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Department of Agricultural Economics
MICHIGAN STATE UNIVERSITY
East Lansing, Michigan 48824

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Mei-chin Chu, Scott M. Swinton, and Sandra S. Batie[2]
chumeich@pilot.msu.edu,swintons@pilot.msu.edu, batie@pilot.msu.edu

Department of Agricultural Economics
Michigan State University
East Lansing, MI 48824-1039

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[2]The authors are, respectively, graduate assistant, assistant professor, and Elton R. Smith Professor in Food and Agricultural Policy, Dept. of Agric. Economics, Michigan State University.
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A Risk-Programming Approach to Designing Contracts to Reduce Nitrate Leaching

Abstract

As contractual agriculture expands, contract design offers a non-regulatory opportunity to reduce non-point source pollution. A risk programming analysis of seed corn contract designs illustrates a tractable empirical principal-agent model, and shows that grower risk preferences affect contract acceptability and efficiency at reducing nitrate leaching.

15 pages.

A Risk-Programming Approach to Designing Contracts to Reduce Nitrate Leaching

The spread of contractual production in U.S. agriculture (Drabenstott, 1994) offers new opportunities to address public concerns over agricultural non-point source pollution (NPSP). Both processor concerns about brand reputation and the opportunity to market "identity-preserved" goods (Urban, 1991) give processors reason to care about how their customers perceive their environmental reputations. The greater vertical coordination offered by agricultural production contracts, in turn, allows processors to influence the environmental stewardship exercised in production of commodities they process and market. Hence, contracts present an opportunity to achieve public environmental goals without government regulation and its associated transactions costs.

The economic theory of contract design examines how a "principal" who cannot fully observe what an "agent" is doing can, nonetheless, influence the agent to behave in a desirable fashion. In our case, the question is how a an agricultural processor can design a "green" contract to induce grower contractors to meet both production goals and environmental ones. Principal-agent theory suggests that risk to the agent plays an important role in the design of suitable incentives (Holmstrom and Milgrom, 1987). This research will develop an empirical principal-agent framework to examine how agent risk attitudes affect the acceptability and environmental cost efficiency of "green" agricultural production contracts.

Our specific application is to seed corn production contracts designed to reduce nitrate leaching under different levels of grower risk aversion. In a typical seed corn production contract, the processing firm offers price premiums to encourage contractual growers to achieve high yields. One way to accomplish this goal is to fertilize heavily with nitrogen, which can lead to excessive nitrate leaching. The objectives of the paper are to examine 1) how the risk attitudes of representative seed corn growers affect their preferred crop mixes and practices; 2) how these cropping practices affect predicted nitrate leaching; 3) how seed corn production contracts can be redesigned to induce seed corn growers with various risk attitudes to reduce nitrate leaching; and 4) how costs are shared between processor and grower under alternative contracts.

Chu et al. (1995) have shown that a principal-agent model can be adopted to design a "green" agricultural production contract and that risk attitudes are important. The general structure of a principal-agent model adapted to the seed corn processor-grower context can be outlined as follows (Candler and Townley, 1982):

$$\max_{s} E\{G[y-s(y)]\},$$

subject to

$$E\{H[s(y),n]\} \geq U^0 \quad (1)$$

$$n \in \underset{n,\, n' \in N}{\operatorname{argmax}} E\{H[s(y), n']\} \quad (2)$$

where ***n*** and ***n'*** are alternative nitrogen use. The processor chooses an incentive payment, ***s(y)***, based on observable seed corn yield, ***y***, which induces the grower to choose a nitrogen application rate, ***n***, conditioned on two constraints: participation (equation 1) and incentive compatibility (equation 2). The participation constraint ensures the contractor-grower will earn at least enough to reach his or her reservation utility level, U^0. The incentive compatibility constraint guarantees that the grower's choice will maximize the processor's objective function ***G(·)***.

Consider an example seed corn contract which has a linear payment (Shaw et al., 1989):

$$s(y) \quad = a + b\, y \tag{3}$$

where s is total payment from the seed processor to the contractor-grower; y is grower yield of seed corn; a and b are fixed and variable payments, conditioned on the observable outcome, y. The seed processor chooses a and b to design an incentive payment.

In theory, a principal-agent model can be solved empirically using two-level mathematical programming (Bard and Moore, 1990; Candler et al., 1981; Candler and Townley, 1982; Kornai and Liptak, 1965). However, two practical barriers impede all but the simplest attempts. First, due to the model's inherent non-convexity, convergence to the global optimum is not guaranteed (Candler, et al., 1981; Bard and Moore, 1990). Second, due to the complexity of stating interdependent objective functions, applications must be limited to small matrices.

To overcome these barriers, we decompose the general principal-agent model into two stages. Because any constrained optimization must first satisfy its constraints, we begin by modeling the behavior of the representative seed corn contractor-grower. A representative whole-farm model verifies whether the principal's incentive-compatibility and participation constraints are met when the grower's objective function is maximized. In the second step, we evaluate the impacts of different contract specifications for both processor-principal and grower-agent. We then identify the preferred contract designs for each party and which of these are potentially acceptable to both parties.

A Representative Whole-Farm Model

A representative southwestern Michigan seed corn farm is chosen to model the first stage of the principal-agent model. Mean-variance (EV) analysis is employed to model the grower's behavior under risk (Freund, 1956). The EV model has been shown to be consistent with the expected utility function under certain circumstances (Meyer, 1987; Robison, 1994), and it has been used extensively in analyzing farm-level decisions (Musser and Stamoulis, 1981; McSweeney and Kramer, 1986; Feinerman, Herriges and Holtkamp, 1992). In our EV model, we use coefficients of absolute risk aversion (CARA) equal to 0, 10^{-5}, $5*10^{-5}$, and 10^{-4}. Nitrate leaching and yield data are simulated from a crop growth simulation model and then are incorporated as "states of nature" into a whole-farm quadratic programming (QP) model. The QP model is adapted from a whole-farm risk programming model (Dobbins et al., 1996) developed from the Purdue Crop/Livestock Linear Programming model (Dobbins et al., 1994).

The representative seed corn grower is assumed to own 1,200 acres of cultivable land, and may rent up to 500 additional acres. All the land is irrigated. A contract is available for up to 500 acres of seed corn production. The farm is operated by one adult with a typical machinery complement and the option to hire supplementary labor. In addition to seed corn, the crop enterprises include commercial corn and soybean, plus the option to take a cash rental contract for potato production.

Crop rotations with associated nitrogen carryover and yield are modeled using DSSAT v3.0 (Tsuji et al., 1994), adjusted for organic matter decay rate (Gabrielle and Kengni, 1996; Vigil, Kissel, and Smith, 1991). Three nitrogen fertilization rates on seed corn are examined (low, medium, high). The rates vary by rotation crop, ranging 89.3 - 107.1 lb/ac in rotation with soybean, 107.1 -125 lb/ac in rotation with potato, and 98.2 - 116.1 lb/ac in continuous seed corn.

Ten states of nature were constructed to represent the distribution of crop yields and nitrate leaching. First, 42 years of yield and nitrate leaching were simulated using 1951-1992 rainfall, temperature and precipitation data from the case study area (Three Rivers, Michigan) and solar radiation data from nearby Ft. Wayne, Indiana. Second, after truncating the data from the first two years (to remove starting point carryover bias), the remaining 40 years of data were sorted according to the yield of continuous seed corn with "medium" nitrogen fertilization. Third, the sorted data were divided into ten sets of four ranked years. Finally, each set of four data-years was averaged to construct ten "states of nature" for use in the risk programming model.

Costs of machinery (Fuller et al., 1996), variable inputs, labor and land (Nott et al., 1995; King, 1996) were used to set up enterprise budget data for this representative farm. Corn, soybean, and nitrogen fertilizer prices were assumed to be \$2.70/bu, \$6.75/bu, and \$0.25/lb, respectively. The land rental rate for a potato contract was assumed to be \$245/ac.

Whole farm QP analysis to compare alternative contract designs

The analysis examines seven alternative contract specifications in three general categories: *1) Restrictions* on a) nitrogen application, b) permissible nitrate leaching, and c) rotation with potatoes (which results in heavy nitrate leaching); *2) charging a fee* on a) nitrogen use, or b) nitrate leaching; and, *3) varying the incentive payment* by lowering the variable payment in the contract to reduce the marginal value of nitrogen use[3] (Chu et al. 1995, 1996). The restriction on nitrogen use on seed corn fields is set at a mean 98.2 lb/ac, the lowest rate allowed for continuous seed corn. The nitrate leaching restriction set at 40 lb/ac, the lowest level is achievable at every risk preference level. The processor-imposed fees considered include 20¢/lb on nitrogen applications over 89 lb/acre, the lowest rate in the model, and 75¢/lb for projected nitrate leaching over 40 lb/ac. The base scenario incentive payment includes a fixed payment of $168.93/ac plus a variable payment of $5.94/bu seed corn yield. The first alternative scenario lowers the variable payment to $3.27/bu which induces a risk-neutral or mildly risk-averse grower to lower the nitrogen rate. The second alternative scenario is a lump-sum contract payout of $428.60/acre, the lowest payment to keep a risk-neutral grower growing 500 acres of seed corn.

Before examining how alternative contract designs performed, a word is needed about the nitrate leaching data, simulated from DSSAT v3.0. The seed corn crop -- which is susceptible to contract design manipulation -- is not the crop responsible for the most nitrate leaching. Average nitrate leaching is 63 lb/ac for seed corn in rotation with potatoes versus 39 lb/ac in continuous seed corn, 118.5 lb/ac for potatoes, 23 lb/ac for corn or 53 lb/ac for soybeans.

The results show that risk attitudes affect the amount of nitrate leaching from the whole farm as well as from seed corn production. Columns 2 and 3 of the Table 1 lists the average nitrate leaching from the whole-farm (***ANL***) and from the seed corn field (***ASNL***). For the risk-neutral grower, the average nitrate leaching is 36 lb/ac from the whole farm and 45 lb/ac from

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[3] Other contracts designs include *providing information to the grower*, and *providing insurance* (Feinerman et al., 1992).

seed corn land. By contrast, the two most risk-averse growers (i.e., CARA $\geq 5*10^{-5}$) had 84-89 lb/ac whole-farm leaching and 61-62 lb/ac leaching on seed corn land. This differences arises from seed corn - soybean rotation in the risk-neutral case versus seed corn - potato rental in the more risk averse cases, since potato land rental provides more the reliable income, but potato production uses more nitrogen fertilizer and causes more nitrate leaching.

Grower risk attitudes also affect the shadow prices of land and contracts. The shadow price of land declines with increasing grower risk aversion, from $224/ac for a risk-neutral grower to $120/ac for the highly risk-averse grower (CARA = 10^{-4}). The shadow price of the seed corn contract remains fairly stable, ranging only from $200/ac for the risk-neutral grower to $227/ac for the risk-averse grower (CARA = $5*10^{-5}$).

Which contract designs are able to reduce nitrate leaching for growers with different risk attitudes? Contracts which directly charge a fee on or directly restrict nitrate leaching above a specified level reduce leaching for all risk preferences. When growers are risk-neutral, restrictions on nitrogen use or rotation are not binding since these targets are already met. However, charging for nitrogen use or nitrate leaching, restricting nitrate leaching, or varying incentive payments can further reduce the amount of nitrate leaching. For the most risk-averse grower, charging a fee on nitrogen use, or varying the variable payment are not effective in controlling nitrate leaching. Only direct restrictions or a fee on nitrate leaching are effective.

The opportunity cost to the grower of reduced nitrate leaching varies by contract design and grower risk preference. Varying the incentive payment by increasing fixed part to $376/ac and decreasing the variable part to $3.27/bu gives the highest expected utility for each risk preference examined. Although imposing a restriction or charging a fee on nitrate leaching are effective approaches to control nitrate leaching, they are more costly to risk-averse growers than restricting rotation with potato land rental.

In the second stage of our analysis, we evaluate 1) the acceptability of the contract design to both processor and grower, and 2) the cost efficiency of each contract at achieving nitrate leaching reduction. We construct the processor's gross margin over specified production and marketing costs by subtracting the grower payment from marginal revenue,

$$\textbf{\textit{Processor Gross Margin}} = \left(1 - \frac{SCMC}{TR}\right) * P_w - s(y) \tag{4}$$

where P_w is the wholesale price of corn seed per 80,000-kernels bag (@\$71.50); $\frac{SCMC}{TR}$ (assumed to be 0.40) is the proportion of seed conditioning plus marketing costs (***SCMC***) to total seed corn operating income (***TR***); and ***s(y)*** is the payment to the grower (as in Equation (3)).

Expected seed corn yield, expected utility of the grower (***EU(G)***), and gross margin of the processor (***GM(P)***), are listed in Table 1 under varying levels of grower risk aversion. The last two columns of Table 1 list the costs for one unit of nitrate leaching reduction for processor and grower, calculated by the reduction in expected utility or gross margin per pound reduction in nitrate leaching, $MU(G)= \Delta EU(G)/\Delta TSNL$ and $MGM(P)=\Delta GM(P)/\Delta TSNL$, where $\Delta TSNL$ is the change in total nitrate leaching from seed corn production.

In order to evaluate these contract designs from both grower and processor perspectives, we will introduce two definitions of dominance. *Contract acceptability dominance* for the processor is based on gross margin and nitrate leaching. It is defined such that a strategy **A** dominates strategy **B** iff. [$\mathbf{GM(P)_A > GM(P)_B}$ and $\mathbf{ASNL_A \leq ASNL_B}$] or [$\mathbf{GM(P)_A \geq GM(P)_B}$ and $\mathbf{ASNL_A < ASNL_B}$]. The contract is assumed to be acceptable to the grower if it will reduce **EU(G)** by less than 1 percent. To identify the dominant contracts, we first eliminate contracts that are unacceptable to the grower across all risk preferences, specifically the one paying a fixed $428.60/ac. Next, we identify contracts which are undominated from the processor's viewpoint (Table 2). These contracts vary by grower's risk attitude: charging 75¢/lb for nitrate leaching above 40 lb/ac is undominated for CARA $\leq 5*10^{-5}$; imposing a restriction on rotation with potatoes or nitrate leaching level are undominated options when the grower is risk-averse.

In order to evaluate the efficiency of these contracts at reducing nitrate leaching, *cost efficiency dominance* is defined as follows: strategy A dominates strategy B if it reduces marginal nitrate leaching at lower cost for the grower without increasing costs for the processor or vice-versa. Algebraically, strategy A dominates strategy B iff. $[MGM(P)_A \geq MGM(P)_B \text{ and } MU(G)_A > MU(G)_B]$ or $[MGM(P)_A > MGM(P)_B \text{ and } MU(G)_A \geq MU(G)_B]$. The strategies that are not dominated under this definition are listed in Table 3. Again, the undominated contracts vary across different levels of grower risk attitudes. Shifting to a fixed incentive payment is undominated for CARA $\leq 5*10^{-5}$. Charging 75¢/lb for nitrate leaching above 40 lb/ac is undominated in every case but the mildly risk-averse (CARA = 10^{-5}). Restricting nitrate leaching is undominated only when the growers are risk neutral or mildly risk-averse, while restricting rotation with potatoes is undominated for more risk-averse growers (CARA $\geq 5*10^{-5}$).

The magnitude and incidence of costs imposed by these contract designs also depends on grower risk preferences. For the risk-neutral grower, the 75¢/lb fee on nitrate leaching over 40 lb/ac was highly cost-effective. However, for the mildly risk-averse grower, the nitrate leaching restriction was more cost efficient. For the two most risk-averse cases, restricting rotation with potato rental achieved less nitrate leaching at lowest cost for the grower and net gains for the processor. Both alternative incentive payment approaches involved large income transfers with little cost efficiency. These “win-lose” outcomes are likely to be unacceptable to either processor or grower. However, certain cases (e.g., the risk-averse grower), suggest that further research may reveal other incentive payments that could accomplish cost-effective leaching reduction.

Conclusions

This study shows that agent risk attitudes play an important role in the design of agricultural production contracts intended to reduce nitrate leaching. The designs with a fee or a restriction on nitrate leaching appeared to be cost-efficient (for risk-neutral and mildly risk-averse growers), but they assume costless leaching information when in fact leaching data costly and impractical to obtain. The restriction on rotation with potato was cost effective for the two more risk averse growers and it has very low information cost. But the analysis reveals that no one contract design is dominant across all grower risk attitudes, so a processor should have some knowledge of risk attitudes among prospective growers in order to design an effective contract. Extensions of this work will examine whether alternative incentive payment schemes might be suitable to growers with this range of risk attitudes.

The two-stage empirical principal-agent model implemented here is the only one of its kind of which we are aware. It focused first on modeling agent behavior in order to capture the principal’s participation and incentive-compatibility constraints. The principal’s preferences among feasible agent outcomes are interpreted and optimized in a second stage.

The potential impact of contracts for reducing NPSP is becoming more important as production contracts spread. Many researchable issues remain that warrant attention. First, this case study neglected the dynamics involved with contract premiums designed to incite growers to strive for increasing yields. If contract redesign for NPSP control interferes with this incentive, then the contracts may no longer meet with the processors' approval. Second, risk management approaches outside the contract deserve attention. Third, our model's results are doubtless sensitive to the assumption that the grower has no preference for reduced leaching, yet evidence exists that growers do care to reduce nitrate levels in groundwater (Poe and Bishop). Finally, the EV risk model used here assumed symmetric risk preferences, but if grower yields result in asymmetric income distributions (Babcock) this model may be unsuitable.

Table 1: Nitrate leaching, yield, expected utility and marginal impacts from leaching reduction

Coefficient of absolute risk-aversion (λ)	ANL (lb/ac)	ASNL (lb/ac)	Yield (bu/ac)	EU(G) ($)	GM(P) ($)	MU(G) ($/lb)	MGM(P) ($/lb)
λ = 0							
Base model	35.62	45.10	77.58	458700	1663412	NA	NA
Restrict N≤98.2 lb/ac	35.62	45.10	77.58	458700	1663412	-	-
Restrict NL≤40 lb/ac	35.12	40.00	77.38	457660	1658906	0.41	1.77
Restrict rotation with potato	35.62	45.10	77.58	458700	1663412	-	-
Charge 20¢/lb for N>89 lb/ac	35.32	44.07	76.90	457820	1648092	1.70	29.63
Charge 75¢ for NL>40 lb/ac	35.83	39.24	77.71	457040	1666341	0.57	-1.00
Fix: $376/ac; Var: $3.27/bu	35.32	44.07	76.90	458930	1647219	-0.44	31.32
Fix: $428.60/ac; No Var	35.32	44.07	76.90	359270	1746950	192.32	-161.58
λ = 10^{-5}							
Base model	46.02	46.47	77.92	439150	1671073	NA	NA
Restrict N≤98.2 lb/ac	45.62	45.10	77.58	438810	1663412	0.50	11.18
Restrict NL≤40 lb/ac	42.60	40.00	77.02	433800	1650796	1.65	6.27
Restrict rotation with potato	46.02	46.47	77.92	439150	1671073	-	-
Charge 20¢/lb for N>89 lb/ac	45.32	44.07	76.90	438090	1648092	0.88	19.12
Charge 75¢ for NL>40 lb/ac	45.62	45.10	77.58	436890	1665325	3.30	8.39
Fix: $376/ac; Var: $3.27/bu	45.32	44.07	76.90	445940	1647219	-5.65	19.85
Fix: $428.60/ac; No Var	45.32	44.07	76.90	352211	1746950	72.33	-63.13
λ = 5* 10^{-5}							
Base model	83.60	60.86	77.20	374740	1654851	NA	NA
Restrict N≤98.2 lb/ac	57.84	45.10	77.58	370580	1663412	0.53	-1.09
Restrict NL≤40 lb/ac	62.90	40.00	77.02	354290	1650796	1.96	0.39
Restrict rotation with potato	58.25	46.47	77.92	372680	1671073	0.29	-2.25
Charge 20¢/lb for N>89 lb/ac	81.78	59.07	76.48	372860	1640409	2.11	16.17
Charge 75¢ for NL>40 lb/ac	58.44	46.57	77.90	370250	1673086	0.63	-2.55
Fix: $376/ac; Var: $3.27/bu	80.72	58.03	76.30	405040	1632900	-21.38	15.49
Fix: $428.60/ac; No Var	60.19	45.66	76.83	331630	1745165	5.67	-11.89
λ = 10^{-4}							
Base model	89.21	62.37	76.11	322510	1630293	NA	NA
Restrict N≤98.2 lb/ac	46.34	44.07	76.90	312190	1648092	1.13	-1.95
Restrict NL≤40 lb/ac	45.63	40.00	77.02	290880	1650796	2.83	-1.83
Restrict rotation with potato	47.35	46.47	77.92	315070	1671073	0.94	-5.13
Charge 20¢/lb for N>89 lb/ac	89.21	62.37	76.11	320730	1632073	-	-
Charge 75¢ for NL>40 lb/ac	73.97	56.54	76.77	314460	1651366	2.76	-7.23
Fix: $376/ac; Var: $3.27/bu	88.20	62.37	76.11	369030	1628365	-	-
Fix: $428.60/ac; No Var	87.93	62.37	76.11	315900	1726805	-	-

Note: ANL and ASNL are average nitrate leaching from the whole-farm and from seed corn field; EU(G) is expected utility of the grower, and GM(P) is gross margin of the processor; MU(G) is marginal utility to the grower and MGM(P) is marginal gross margin to the processor for one unit nitrate leaching reduction.

Table 2: Contracts that are not dominated under contract acceptability dominance[1] for seed corn processor to achieve lower nitrate leaching from seed corn production under varying levels of grower risk aversion

Coefficient of Absolute Risk-Aversion (λ)			
λ = 0 (risk neutral)	$\lambda = 10^{-5}$ (mildly risk averse)	$\lambda = 5 * 10^{-5}$ (risk averse)	$\lambda = 10^{-4}$ highly risk averse)
Charge 75 ¢/lb for NL>40 lb/ac	Base model*	Restrict N≤98.2 lb/ac	Restrict NL≤40 lb/ac
	Restrict rotation with potato*	Restrict NL≤40 lb/ac	Restrict rotation with potato
	Restrict NL≤40 lb/ac	Restrict rotation with potato	
	Charge 75 ¢/lb for NL>40 lb/ac	Charge 75 ¢/lb for NL>40 lb/ac	

Note: [1] These contracts are undominated in the sense that a shift to a different contract cannot be made without either increasing nitrate leaching or reducing processor gross margin.
[*] Contracts equivalent to base case for both processor and growers.

Table 3: Contracts that are not dominated under environmental cost dominance per unit of leaching reduction under varying levels of grower risk aversion

Coefficient of Absolute Risk-Aversion (λ)			
λ = 0 (risk neutral)	$\lambda = 10^{-5}$ (mildly risk averse)	$\lambda = 5 * 10^{-5}$ (risk averse)	$\lambda = 10^{-4}$ (highly risk averse)
Fix:$376/ac; Var:$3.27/bu	Fix:$376/ac; Var:$3.27/bu	Fix:$376/ac; Var:$3.27/bu	Restrict rotation with potato
Fix:$428.60/ac; No Var	Fix:$428.60/ac; No Var	Fix:$428.60/ac; No Var	Charge 75¢/lb for NL>40 lb/ac
Restrict NL≤40 lb/ac	Restrict NL≤40 lb/ac	Restrict rotation with potato	
Charge 75¢ for NL>40 lb/ac	Restrict N≤98.2 lb/ac	Charge 75 ¢/lb for NL>40 lb/ac	

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