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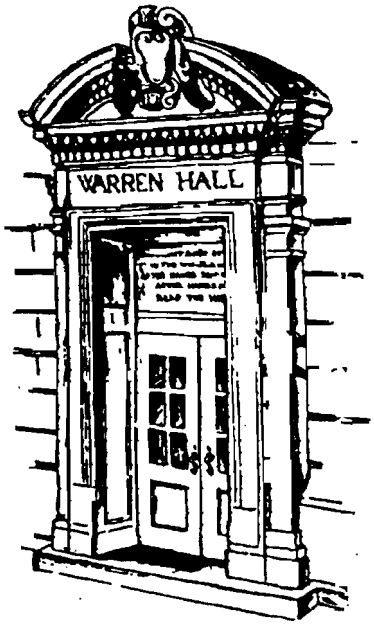

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Department of Agricultural, Resource, and Managerial Economics
Cornell University, Ithaca, New York 14853-7801 USA

OPTIMAL "GREEN" PAYMENTS TO MEET CHANCE CONSTRAINTS ON NITRATE LEACHING UNDER PRICE AND YIELD RISK

Jeffrey M. Peterson and Richard N. Boisvert

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Optimal "Green" Payments to Meet Chance Constraints on Nitrate Leaching Under Price and Yield Risk

By

Jeffrey M. Peterson
and
Richard N. Boisvert[#]

[#] Jeffrey M. Peterson and Richard N. Boisvert are graduate research assistant and Professor in the Department of Agricultural, Resource, and Managerial Economics, Cornell University. This research was supported by a Cooperative Agreement, Economic Research Service, USDA, 43-3AEM-2-800900 and Hatch Project NY(C) 121444, USDA.

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Abstract

A program of "green" payments is designed for farmers to voluntarily reduce nitrate leaching by restricting nitrogen application on corn. Price and weather risk are considered, information is asymmetric, and environmental quality is regulated by chance constraints. Empirically, risk and asymmetric information have implications for the value of information, program costs, and producer benefits.

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U.S. agricultural programs to redistribute income from taxpayers and consumers toward farmers are characterized by their variety and voluntary nature (Chambers, 1992). This variety is reflected in the environmental provisions of recent farm bills, whereby eligibility for farm subsidies is conditioned on the adoption of conservation measures, and in the market-oriented proposals to reduce environmental damage. As pressure to reduce agricultural subsidies mounts, we must identify creative policies to reduce environmental damage from agricultural production.

As an alternative to taxes or quantity restrictions on environmental residuals or on chemical inputs, Wu and Babcock (1995) discuss the optimal design of a "green" payment program under asymmetric information. Their policy is designed to maximize the social surplus from agricultural production, which is equal to farm income less the social cost of pollution and the marginal social cost of raising tax revenue to support the government payments. The program is voluntary, and "green" payments to farmers, as an incentive to adopt environmentally sound production practices, are designed for farms with different resource situations. Payment levels are set so that producers have no incentive to choose an option intended for another group. Their analysis assumes that net returns and environmental damages are known with certainty; it was also necessary to set the social costs of pollution and of raising tax revenue at arbitrary levels.

This paper extends the analysis of this type of "green" payment scheme in several important ways. Two sources of risk are considered. Following Lichtenberg and Zilberman (1988) and Zhu, *et al.* (1994), the government's policy objectives are articulated as a chance constraint which limits the probability of severe environmental damage. The self-selection or incentive compatibility constraint, which insures producers have no incentive to select the wrong option, recognizes both

price risk and yield risk due to weather. We estimate the additional government cost resulting from the asymmetric information concerning the resource endowments of farm groups. The model is formulated to examine "green" payments to reduce nitrogen fertilizer application on corn to control nitrate leaching and runoff, but it can be modified in obvious ways to examine other "green" payments for the adoption of other environmentally sound practices.

The Model

A "green" payment scheme compensates farmers for their choice of environmentally sound production practices. The government presents producers with a policy menu, each item consisting of a particular production practice (such as specific input or output levels or production techniques) and an associated government payment. Each item on the menu is designed for farms with a particular resource endowment or other distinguishing characteristic, but the government either has insufficient information to classify farms by this criterion or avoids using it as an overt basis for setting program payments (Chambers, 1992). This asymmetry of information, combined with the facts that the program is voluntary and each item on the menu is available to farmers in all groups, requires that payments be set so that there is no incentive for farmers select the wrong option. In our model, the government formulates the policy menu in two steps. First, the desired production practice for each group is determined, and second, the payment to induce producers to adopt those production practices is set.

For simplicity, but with no loss of generality, consider two groups of farmers ($i = 1,2$). Each group produces corn, but is differentiated by the quality of land. Both corn yield, $Y_i = y_i(N_i,W_i|C_i)$, and nitrate leaching and runoff, $L_i = l_i\ (N_i,W_i|C_i)$, per acre are functions of nitrogen applied (N_i),

weather (W_i), and given soil characteristics (C_i). One can assume that $\partial Y_i/\partial N_i > 0$, $\partial L_i/\partial N_i > 0$, $\partial Y_i/\partial W_i > 0$, and $\partial L_i/\partial W_i > 0$. Initial nitrogen fertilizer levels are at N_{i0} and yields are Y_{i0}. Net return is $R_{i0} = PY_{i0} - rN_{i0}$, where r is the price of nitrogen and P is the net return per bushel, exclusive of nitrogen cost. With weather and net returns for corn as random variables, the cumulative distribution function (c.d.f.) for this net return is $F_i(R_{i0}|N_{i0}) = \int_{-\infty}^{R_i} f_i(t_i|N_{i0})dt_i$.

The government's objective is to minimize the cost of insuring that on all land in corn, the probability of combined leaching and runoff exceeding L^* is less than or equal to α. In step 1, nitrogen levels, N_i, are selected for each group that satisfy this constraint. In step 2, assuming that farmers are risk averse, the green payments must be set so that the post-policy distribution of net return for each group who self select the appropriate policy dominates the pre-policy distribution by second degree stochastic dominance (SSD).[1] Assuming A_i acres in each group, the problem becomes:

(1) Min. $\sum_i A_i S_i$

(2) subject to $P[l_i(N_i,W_i|C_i) \geq L^*] \leq \alpha$, $(i = 1,2)$,

(3) $F_1^2(R_{11}+S_1|N_1) \leq F_1^2(R_{10}+0|N_{10})$,

(4) $F_2^2(R_{22}+S_2|N_2) \leq F_2^2(R_{20}+0|N_{20})$,

(5) $F_1^2(R_{11}+S_1|N_1) \leq F_1^2(R_{12}+S_2|N_2)$,

(6) $F_2^2(R_{22}+S_2|N_2) \leq F_2^2(R_{21}+S_1|N_1)$,

---

[1] Assuming that producers prefer more income to less and are risk averse, i.e., $U'(R) > 0$ and $U''(R) < 0$, the conditions for SSD can be used to represent producers' preferences over distributions of net returns (Hadar and Russell, 1969). Under SSD, an alternative F dominates G if the area under the c.d.f. of F is nowhere more than that of G and is somewhere less than the area under the c.d.f. of G. Or, F dominates G if and only if $F^2(Y) \leq G^2(Y)$, with strict inequality for at least one value of Y, where $F^2(Y) = \int_{-\infty}^{R} F(t)dt$.

for possible values of $R_{ij} + S_i$, with a strict inequality for at least one value, where $F_i^2(R_{ij} \mid N_i) = \int_{-\infty}^{R_{ij}} F_i(t_{ij}|N_i)dt_{ij}$, and where the subscripts ij refer to the net returns to the i^{th} group evaluated at nitrogen levels designed for the j^{th} group ($j = 0$ corresponds to pre-policy returns for group i). N_i and S_i are the post-policy nitrogen and "green" payment levels for group i, respectively. The "green" payment for the pre-policy situation is zero for both groups. This model is the mechanism design problem that the government faces in formulating a policy that will operate under these circumstances. The government's solution will lead to a policy menu including three items: no participation and no payment, $(N_{i0},0)$, and production practices designed for producers in each group with an associated payment, (N_1,S_1), and (N_2,S_2).

Because most of the equations in the model are conditions for SSD, it is impossible to solve this model analytically, but one can draw general conclusions about the nature of the policy menu. Equations (2) are the chance constraints on nitrate leaching and runoff, whereas equations (3) and (4) guarantee that the post-distribution of net returns plus the "green" payment dominates the pre-policy distribution of net returns by SSD for each group individually. To meet the chance constraint, it is reasonable that $N_i < N_{i0}$, $Y_{ii} < Y_{i0}$, and $R_{ii} < R_{i0}$. Thus, for equations (3) and (4) to hold, $S_i > 0$. In addition, the SSD conditions in (5) and (6) guarantee that producers in group i will self select the policy designed for that group and will have no incentive to choose an option designed for other groups. These equations, called *self-selection* constraints, are particularly difficult to disentangle analytically, because even though nitrogen levels are reduced for both groups, $N_j <=> N_{i0}$. This, combined with the fact that the yield response functions differ, implies that $R_{ij} <=> R_{i0}$, and if $R_{ij} > R_{i0}$ then the "green" payment needed to meet the self-selection conditions may be larger than what is

necessary to satisfy only conditions (3) and (4). Put differently, the "green" payments required for self-selection could be higher than those required if information was not asymmetric and producers could only volunteer for the program designed for their group. This difference is the opportunity cost of information.

An Application to Corn Production in New York

This model is applied to production of corn silage in central New York, the two groups of producers having soils with different yield and nitrogen leaching potential. Soils for group 1 are typical of those in hydrologic group A, while those for group 2 are typical for hydrologic group B. These soils are the most suitable for raising corn, and according to National Resources Inventory and soils data from over 150 farms, about 10% and 50% of New York's cropland are in hydrologic groups A and B, respectively (Boisvert, *et al.*, 1995 and Thomas, 1994). The distributions of yields, nitrate leaching and runoff, and net returns are simulated using corn and fertilizer prices and weather data for a 30-year period, beginning in 1963. Corn silage prices are based on a corn grain equivalent, and prices and production costs are converted to constant 1992 dollars. Variable production costs for corn excluding nitrogen are taken from corn enterprise budgets in Schmit, and USDA-ERS.

The Data and Initial Production Levels

Silage yields (tons/acre) for the two groups (Y_i) are simulated from yield functions, which depend on nitrogen application in lbs./acre (N), growing season rainfall in inches (W), and accumulated growing degree days during the growing season (G). The data used to estimate these yield relationships were from field trials at several sites in New York. Averaging the replications of each fertilization level at each site generated 66 observations of yield, fertilization rates, and weather.

The model was estimated with slope and intercept dummy variables for soils by hydrologic group. The Y_1 equation is for soils in hydrologic group A; Y_2 is for the soils in hydrologic group B. The estimated yield equations (t-ratios) are ($R^2 = 0.72$)[2]:

$$
\begin{array}{lcccccc}
Y_1 = & 16.32 & +0.096N & -0.0003N^2 & +1.56W & +0.007G & -0.0018N \times W \\
 & (-10.09) & (6.32) & (-4.43) & (5.49) & (3.23) & (-1.51) \\
Y_2 = & 11.17 & +0.096N & -0.0002N^2 & +0.066W & +0.007G & -0.0018N \times W \\
 & (-3.17) & & (1.15) & (-5.32) & &
\end{array}
$$

Estimates of nitrate leaching and runoff are from statistical relationships relating nitrate leaching and runoff on New York soils to nitrogen application, five soil characteristics, and several rainfall variables (table 1). They are estimated from runoff and leaching data generated by GLEAMS (Leonard *et al.*, 1987) representing 1,350 combinations of weather, soil characteristics, and nitrogen levels. Using predicted values of runoff in the leaching equation was equivalent to an instrumental variable procedure for this recursive system (Judge *et al.*, 1988). To help in the interpretation of these functions that are quadratic in logarithms (Bailey and Boisvert, 1991), the elasticities of leaching and runoff are reported for mean levels of the important explanatory variables, and for the most part, have the expected signs. Further, Boisvert *et al.* (1995) report that the leaching equation predicts well, particularly in the upper tail which is most critical for policy purposes.

To begin the policy experiment, the second-degree stochastic efficient (SSE) set of nitrogen application rates was determined using a program in Anderson, *et al.* (1977). The SSE nitrogen fertilization rates range from 129 to 138 lbs./acre for group 1, and 142 to 160 lbs./acre for group 2. It seemed reasonable to set initial rates of nitrogen fertilization at the midpoints of these ranges. These rates are in table 2, along with the corresponding averages and standard deviations in

[2]Since the equations were estimated in a pooled regression, t-ratios reported for the second equation correspond to interaction terms with the group 2 dummy variable, i.e., the t-ratios given correspond to D_2, $D_2 \times N^2$, and $D_2 \times W$, respectively.

Table 1. Regression Equations for Nitrogen Runoff and Leaching

Variable*	Description	Runoff			Leaching		
		Coef.	t-ratio	Elast.	Coef.	t-ratio	Elast.
		R^2=0.509			R^2=0.494		
Constant		-4.402	-7.02		-75.568	-9.35	
L(NITRUN)**	Nitrogen runoff (lbs./acre)				-6.739	-4.38	-4.52
L(NITRUN)SQ					2.119	1.76	
L(H1)	Soil horizon depth (in.)				5.638	7.33	0.21
L(SLP)	Average field slope (%)				-1.154	-4.37	-0.46
L(SLP)L(H1)					0.453	2.66	
L(KAY)	K erodibility factor	0.058	2.09	0.06	-5.594	-7.91	-2.11
L(KAY)L(H1)					2.287	6.80	
L(ORG)	Organic Matter (%)	3.241	9.24	0.26	5.235	5.51	2.00
(LORG)SQ		-1.039	-8.47				
L(ORG)L(H1)					-2.127	-5.01	
L(MINN)	Nitrogen mineralized by soil (lbs./acre)	-0.581	-6.60	-0.58	5.442	5.81	5.44
L(RAIN)	Total annual rainfall (in.)	0.652	15.27	0.65	5.768	9.33	5.77
L(PRSTM)	Rainfall 14 days of plan (in.)*	0.089	5.94	0.01			0.10
(LPRSTM)SQ++		0.023	6.47		0.056	3.34	
L(NIT)L(PRSTM)					0.363	3.75	
L(FRSTM)	Rain w/in 14 days of fert. (in.)*			-0.01	0.256	5.05	0.10
(LFRSTM)SQ		0.005	5.82		0.094	6.59	
L(LBMAN)	Total fertilizer (lbs./acre)**	0.628	7.05	0.63	4.824	4.78	4.82
L(ROT)	Years of corn in rotation				-0.627	-4.55	-0.63
LAGCORN	Dummy, corn previous year				-0.668	-6.49	
L(HRSTM)	Rain w/in 14 days of har. (in.)*				0.039	1.18	0.04
HYDA	Dummy, hydrologic soil group A+	-0.453	-23.06		0.290	2.87	
HYDB	Dummy, hydrologic soil group B+	-0.359	-22.11				
MANURE++	Dummy, manure application				0.235	1.62	

Source: Boisvert, *et al.*, 1995.

*Except for the dummy variables, the variables are logarithmic transformations; some of the variables represent a square of the logarithm (sq) or the product of two logarithms. NITRUN is the logarithm of estimated runoff from the runoff equations.

**Chi-square test statistics for heteroskedasticity were 229 for the runoff equation and 246 for the leaching equations. Standard errors were recalculated as the square root of the diagonal elements of the estimated asymptotic covariance matrix. These standard errors are consistent (White, 1980).

+To purge the runoff variables from any unexplained random component, the predicted values from the runoff equation are used in the leaching equation (Judge *et al.*, 1988).

++Commercial fertilizer application is combined with the nitrogen equivalent included in the various rates of manure application; any differential effect is captured through a dummy variable.

Table 2. Yields, Net Returns, "Green" Payments and Nitrate Leaching and Runoff, by Farm Group and Safety Level

	Safety Level (Nitrate Leaching and Runoff, lb./acre)[a]											
	Group 1						Group 2					
Item	66[b]	40	35	30	25	20	50[b]	40	35	30	25	20
Nitrogen Fertilizer Applied (lb./acre)	133	99	92	84	75	63	151	128	119	109	98	80
Leaching and Runoff (lb./acre)												
Mean	38.6	24.7	22.6	20.4	18.4	16.1	34.2	24.6	22.5	20.4	18.5	16.1
Standard Deviation	19.5	11	9.8	8.6	7.5	6.4	16.8	10.9	9.7	8.5	7.5	6.3
Corn Silage Yield (tons/acre)[c]												
Mean	20.3	19.5	19.3	19.0	18.6	18.0	17.3	16.7	16.4	16.0	15.6	14.8
Standard Deviation	4.21	4.41	4.46	4.50	4.56	4.63	1.09	0.98	0.94	0.89	0.85	0.78
Net Returns From Corn Production ($/acre)												
Mean	188	184	182	179	174	165	121	118	115	111	106	96
Standard Deviation	108	110	111	111	111	112	53	51	50	49	48	46
"Green" Payment ($/acre)		10	15	20	26	39		4	6	10	15	25
Mean Net Revenue Including "Green" Payments ($/acre)		194	197	199	200	203		121	121	121	121	121
Average Loss in Net Returns From Corn Production ($/acre)[d]		4	7	10	14	23		4	6	10	82	92
Green Payment in Absence of Self-Selection ($/acre)[e]		7	10	13	18	28		4	6	10	15	25

[a] L* from equation (2), for $\alpha = 0.1$ [b] Implicit safety levels associated with pre-policy nitrogen application levels.
[c] Assumes 15% field and other losses. [d] This is the loss in revenue from reduced nitrogen application regarding "green" payments.
[e] "Green" payments if appropriate policies can be assigned by group (i.e., symmetric information; ignoring equations (5) and (6)).

combined leaching and runoff, yields (adjusted for 15% field losses), and net returns. Soils for group 1 are slightly more productive than for group 2 (20 vs. 17 tons/acre), but yields and net returns are more variable. Relative to the mean, net returns are more variable for both groups than are yields. Since yield variability is affected only by weather, most of the variability in net returns is due to price. Average leaching is about 39 and 34 lbs./acre for groups 1 and 2, respectively; it is more variable on group 1 soils.

The Safety Levels

For the policy experiment, five safety levels for the chance constraints (equation (2)) were selected, $L^* = 40$, 35, 30, 25, and 20 lbs./acre, and the probability of exceeding these levels was set at $\alpha = 0.1$. As a point of reference, according to the 30-year empirical distributions in figures 1 and 2, the implied safety levels for combined leaching and runoff corresponding to the initial nitrogen application rates (the level of nitrate leaching and runoff which is exceeded in only 3 out of the 30 years) are 66 lbs./acre for group 1 and 50 lbs./acre for group 2. To identify the reduction in nitrogen application rates needed to reach the four more stringent safety levels, successively lower rates were substituted into the nitrate leaching and runoff functions in Boisvert *et al.* (1995) until the other empirical distributions in figures 1 and 2 were obtained. To meet the safety level of 35 lbs./acre, for example, commercial fertilizer application would have to fall to about 92 and 119 lbs./acre for the two groups, respectively. As expected, for more stringent safety levels, the means and standard deviations in leaching fall. Average yields fall as well, but yield variability increases slightly for group 1.

Figure 1. Distribution of Nitrate Leaching and Runoff on Group 1 Soils, Alternative Safety Levels

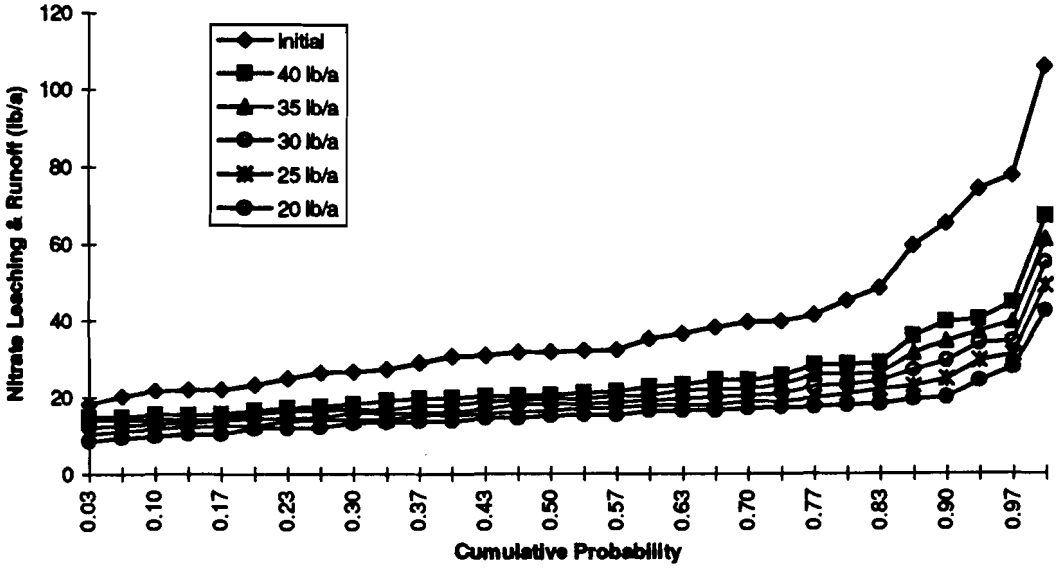
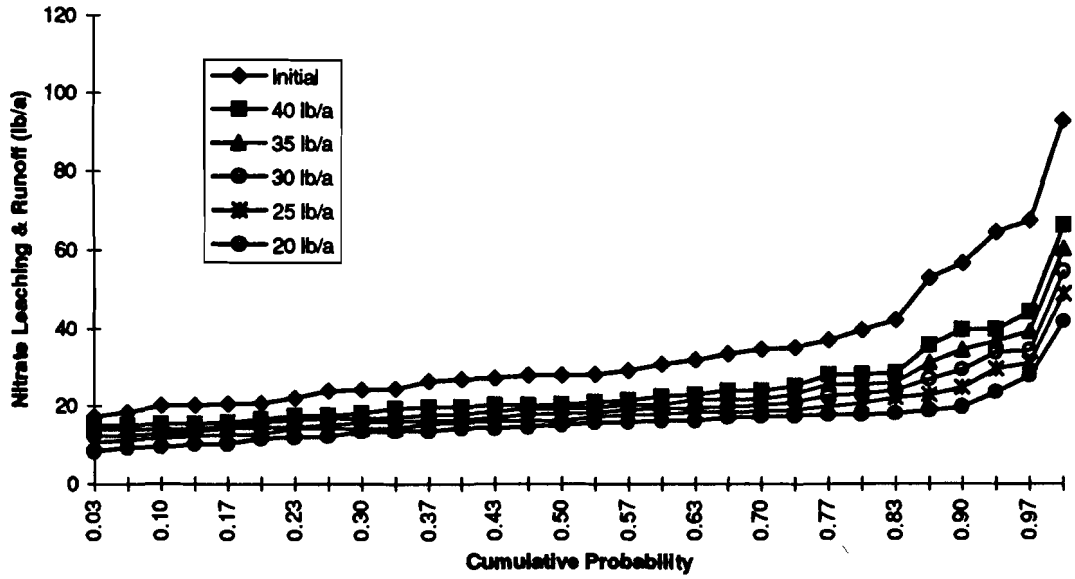


Figure 2. Distribution of Nitrate Leaching and Runoff for Group 2 Soils, Alternative Safety Levels



Note: The safety levels in the legends are the same as those described in table 2.

The "Green" Payments

Because our model cannot be solved analytically, an iterative strategy was used to identify the appropriate size of "green" payments to induce voluntary participation by each group. The most basic requirement of the "green" payments is that they provide an incentive for producers in both groups to participate in the program. Accordingly, for each safety level, the smallest value of S_i, for which the distribution of post-policy net returns designed for each group dominates its pre-policy distribution, was calculated by successively incrementing S_i from zero. These distributions were ranked against the initial situation, again using the program in Anderson *et al.* (1977). The payments derived in this way correspond to the situation where the government's policy mechanism ignores self-selection conditions. Put differently, these are the payments needed to induce voluntary participation if the government could identify a producer's group and offer only the policy designed for that group. For this situation, the "green" payments required range from \$7 to \$28/acre, and \$4 to \$25/acre for groups 1 and 2, respectively (table 2).

Where information is asymmetric, "green" payments must be set so that producers will voluntarily select the proper policy option, otherwise the chance constraints will be violated. The payments required in order to satisfy these *self-selection* conditions may be higher still. In our case, without such an added incentive, group 1 producers would also select group 2's policy because the payment, relative to the reduction in net returns, would be larger. If, for example, $L^* = 30$ is judged to be the appropriate safety level, the distribution of net returns for group 1 producers choosing $(N_2,S_2) = (109,10)$ will dominate the distribution of net returns if $(N_1,S_1) = (84,13)$ is chosen. As a

result, the "green" payments associated with group 1 policy options must be increased significantly, ranging from \$10 to \$39/acre, compared with \$4 to \$25/acre for group 2 (table 2)[3].

Policy Implications

In this paper, we have developed a strategy for designing "green" payments needed for voluntary adoption of environmentally sound management practices where price and yield risk are considered explicitly and environmental quality is defined according to chance constraints on the level of environmental damage. In our empirical application to New York, groups of farmers are offered payments to reduce nitrate leaching and runoff by restricting nitrogen application on corn, under the assumption that farmers respond in a risk averse way. Price uncertainty is an important source of risk, since the yield variability due to weather (the one random factor also affecting the level of nitrate leaching) accounted for only a small proportion of variability in total net returns.

From a policy perspective, the higher "green" payments to one group to insure voluntary participation and self selection under asymmetric information suggest that the gains from not revealing one's true resource situation could be substantial, in our case, 50% larger than when the *self-selection* conditions are ignored. In our case, the group whose payments are substantially above those under assumptions of symmetric information own only a small fraction of the total resource base, but that need not always be the case. Therefore, the implications for government costs could be substantial, and the size of the payment differential is a good indication of the value of collecting

[3] For group 2 producers, the distribution of net returns under (N_2,S_2) does not dominate the distribution under (N_1,S_1). This occurs because the yield responses from nitrogen are quite similar for the two groups in the range $[N_1,N_2]$; any S_1 large enough so that (N_1,S_1) is preferred by group 1 producers makes the alternatives indistinguishable for group 2 in terms of stochastic dominance. This implies that some risk averse decision makers in group 2 may choose group 1's policy. In our case, $N_1 < N_2$; thus, by choosing group 1's policy, group 2 producers would generate further improvements in environmental quality beyond the chance constraint. However, their government payments would be substantially higher, and if many group 2 producers chose the wrong policy, the impact on total program costs could be large.

information needed to classify farms for policy design purposes. The value of this information must be weighed against the cost of collecting it.

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