P1

[a] Refer to text for definition of "real net returns."

[b] Strategy names indicate total amount of N-fertilizer applied (lbs./acre)/participation (P) or nonparticipation (N) in the basic government commodity program, and number of applications (1 indicates all N-fertilizer applied pre-plant; 2 indicates half of N-fertilizer applied pre-plant and half applied pre-tassel).

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