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Mitigating the Compliance Cost of a Phosphorus-Based Swine Manure Management Policy

Crystal Yap, Ken Foster, Paul Preckel, Otto Doering, and Brian Richert

Regulatory changes by federal and state agencies portend a switch from nitrogen-based livestock manure disposal policies to phosphorus-based policies. This paper estimates the compliance costs of such a policy change for a hypothetical hog–grain farm in North Central Indiana. The farm includes 1,500 acres of cropland and has the capacity to raise 11,970 grow–finish hogs annually. The farm model also has the potential to produce four different crops on six different land types. A nonlinear math-programming model was developed to determine the optimal mix of management activities for a phosphorus-based regulation. The model allows mitigation of compliance costs via the choice between four different pig diets, three alternative methods of manure disposal, changes in timing of manure application, and crop pattern adjustments. This analysis concludes that the new regulation will result in a decrease in whole-farm returns above variable costs, the use of phytase enzyme in pig diets, and an increase in wheat acreage. The model also reveals that it is optimal for the farmer to hire a custom hauler to assist in application of manure in an effort to reduce the degree to which available field days constrain farming activities and land application of manure. The estimated cost to the farmer, as a result of the policy change, ranges between \$0.56 and \$21.74 per unit of pig production capacity.

Key Words: environmental policy, manure management, pork production

JEL Classification: Q18

Structural changes in the pork industry have led to large declines in the number of hog

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farms and a dramatic increase in the average number of animals produced by remaining farms. This means that the pigs are being concentrated much more densely at the farm level. The increase in animal density has presented a challenge in the collection, storage, and land application of manure. The current regulation for manure disposal in most states requires that nitrogen from manure cannot exceed the nitrogen needs of crops grown on land. As a result of this policy, phosphorus levels in the soil have increased because, in most cases, the phosphorus-to-nitrogen ratio in manure is greater than the ratio of crop uptake. Sims, Simard, and Joern (SSJ) point out that if swine manure is applied at rates that match crop nitrogen needs, phosphorus applications usually exceed crop phosphorus removal by 300% to

500%.¹ Some state agencies have proposed rules that would require hog producers to apply manure at agronomic rates, and the Environmental Protection Agency–U.S. Department of Agriculture joint strategy on animal waste suggests that a similar regulatory approach at the federal level is on the horizon.² Using the estimates by SSJ suggests that a given farm would need access to three to five times more land for manure disposal or would need to drastically reduce pig numbers in the absence of other approaches to mitigate the regulatory impact.

The goal of this paper is to report implications of a phosphorus-based manure application regulation and animal density constraints. The analysis is based on a farm model and estimates the sensitivity of compliance cost under alternative assumptions about the ability to alter diets, hire off-farm disposal, and change cropping patterns.

Previous research has found that a phosphorus-based policy would decrease profits because of an increase in manure disposal costs (Boland, Preckel, and Foster; Fleming, Babcock, and Wang; Massey and Krishna; Pratt, Jones, and Jones; Schnitky and Miranda). According to Massey and Krishna, there are three adverse effects on the costs of applying manure on the basis of a phosphorus standard.³ First, the distance traveled to haul the manure will increase. Second, the adjusted application rates are much lower than under the nitrogen standard, and the farmer will then need to pass over the field a second time to supply the remaining nitrogen needed by crops. This will cause the farmer to bear both a manure and commercial fertilizer application

cost for the same land area. Third, the time needed to apply the manure is increased.

Additionally, Schnitkey and Miranda found that a phosphorus standard would lead to a decrease in the optimal number of hogs raised. However, the previous studies have tended to not account for the ability of farmers to mitigate some of the policy cost by adjusting feed rations or did not account for the possibility of off-farm disposal and land availability restrictions.

Swine Diet Manipulation

Farmers do have limited control over the amount of nutrients excreted by their pigs. The control mechanisms include the use of alternative ingredients in the pigs' diet that reduce the concentration of excreted nutrients. Alternative feed ingredients examined in this study include the enzyme phytase and reduced crude protein supplemented with synthetic amino acids.

Phytase is an enzyme that breaks down phytate so that some of the previously indigestible phosphorus in feed can be digested. Pigs are essentially unable to digest the phytate form of phosphorus in feed, and therefore it is excreted in the absence of phytase (McKnight). Phytase has been shown to reduce phosphorus excretion by 25–50% in research trials (Cromwell et al. 1993a,b; Jongbloed, Mroz, and Kemme; Knabe and O'Quinn; Kornegay; Lei et al.; Simons et al.). This is because a diet supplemented with phytase does not require additional supplementation with mineral phosphorus to satisfy the pig's dietary requirements.

Another approach that farmers can use to further reduce phosphorus excretion is to reduce the crude protein in the diet by supplementing with synthetic amino acids and phytase. With this alternative diet, the amount of nitrogen excreted in manure has been known to decrease by 28–45% and phosphorus excretion can be reduced (relative to a diet containing phytase and no synthetic amino acids) by 14% (Sutton et al. 1998a,b). Reducing the ratio of nitrogen to phosphorus in the manure can make the manure a more complete fertil-

¹ At very high levels, P becomes mobile in the soil profile and has the potential to degrade ground water. In addition, runoff of P-laden soil into bodies of water can contribute to eutrophication and algae blooms.

² The term agronomic rate implies that the application of nutrients does not exceed the uptake of that nutrient by the crop grown on the land.

³ Phosphorus standard, in the context of this paper, refers to the policy that manure must be spread on the basis of the phosphorus needs of crops, and nitrogen standard refers to the policy that manure must be spread on the basis of the nitrogen needs of crops.

izer and reduce reliance on commercial fertilizer, as well as mitigate the land disposal burden implied by a phosphorus standard by allowing application at higher rates.

The Model

To estimate the impact of a phosphorus-based manure application policy, a math-programming model was developed that chooses both crop and livestock activities to maximize farmer returns above variable costs subject to resource and regulatory constraints. This model uses a typical hog-crop operation located in North Central Indiana where the majority of Indiana hog production occurs. Most Indiana farmers are faced with a limited supply of land, days suitable for fieldwork, and capital. Consequently, they must choose the production bundle of crops and livestock that will maximize profits subject to the limits on factors of production and regulatory constraints. The base model allows choice of three crop enterprises: rotation corn-soybeans, wheat, and continuous corn grown on six land types defined by low, medium, and high productivity and near and far distance from the hog production facility.⁴ The base model also allows choice of the number of finished hogs raised; where, when, and how to apply manure and commercial fertilizer (including the option to hire custom application of manure both on and off of the farm); allows choice between alternative pig diets that have different implications for excreted nutrients, and keeps track of accumulated manure in storage, which is also capacity constrained. The notation for the model and complete model details of the objective function and constraints is contained in an Appendix at the end of the paper.

The model was solved with the General Algebraic Modeling System—GAMS (Brooke, Kendrick, and Meeraus). The goal of building the model was to indicate what crops will be

grown, how many acres of each crop will be grown, how many grow-finish pigs will be raised, when and on what land the manure will be disposed, and what diet the pigs will be fed. The model was solved with two alternative regulatory constraints reflecting the nitrogen and phosphorus standards, as well as alternative assumptions about the availability of off-farm manure disposal and alternative diets. The general hog production facility design and production are based on Foster, Hurt, and Hale. Table 1 provides some of the basic assumptions about the modeled farm and alternative diets.

Figure 1 is a representation of the farm and depicts the distribution of alternative land types over the farm space. Distances from the hog facility and the cropland are important for determining the cost of manure disposal. Massey's manure disposal cost analyzer was used to develop costs of disposal for alternative rates, distances, and field sizes for 126 different combinations of the application rate in thousands of gallons of manure per acre (R), field size in acres (A), distance traveled from the manure storage to the field (D), and total acres covered by manure in a given year (S). A disposal cost per thousand gallons of manure (C) function was estimated using ordinary least-squares regression on the 126 data-generated data points. R^2 for the regression was 0.99 and Glejser test statistic for heteroscedasticity failed to reject homoscedastic residuals. The estimated cost equation is⁵

$$(1) \quad C = -0.4 + 0.05R + 8.09(1/R) + 0.003A \\ (10) \quad (117) \quad (34) \\ + 0.89D + 0.0003S. \\ (83) \quad (10)$$

To obtain a cost per acre, this equation was multiplied by the application rate (R) and to obtain the total annual cost of manure application, the product is multiplied by total acres on which manure is applied (S).

The programming model divides the annual decision process into six equal periods

⁴ The hog facility is located on the low-yield land to reduce the opportunity cost of lost crop production and perhaps to place the facility on higher-elevated land (usually of lower quality) for drainage and ventilation considerations.

⁵ Numbers in parentheses are t -statistics.

Table 1. Basic Assumptions of the Model Farm

Crop Land Base	1,500 acres
Hog Production Capacity	11,970 hogs annually
Three Soil Types	25% low yield (Miami) 40% average yield (Crosby) 35% high yield (Brookston)
Crops	Continuous corn (CC) Rotation corn (RC)/Rotation soybean (RB) Wheat (W)
Manure Storage Capacity	120 d
Manure Storage/Disposal	Deep pits with injection
Diet Options	Diet 1: Standard industry diet Diet 2: Diet 1 adjusted for phytase use Diet 3: Diet 1 adjusted for phytase and synthetic amino acids Diet 4: Diet 3 with supplemental fiber

Notes: Diet 3 results in a change of carcass composition that affects the price via carcass lean premiums. Diet 4 maintains carcass quality while reducing nutrient excretion. The Brill Corporation Diet Sequence Program was used to generate least-cost rations.

during which pigs are raised and sold and seasonal cropping activities are undertaken. The model uses data from Doster et al. and Purdue University Cooperative Extension Service, ID205, to constrain the availability of field

days for cropping activities and manure disposal as well as estimate manure nutrient losses based on deep pit storage. Table 2 defines the six decision periods and indicates the main farm activities that take place in each period.

Figure 1. Configuration of the Farmstead

Table 2. Timing of Farm Activities

Period	Planting	Harvesting	Spread Manure	Pigs
1. Dec.–Jan.				Raise
2. Feb.–Mar.			Beans & corn	Raise/sell
3. April–May	Beans & corn		Beans & corn	Raise
4. June–July		Wheat	Beans & corn	Raise/sell
5. Aug.–Sept.			Wheat	Raise
6. Oct.–Nov.	Wheat	Beans & corn	Beans & corn	Raise/sell

Results

The impact of manure application policy changes was measured by calculating the differences in returns above variable cost levels between the results of alternative solutions of the model. The first model solution represents the management decisions the farmer would be expected to make on the basis of applying manure according to the nitrogen standard (N-RATE). The second model solution represents the management decisions made by the farmer where land application of manure is based on a phosphorus standard (P-RATE).

The only difference between N-RATE and P-RATE models are the manure application rate constraints. In addition, the model constrains the amount of manure nitrogen to be no more than 150 pounds per acre per year, as dictated by current Indiana Department of Environmental Management guidelines.

Alternatively, P-RATE does not allow for manure phosphorus to exceed the phosphorus needs of crops. Thus, P-RATE represents the

proposed regulatory environment. Comparing the results between N-RATE and P-RATE solutions illustrates actions that the typical farmer would take to mitigate the costs of phosphorus-based regulations.

Crop Selection

Table 3 presents the optimal cropping decisions for each regulatory scenario. In both cases, the model dictated that the entire 1,500 acres were used for crop production. For the N-RATE scenario, a total of 697.32 acres were grown in rotation corn, 697.32 acres were grown in rotation beans, and 125.36 acres of wheat were produced. The crop mix under the P-RATE scenario resulted in 664.36 acres of rotation corn, 664.36 acres of rotation beans, and 171.18 acres of wheat. The most significant change came from the introduction of 46 acres of wheat on average yield far land for the P-RATE scenario.

Table 3. Optimal Crop Mixes for N-RATE and P-RATE Models

Crop	Low Yield		Average Yield		High Yield	
	Near	Far	Near	Far	Near	Far
N-RATE Crop Distribution						
CC	0	0	0.0	0	0	0.0
RC	50	75	119.8	180	105	157.5
RB	50	75	119.8	180	105	157.5
W	50	75	0.4	0	0	0.0
P-RATE Crop Distribution						
CC	0	0	0	0.0	0	0.0
RC	50	75	120	156.9	105	157.5
RB	50	75	120	156.9	105	157.5
W	50	75	0	46.2	0	0.0

Table 4. Optimal Number of Pigs Fed Each Diet by Period for Each Scenario

Period	Diet 1	Diet 2
N-RATE		
1-2	3,990	0
3-4	3,990	0
5-6	3,990	0
P-RATE		
1-2	3,247	743
3-4	2,490	1,500
5-6	231	3,759

Note: Diets 3 and 4 were not fed under either scenario.

Number of Pigs Raised and Diet Selection

Table 4 shows the number of pigs raised in each period, as well as the number of pigs fed each diet. For the N-RATE scenario, it is optimal to raise the maximum possible number of pigs (11,970) and feed them all diet 1 (industry standard). For the P-RATE scenario, the number of pigs per period and in total did not change, but the diet was modified (5,968 pigs were fed diet 1 and 6,002 were fed diet 2). Recall that diet 2 contains the enzyme phytase, which reduces the phosphorus excretion.

Manure Application

One of the interesting outcomes from the change in manure disposal policy is the change in land application practices. This includes the timing of when the manure is applied, how it is applied, and on what part of the farm it is applied. The most significant change from the N-RATE scenario to the P-RATE scenario is that the farmer chooses to hire a custom hauler to dispose of manure on soybean fields. That is, under the P-RATE scenario the time constraints become binding and hiring a custom hauler is optimal.⁶

Under the P-RATE scenario, the farmer cannot dispose of all manure on corn and wheat land. Soybeans do not need applied nitrogen, but will take up substantial nitrogen

from the soil if it is supplied. Furthermore, applying at the lower P-RATE requires more time regardless of the crop and further motivates the use of the custom hauler.

Estimated Cost of the Regulation Change

Even though farmers would attempt to mitigate the policy impacts, the results suggest that farm returns above variable costs would decline as a result of the regulation change. The estimated whole farm reduction is just under \$7,000. This was mainly a result of an increase in manure disposal costs and a reduction in net revenue received from crops and hogs.⁷

It is useful to normalize the regulatory cost on a per unit of hog production capacity basis because the number of pigs produced could change under different policies. The cost of compliance per unit of hog production capacity is estimated as the change in net returns between the two scenarios divided by the total capacity to produce hogs (11,970). The estimated cost is \$0.56 per unit of hog production capacity. This does not appear to be an extremely prohibitive cost.⁸

Sensitivity Analysis

Four additional scenarios were also evaluated to reflect alternative situations that farmers might encounter and determine the importance of key model assumptions. Each of these scenarios assumes a phosphorus-based manure application policy, and the results are compared to those of the P-RATE scenario discussed above. The results of these scenarios serve to emphasize the benefits from having a choice between alternative diets and methods of manure disposal, as well as reflect the pos-

⁷ Wheat is less profitable than corn and soybeans, and hogs fed diet 2 have an increased cost of production.

⁸ Other proposed changes in regulations involve construction of a manure management plan, increased record keeping, and regular inspections of the waste handling facility. We have not attempted to estimate these costs. However, crop consultants typically charge about \$4 per acre for some of these services.

⁶ Custom hauling rates range between \$0.01 and \$0.021 per gallon of manure depending on the hauling distance.

Table 5. Estimated Cost Per Pig Capacity Due to Regulation Change

Scenario	Returns Above Variable Cost	Total Number of Pigs	Change in Returns from N-RATE ^a	Cost of Regulation (\$/Pig Space) ^b
1	\$842,693	11,970	\$6,689	\$0.56
2	\$842,693	11,970	\$6,689	\$0.56
3	\$842,693	11,970	\$8,197	\$0.68
4	\$715,833	9,450	\$133,549	\$11.16
5	\$589,104	6,922	\$260,278	\$21.74
N-RATE	\$849,382	11,970	—	—

^a The change in returns above variable costs is calculated as N-rate returns above variable costs minus scenario returns above variable costs. This is also the total cost of the regulation change.

^b Cost per pig capacity = change in returns above variable costs/11,970. The cost per pig is referred to as the cost per pig capacity as a result of the regulation change.

sible impact of land availability restrictions such as animal density regulations or set-back restrictions.

Scenario 1 is the base scenario of the P-RATE regulatory environment discussed earlier in the paper. Scenario 2 amends the first scenario by excluding the application of manure off the farm. In the future, liabilities associated with environmental accidents and odor may discourage landowners from entering into manure spreading contracts with hog farmers, and this scenario attempts to model that possibility.

Scenario 3 adjusts the original P-RATE model by allowing only diet 1 to be fed to the pigs. This scenario represents a situation where the farmer does not have the means to supply the pigs with different diets. Handling specialized ingredients like phytase, synthetic amino acids, and fiber requires additional feed storage facilities that may not be available on all farms.

Scenario 4 amends the base scenario by not allowing custom application of manure. That is, all manure must be applied by the farm operator. This scenario can represent a situation where a custom applicator is not available. Such a situation is not unlikely in some areas where there are not many other hog farms or in areas where animal density has been regulated, leading to little or no demand for custom services. Scenario 5 is the most restrictive case where custom manure application is not available and the farmer is unable to feed alternative diets to the pigs.

The model solutions for each of the sce-

narios are presented in Tables 5 and 6. Table 5 shows the returns above variable costs, for each scenario, compared to the N-RATE results. In addition, this table shows how the number of hogs raised changes under each scenario. According to these results, scenarios 4 and 5 are the only instances where it is optimal to reduce the number of pigs raised. The increased cost of compliance for these cases somewhat demonstrates the sizable cost associated with animal density restrictions or other land availability restrictions.

Table 5 also illustrates the estimated cost of the phosphorus-based regulation. This cost is in dollars per unit of hog production capacity. These results show the potential costs that the farm could face depending on the market environment, the extent to which the farmer could adjust, and potential for a constraint on land availability. For scenario 1, the phosphorus-based regulation can cost a farmer \$0.56 per unit of hog production capacity. Alternatively, there are no options for adjustment, as in scenario 5; the phosphorus-based regulation can cost up to \$21.74 per unit of hog production capacity.

It is evident from these results that it is useful for farmers to have an option for different diets and methods of manure disposal. These results also indicate that the benefit of having options for manure disposal is greater than the benefit of alternative diets, as can be seen by comparing the costs from scenarios 1 and 4, where the use of a custom hauler is available for scenario 1 but not available for scenario 4. The estimated benefit from being

Table 6. Changes from Other Scenarios Compared to Scenario 1

Scenario	What is Happening
1	<ul style="list-style-type: none"> — Returns above variable costs decreased by \$6,689 vs. the N-rate — Wheat increased by 46 acres vs. N-rate — Custom applicator disposes of manure on cropland — The custom hauler is not applying manure off-farm — 50% of the pigs are fed diet 1, 50% of the pigs are fed diet 2
	Changes from Scenario 1 (P-RATE)
2	<ul style="list-style-type: none"> — There was no change from the P-rate scenario — Custom applicator use increases relative to the P-rate scenario
3	<ul style="list-style-type: none"> — All pigs are fed diet 1 in this scenario — Wheat production increases by 65 acres vs. the P-rate scenario — 2,520 fewer pigs are raised than in the P-rate scenario
4	<ul style="list-style-type: none"> — Wheat production increases by 130 acres vs. the P-rate scenario — 5,425 pigs are fed diet 4, and 3,990 pigs are fed diet 2 in this scenario
5	<ul style="list-style-type: none"> — 5,048 fewer pigs are raised than in the P-rate scenario — Wheat production increases by 119 acres vs. the P-rate scenario

able to use a custom applicator is \$10.60 per unit of hog production capacity. By comparing scenarios 1 and 3, the benefit from using alternative diets can be measured. The results show that the benefit from phytase diets is \$0.12 per unit of hog production capacity.

Table 6 explains what changed on the farm under the conditions given in the alternative scenarios. The first scenario lists the results from P-RATE. The details listed next to scenario 1 are the adjustments made by the farm as a result of the phosphorus-based regulation with complete flexibility. For the other scenarios, the phosphorus-based manure regulation is also assumed. These results are then compared with the details from scenario 1. It is apparent that most of the adjustments occur

in cropping patterns, manure disposal procedures, and diet manipulation.

Conclusion

Previous research found that the optimal number of animals decreases with a phosphorus standard (Schmit and Knoblauch; Schnitkey and Miranda). However, those studies only provided one option of manure application, whereas our model allows for a custom application service and the use of alternative diets. The number of pigs did not decrease when the model allowed diet choices and custom application of manure.

This study clearly demonstrates that farmers will become time constrained as a result of a phosphorus standard, and custom hauling of manure will become an important facet of the pork industry. In many areas, custom manure hauling is not common and policies to foster the development of such an industry could soften the impact of regulatory change. Furthermore, it is possible that some farms with adequate equipment and labor could enter into the custom hauling activity as a new enterprise that would offset the impact of the regulations on their own farms. Extension service personnel and other advisory services should help farmers determine whether this would be a profitable alternative. Farmers who are not able to obtain custom services may want to consider increasing manure storage capacity so that manure can be stored until the application can be accomplished with the farm's machinery as much as possible. This might be particularly important for farms with a very limited land base relative to the number of pigs raised because in late summer only land that grew wheat is available for manure disposal. Farms with a limited land base will be more dependent on off-farm disposal and would likely need to compensate their neighbors for growing wheat rather than more profitable corn and soybean crops. Consequently, increasing manure storage would allow these farms to delay manure disposal until the fall after corn and soybeans have been harvested, reducing the necessary compensation required

to entice neighboring landholders to cooperate.

The estimate of compliance cost per unit of hog production capacity ranges between \$0.56 and \$21.74; the larger estimates represent the scenarios with the least flexibility in meeting the regulations. This demonstrates the importance of a range of options being available to farmers. Policy makers should keep this in mind when developing the mechanism for enforcement of new regulations. That is, command and control enforcement approaches that prescribe the methods and procedures for manure handling and processing will be more costly to farms than the alternative of allowing farmers to apply the least costly technology that still meets an objective nutrient loading restriction for their farm's circumstances.

Finally, it is clear that farms with relatively small land base relative to animal numbers will face a higher cost of compliance because they are more quickly driven to hire custom haulers or reduce the number of pigs they produce. Thus, a change from a nitrogen-based application standard to a phosphorus standard is likely to support larger farms as those with small land holdings find it impossible to keep costs competitive.

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- The parameters considered in the model are as follows:
- $CORN_l$, corn needed for diet l (pounds)
 $LAND_{jk}$, total land in land type j and distance k (acres)
 $STORAGE_m$, volume of manure in the pit in period m (1,000 gal.)
 $PIT.VOL$, maximum volume in the manure storage pit (1,000 gal.)
 $PIG.CAP$, maximum number of pigs the farmer can raise at one time
 $FIELDAYS_m$, total number of days available for work in period m
 $PHDAY_{im}$, total good field days available to plant and harvest in period m for crop i
 $SPDAY_{im}$, total good field days available to spread manure in period m on crop i
 $CUSDAY_{im}$, total good field days available for the custom hauler to spread manure during period m on crop i
 $CFDAY_{im}$, total good field days available to spread commercial fertilizer during period m on crop i
 CM_{ijk} , contribution margin for crop i , grown on land type j (\$)
 Pp_p , market price for pigs in period p
 Pc_{lo} , cost to raise pigs fed diet l , in period o
 r_{jk} , custom rates to spread manure on land type j at distance k (\$/1,000 gal.)
 w_n , rate for commercial nutrients n (\$/pound)
 fp , price for on-farm corn (\$/pound)
 mp , price for corn bought on the market (\$/pound)
 NUT_{ln} , nutrients contained in manure from diet l (lbs./1,000 gal.)
 NN_{ijkn} , nutrients needed by crop i , grown on land type j , at distance k (lbs./acre)

Appendix

This appendix presents a description of the mathematical programming model used in the analysis. The notation is defined, the objective function presented, and the various constraints on resource use and due to regulations are presented. Because of the disposal cost function, the program is nonlinear and solved in GAMS.

The sets considered in the model are as follows:

- i , crops grown; continuous corn, rotation corn, rotation beans, and wheat
 j , land types; low yield, average yield, high yield
 k distances; near, far
 l , pig diets; diets 1-4
 m , time periods; 1-6
 o , subset of m ; 1, 3, 5; diet choice for pigs occurs in these periods
 p , subset of m ; 2, 4, 6; the selling of pigs occurs during these periods
 n , nutrients; N, P, K

The variables considered in the model are as follows:

- Z , farm returns above variable costs (\$)
 ACR_{ijk} , crops i grown on land type j and distance k (acres)
 PR_{lm} , pigs raised on diet l and in period m
 PS_{lm} , pigs sold in period m and were fed diet l
 CUS_{ijklm} , manure spread by the custom hauler on the farm (1,000 gal.)
 FC , corn grown on the farm and fed to pigs (pounds)
 BC , corn bought on the market and fed to pigs (pounds)

PM_{lm} , manure produced by pigs fed diet l in period m (1,000 gal.)

$MANURE_{ijklm}$, manure spread on the land from the farmer and custom hauler (1,000 gal.)

CD_{ijkm} , days used for crop i on land type j , at distance k , and in period m

MSD_{ijkm} , days used for spreading manure on crop i , on land type j , at distance k , from diet l , and in period m

$FertD_{ijkmn}$, days used to spread commercial fertilizer on crop i , on land type j , at distance k , from diet l , and in period m

$CUSD_{ijkmn}$, days used by the custom hauler to spread manure on crop i , during period m

CS_{ijkm} , total cost to spread manure by the farmer

CF_{ijkmn} , amount of commercial fertilizer applied to crops (pounds)

RB , rotation beans (acres)

RC , rotation corn (acres)

W , wheat (acres)

The objective of the model is to maximize the net returns above variable costs from crop and livestock production and is represented mathematically as

$$(A.1) \max_z = \sum_i \sum_j \sum_k CM_{ijk} \times ACR_{ijk} \\ + \sum_l \sum_p PP_p \times PS_{lp} \\ - \sum_l \sum_o PC_{lo} \times PR_{lo} \\ - \sum_i \sum_j \sum_k \sum_l \sum_m \\ \times [CS_{ijkm} + r_{jk} \times CUS_{ijkm}] \\ - \sum_i \sum_j \sum_k \sum_m \sum_n w_n \times CF_{ijkmn} \\ - fp \times FC - mp \times BC.$$

This optimization will be subject to a number of constraints. The first is the availability of land. This constraint [depicted mathematically below in Equation (A.2)] ensures that the sum of acres used to grow the different crops is less than or equal to the total number of acres available on the farm by land type and location.

$$(A.2) \sum_i ACR_{ijk} \leq LAND_{jk}.$$

Rotation corn acres and rotation bean acres should be equal in the long run for a typical corn and soybean rotation. In addition, the location of each crop

should also coincide. Equation (A.3) shows the constraints to impose the corn and bean rotation.

$$(A.3) ACR_{RB'jk} \equiv ACR_{RC'jk}.$$

In practice, Indiana farmers grow wheat in an area where soybeans were grown in the previous crop year. For this reason, wheat acres are constrained by Equation (A.4) to be less than or equal to the number of rotation bean acres.

$$(A.4) ACR_{W'jk} \leq ACR_{RB'jk}.$$

The next constraint ensures that the pounds of corn required to feed the pigs is met through corn grown on the farm, from corn bought from the market, or a combination of the two. The constraint in (A.5) says the pounds of corn needed must be equal to the pounds of corn grown on the farm, plus the pounds of corn bought on the market.

$$(A.5) FC + BC \geq \sum_i \sum_m PR_{lm} \times CORN_i.$$

The constraint in Equation (A.6) is primarily for accounting purposes. It keeps track of how much manure is in the pit at the end of a given period. The constraint dictates that the quantity of manure in storage at the end of period m is equal to the quantity carried over from the previous period, plus manure excreted during period m minus manure applied to land during period m .

$$(A.6) STORAGE_m = STORAGE_{m-1} + \sum_l PM_{lm} \\ - \sum_i \sum_j \sum_k \sum_l MANURE_{ijkl}.$$

Equation (A.7) ensures that the amount of manure in the pit does not exceed its volume in any period.

$$(A.7) STORAGE_m \leq PIT_VOL.$$

The farm can house only a limited number of grow-finish pigs at any one time, which is imposed by Equation (A.8).

$$(A.8) \sum_i PR_{io} \leq PIG_CAP.$$

The model assumes a 2% death loss for grow-finish pigs. Thus, the number of pigs sold is 2% less than the number of pigs raised as shown in Equation (A.9) below.

$$(A.9) PS_{lm} \equiv .98 \times PR_{lm}.$$

The constraint in Equation (A.10) refers to the good field days available for the farmer to perform crop and livestock activities. This constraint considers how long it will take to do each activity and this must be less than or equal to the amount of time available.

$$(A.10) \sum_i \sum_j \sum_k CD_{ijk} + \sum_i \sum_j \sum_k \sum_l MSD_{ijkl} + \sum_i \sum_j \sum_k \sum_n FertD_{ijkn} \leq FIELDAYS_m.$$

Key cropping activities performed by the farmer, such as planting and harvesting, are also constrained. On average, there are a certain number of good field days available for these activities where soil conditions allow for tillage, etc. Thus, constraints of the form in (A.11) are imposed.

$$(A.11) \sum_i \sum_k CD_{ijk} \leq PHDAY_{im}.$$

Good field days available for spreading manure are a source of constraint on the model solution. These constraints are used for both the farmer and the custom hauler. The time used by the custom hauler does not take away from the total time available for the farmer. The custom hauler is just constrained to do the spreading during the times that conditions are suitable for spreading. Equation (A.12) below shows the constraints for the farmer, and Equation (A.13) illustrates the restrictions faced by the custom hauler.

$$(A.12) \sum_j \sum_k \sum_l MSD_{ijkl} \leq SPDAY_{im}$$

$$(A.13) \sum_j \sum_k \sum_l CUSD_{ijkl} \leq CUSDAY_{im}.$$

The model is also constrained to apply commercial fertilizer during certain periods. These days are also associated with the number of good field days available during the periods that commercial fertilizer can be spread. This constraint is written as follows in Equation (A.14).

$$(A.14) \sum_j \sum_k \sum_n FertD_{ijkn} \leq CFDAY_{im}.$$

The constraint in Equation (A.15) ensures that crops receive the required nitrogen, phosphorus, and potassium needed to achieve the crop yield goals. This equation states that the nutrients provided by commercial fertilizer and manure can be greater than or equal to the nutrients needed by crops on each land type.

$$(A.15) \sum_i \sum_m MANURE_{ijk} \times NUT_{in} + \sum_m CF_{ijkn} \geq ACR_{ijk} \times NN_{ijkn}.$$

The following constraints (Equations A.16a,b) represent the regulatory environment faced by the farmer. It is these constraints that will change between the two solutions of the model to measure the impact of policy changes. For current policy, which allows the farmer to apply manure at the nitrogen needs of crops, the constraint will be broken up into two parts. The first requires that the nitrogen provided by manure does not exceed the nitrogen needed by crops. The second regulatory constraint limits the pounds of nitrogen applied per acre from manure to not exceed 150 pounds. These two constraints represent the N-RATE manure disposal regulatory environment in Indiana before January 2003.

$$(A.16a) \sum_i \sum_m MANURE_{ijk} NUT_{in} \leq ACR_{ijk} NN_{ijkn}$$

$$(A.16b) \sum_i \sum_m MANURE_{ijk} NUT_{in} \leq ACR_{ijk} 150,$$

where n = nitrogen.

The change in manure disposal policy will require the application of manure at a rate that will not result in the overapplication of phosphorus. The constraint in Equation (A.17) limits the amount of phosphorus supplied by manure to be less than or equal to the phosphorus needs of crops (the P-RATE manure disposal regulatory environment).

$$(A.17) \sum_i \sum_m MANURE_{ijk} \times NUT_{in} \leq ACR_{ijk} NN_{ijkn}, \text{ with } n = \text{phosphorus}.$$