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Incorporating Environmentally Compliant Manure Nutrient Disposal Costs into Least-Cost Livestock Ration Formulation

Joleen C. Hadrich, Christopher A. Wolf, J. Roy Black, and Stephen B. Harsh

Livestock rations are formulated to minimize feed cost subject to nutritional requirements for a target performance level, which ignores the potentially substantial cost of disposing of nutrients fed in excess of nutritional requirements. We incorporate nutrient disposal costs into a modified least-cost ration formulation model to arrive at a joint least-cost decision that minimizes the sum of feed and net nutrient disposal costs. The method is demonstrated with phosphorus disposal costs on a representative dairy farm. Herd size, land availability and proximity, crop rotation, and initial soil phosphorus content are shown to be important in determining phosphorus disposal costs.

Key Words: environmental compliance, linear programming, livestock rations, manure disposal

JEL Classifications: C61, Q12, Q52

Livestock ration formulation minimizes feed cost subject to animal nutrient requirements for a target performance level. This approach allows the farm manager to make livestock feeding decisions based on the relative prices and nutrient content of available feed products. For example, dairy cow ration formulation has as its primary objective minimizing cost subject to achieving a specified level of milk production and composition, which dictates protein, energy, mineral, and vitamin levels. However, focusing solely on input costs in ration formulation ignores the cost of overfeeding specific nutrients, such as phosphorus, which may accompany the cheapest

protein and energy sources. Overfeeding nutrients leads to nutrient excretion disposed of in manure, which affects crop-livestock nutrient management. This research reconsiders livestock ration formulation to evaluate a joint decision that minimizes feed and nutrient disposal costs.

Manure can contribute to excess phosphorus and nitrogen levels in soil and water. With increasingly rigorous enforcement of environmental regulations, farmers are now facing compliance costs manifested through nutrient management.¹ Most states have defined ac-

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¹Individual farmers take environmental regulations and constraints as exogenous. These regulations originate from the fact that farmers may not realize all costs of nutrient disposal practices (or lack thereof). The appropriate level of constraint, and thus cost, passed on to farmers from policy makers is an interesting question that is beyond the scope of this paper.

ceptable management practices, such as spreading manure at the agronomic rate of the limiting nutrient, to control potential pollution (Bosch, Zhu, and Kornegay; Feinerman, Bosch, and Pease). In many states, these practices are related to a Right to Farm Act (or similar legislation) that mandates specified environmental standards for farms to adhere to in order to avoid nuisance lawsuits. Meeting these standards involves costs associated with the prevention, stabilization, and/or reduction of future pollution. Thus, environmental compliance costs are a component of production costs and should be considered when solving for optimal decision rules.

Actual environmental compliance costs pertaining to phosphorus removal are individual to the farm situation and depend on herd size, land availability, waste management methods, and feeding practices, among other factors (Boland, Preckel, and Foster; Fleming, Babcock, and Wang; Keplinger and Hauck). The cost of handling excess phosphorus is farm-specific, and what one farm might find cost-prohibitive another may not. However, it is clear that environmental compliance costs are significant on many farms and the livestock ration formulation decision is a major source of nutrient import onto the farm.

Nutrient disposal cost considerations in ration formulation are especially timely now, as a large amount of by-products are generated in the growing biofuels industry. By-products of the biofuels industry, such as distillers dried grains with solubles (DDGS), are lower-cost sources of protein and energy that permit substitution for corn grain and soybean meal in livestock rations but may also supply phosphorus in excess of nutritional requirements.² Due to the direct link between phosphorus intake and phosphorus excretion in dairy cattle (Knowlton et al.; Morse et al.; Myers), feeding management is a critical control point for phosphorus management

on dairy farms in order to prevent nutrient loading (Cerosaletti, Fox, and Chase; Dou et al.; Rotz et al.; Spears, Young, and Kohn; Toor, Sims, and Dou; Wu, Satter, and Sojo). This potential trade-off between lower-cost feedstuffs and higher nutrient disposal costs can be derived to arrive at economically desirable management decisions.

Incorporating nutrient disposal costs in ration formulation allows the producer to evaluate a joint decision that minimizes the total ration cost, which includes both feeding and nutrient disposal costs. Thus, a tool to be used at an operational level can assist producers and nutritionists in designing true least-cost rations using a systems approach. The objectives of this paper are to: (a) develop a nutrient disposal cost function that accounts for herd size, land availability, crop selection, hauling distance, soil nutrient stocks, manure disposal technology, and environmental regulations; (b) develop a ration formulation model that recognizes nutrient disposal costs; and (c) demonstrate the methods and assess implications for feeding decisions on a representative dairy farm.

The paper proceeds as follows: The next section derives a farm manure disposal cost with environmental regulation constraints and requirements considered; the third section builds nutrient disposal costs into a least-cost ration formulation model; the fourth section illustrates the effects of key factors on a representative Michigan dairy farm; and the fifth section summarizes and concludes. The representative farm has a 200-cow dairy herd with accompanying dry (nonlactating) cows and replacement heifers and a corn-hay-soybean cropping program. The nutrient considered is phosphorus, a nutrient whose balance is relatively straightforward to track from feeding to manure excretion and soil levels. The general method used is applicable to other livestock operations and sizes as well as other nutrients. The result is that it is possible, and in many cases quite simple, to modify livestock ration formulation programs to account for nutrient disposal costs in addition to feed input costs to arrive at an efficient joint decision.

²Distillers grains with solubles are processed in two forms: dried distillers and wet distillers. For the purposes of this paper, dried distillers grains with solubles will be considered.

Net Manure Disposal Costs with Environmental Regulations

An economic engineering approach is used to determine a farm nutrient disposal cost. This approach allows us to estimate nutrient disposal costs dependent on farm characteristics, practices, and technologies. Manure application was assumed to be a source of fertilizer for the farm's cropping program, supplemented with commercial fertilizer as needed. The total cost to dispose of manure was adopted from Harrigan (2001) and calculated as

$$(1) \quad MDC = \left[\sum_{n=1}^N (LT + TT_n + UT_n + IT) \right] * HR,$$

where *MDC* is the manure disposal cost (\$), *n* indicates field available for manure spreading (whether owned, rented, or used through some other agreement), *LT* is the manure-loading time (hrs.), *TT_n* is the manure-transportation time (hrs.) as a function of the distance to field *n*, *UT_n* is the manure-unloading time (hrs.) as a function of field *n* characteristics, *IT* is the manure-incorporation time (hrs.), and *HR* is the hourly rate (\$/hr.) for manure disposal. An hourly rate is used rather than a cost based on mileage, since the distance manure must be hauled for disposal is a function of the time needed for transport (Harrigan 2001).³ The hourly manure disposal cost incorporates yearly machinery, fuel, and labor costs for loading, transportation, unloading, and incorporation time of manure. Each of the time components of the manure disposal cost is described in turn below.

Loading time (*LT*) includes agitating the manure, maneuvering the spreader, and pumping manure into the spreader. Loading time is a function of the quantity of manure

produced, which is dependent on the number and type of animals on the farm. It is also a function of the pump, agitator, and spreader used. Typical time allocations for these tasks can be found in extension bulletins (e.g., Harrigan 2001).

Transportation time (*TT*) is the time needed to transport a full load of manure from the manure storage facility to the field and return the empty spreader. *TT* is a function of the quantity of manure produced, manure-transportation equipment technology, the distance the manure must be hauled for disposal, and road conditions.

There are numerous spreader options for manure disposal, such as tractor-drawn tank, truck-mounted spreader, and nurse trucks to transport manure to remote locations. The producer matches the appropriate tractor and spreader type with farm size and hauling distance. It should be noted that truck-mounted spreaders and nurse trucks are more appropriate for disposing of manure over longer distances. The average speed of the tractor varies with road conditions, distance, and whether the spreader is empty or full (Harrigan 1997).

The distance manure must be hauled for disposal is a function of the initial soil nutrient content of available acres. As the soil nutrient content increases, less manure can be applied, necessitating farther hauling distances. Available acres are a function of owned and rented acres, as well as the availability of other acreage that may be obtained through agreements (for a fee or not). For our example, rented and other spreadable acreage was assumed to be farther from the manure storage facility than owned acreage.

Unloading time (*UT*) is a function of the quantity of manure produced, the manure application rate, and manure spreader capacity. The manure application rate is a decreasing function of the nutrient density of the manure, an increasing function of crop removal rates, and a decreasing function of the initial phosphorus content of the soil.

Incorporation time (*IT*) is the amount of time needed to incorporate (e.g., disk) the applied manure into the soil, which is a

³ Manure application was priced at an hourly cost, since many custom applicators felt time more appropriately accounted for the lower manure application rates and the farther distances manure must be hauled to comply with environmental regulations.

function of the acres utilized for manure application. It is assumed that, during incorporation, the tractor is driven at a constant speed. *IT* increases as manure application rates decrease, since more acreage will be needed for manure disposal of nutrients. *IT* is often a necessary component of manure disposal, since many state regulations require incorporation.

The amount of manure produced and the nutrient content of that manure, such as nitrogen (N), phosphorus in the form of phosphate (P_2O_5), and potassium (K_2O), vary with animal species and the ration fed. When phosphorus is fed and excreted in manure (as fertilizer), it takes the form of phosphate (P_2O_5).

Phosphorus excreted by lactating cows was calculated as (Myers)

$$(2) \quad P_C = (P_{FED} - P_{MILK}) * 2.3,$$

where the components of this equation were calculated as

$$P_{FED} = P_L * C * 365$$

and

$$P_{MILK} = 0.0009 * MY.$$

P_C is the total P_2O_5 (lbs.) excreted in lactating-cow manure (all lactating cows for the entire year); P_{FED} is the total phosphorus (lbs.) fed in the lactating-cow ration; P_{MILK} is the yearly amount of phosphorus (lbs.) secreted in milk; P_L specifies phosphorus (lbs.) fed (cow/day); C is the number of lactating cows in the herd; 365 represents the days the ration is fed; 0.09% represents the average phosphorus content of secreted milk (NRC); and MY is the total farm milk yield production (lbs./year). The conversion of phosphorus to P_2O_5 is calculated by multiplying phosphorus by 2.3 (Michigan Department of Agriculture).

Phosphorus excretion amounts for heifer and dry cow manure were calculated as (Vandehaar et al.)

$$(3) \quad P_i = (P_{FED}^i - P_{RET}^i) * 2.3,$$

where the components of this equation were calculated as

$$P_{FED}^i = P_L^i * N * 365$$

and

$$P_{RET}^i = 0.007 * ADG * 365,$$

where i indicates heifer (H) or dry cow (D) group, P_i is the P_2O_5 (lbs.) excreted in the heifer or dry cow manure (all animals for the entire year), P_{FED}^i is the total phosphorus (lbs.) fed in the heifer or dry cow ration, P_{RET}^i is the yearly amount of phosphorus (lbs.) retained by the dry (nonlactating) cow, P_L^i is the amount of phosphorus (lbs.) fed (heifer or dry cow/day), N is the number of heifers or dry cows in the herd, 0.7% represents the average phosphorus retained by the animal (Vandehaar et al.), and ADG is the average daily growth (lbs.) of the animal. The ADG for heifers and dry cows is dependent on age and on stage of pregnancy where applicable (NRC; Vandehaar et al.).

Total farm P_2O_5 excreted was calculated as

$$(4) \quad P_{MANURE} = P_C + P_D + P_H.$$

The nutrient density of the manure was calculated by dividing the nutrient content of the total farm manure (lactating cows, dry cows, and heifers) by the total farm gallons of manure.

Crop agronomic nutrient removal rates are a function of the acres planted and the potential yield of crops. Different crops remove different amounts of nutrients, based on crop species and yield. For example, in Michigan, corn silage with an average yield of 22 tons per acre removes approximately 73 pounds per acre of P_2O_5 from the soil, whereas corn grain with an average yield of 150 bushels per acre removes 56 pounds per acre of P_2O_5 (Warncke et al.). Therefore, a farmer may choose to plant corn silage in a field with high soil phosphorus concentrations to draw down soil phosphorus levels. These differences in phosphorus utilization/uptake demonstrate the importance of manure management decisions on the cropping program and nutrient disposal. Of course, in order to actually improve

nutrient balance, the crop or the animal product from the crop must leave the farm.

Initial soil phosphorus content is determined by soil tests on farms. Current environmental guidelines monitor nutrient levels in soil in an effort to alleviate detrimental environmental effects of nutrient loading. The soil phosphorus content dictates the rate at which manure can be applied, as specified by state and local environmental regulators.

Manure application rates are calculated based on soil tests, crops to be grown, and yield goals. The manure application rate measured in gallons per acre for nitrogen and phosphorus in the manure was calculated as (Michigan State University Extension 2006)

$$(5) \quad MAR_{js} = \frac{NR_{rs} - NC_s}{ND_k} * 1000,$$

where MAR_{js} is the j th manure application rate (three application rates based on environmental standards) for crop s , NR_{rs} is the r th nutrient removal for crop s (lbs./acre), NC_s is the nutrient credit for crop s (lbs./acre)—which is applied only to the nitrogen application rate given in the form of N credits based on N fixation in legume crops, as specified by Warneke et al.—and ND_k is the nutrient density of the manure for the k th level of phosphorus intake (lbs./1,000 gal.).

Manure contains nutrients that may reduce or eliminate the need for commercial fertilizer application. Therefore, it is appropriate to calculate a fertilizer value of manure to calculate the total manure disposal costs net of fertilizer. This fertilizer value was calculated only for manure applied at the agronomic phosphorus removal rates. If manure was applied off farm, it was assumed that the farmer did not realize a fertilizer credit, since the manure was not fertilizing owned crop acres. The P_2O_5 content of manure was multiplied by the U.S commercial fertilizer price, \$0.25 per pound (Rausch), to determine the fertilizer value of manure. This value was subtracted from the MDC to obtain the total manure disposal costs net of fertilizer value, $NMDC$.

The dietary requirement for phosphorus in the dairy ration was calculated as the summa-

tion of absorbed phosphorus needed for maintenance, growth, pregnancy, and lactation divided by the absorption coefficients. For example, nutritional requirements for a lactating cow to produce 67 pounds of milk per day require a dry-matter intake of 52 pounds per day, of which 0.17 pounds is composed of phosphorus (NRC). This phosphorus consumption level correlates to 0.10 pounds per cow of daily excess phosphorus to dispose of in manure application, indicating that some disposal cost is unavoidable. Therefore, the relevant disposal cost to consider when changing the ration formulation is the increase in the disposal cost above this minimum unavoidable level that results from the ration selected. The minimum unavoidable level changes, dependent on the dry-matter intake, to obtain a corresponding milk production level. The whole farm phosphorus disposal cost was calculated from the MDC as

$$(6) \quad PDC = \frac{NMDC_{Fed} - NMDC_{Req}}{P_{Fed} - P_{Req}},$$

where PDC is the average cost to dispose of one excess pound of phosphorus (\$/lb.), $NMDC_{Fed}$ is the farm manure disposal cost net of fertilizer value for the phosphorus fed in the ration formulation (above requirement), $NMDC_{Req}$ is the manure disposal cost net of fertilizer value for the minimum level of phosphorus to dispose of (phosphorus requirement level), P_{Fed} is the amount of phosphorus (lbs.) fed in the ration formulation, and P_{Req} is the minimum amount of phosphorus (lbs.) fed to achieve the nutritional requirement. The $NMDC_{Req}$ value varies with the distances manure must be hauled for disposal and the fertilizer value given to the phosphorus.

The daily total farm disposal cost of excess phosphorus was calculated by multiplying PDC by the pounds of excess phosphorus fed above nutritional requirements in the total farm ration. This procedure was repeated for a range of phosphorus inclusion levels in the total farm ration to derive the phosphorus disposal cost function. Therefore, the PDC is a function of total farm manure disposal costs.

Least-Cost Livestock Rations with Disposal Costs

There are many potential methods to optimize a dairy ration and minimize costs subject to nutritional and environmental constraints. Many multiple-objective programming methods have been explored to solve this problem, including multigoal programming, compromise programming, goal programming with penalty functions, and weighted goal programming (Romero and Rehman). Multigoal programming in an applied dairy setting was evaluated by Lara and Romero, who argued that producers were more interested in the optimal ration that achieves a compromise amongst several objectives versus the least-cost ration; therefore, utility functions were incorporated in the model to account for individual farmer preferences. This method works well in theory, but in practice the difficulties of defining utility functions make application difficult. Stokes and Tozer implemented a ration formulation using distance functions in a compromise-goal setting to reduce excess nutrient excretion from dairy cows. However, the lack of information regarding the appropriate weights and measures to use in the compromise programming makes this model difficult to apply in a real-world setting.

Jean dit Bailleul et al. modified the traditional least-cost ration formulation algorithm for swine rations by including a cost associated with excess nitrogen excretion levels. This nutrient cost was determined exogenously and included in the objective function of the ration formulation in a stepwise form. Pomar et al. applied the same technique to reduce the amount of phosphorus concentration in pig rations by accounting for disposal and feed input costs. The cost included in this application pertained to the excess and unavailable phosphorus in the swine rations. In the research by Jean dit Bailleul et al. and Pomar et al., the environmental compliance costs were entered exogenously, which fails to recognize that a joint decision can be used to minimize the total feeding and disposal cost.

The appropriate farm decision can be accurately incorporated in a useable model by determining the excess nutrient costs endogenously from manure disposal costs and marrying these results with the linear programs that livestock industries already utilize. Our model allows the farm decision-maker to assess trade-offs between higher costs for livestock rations and the resulting environmental compliance costs by evaluating a joint decision.

The least-cost ration formulation is estimated using linear programming (LP). LP has been widely used in the area of optimizing cost performance subject to animal performance and the nutritional requirements that a specified performance level dictates and, hence, is an appropriate model for this research problem (Black and Hlubik; Coffey; France and Thornley; Tozer).

For LP, the objective function and the constraints must be linear and deterministic. The nutrient disposal function is nonlinear, necessitating separable programming to replace this function with a piecewise linear approximation (France and Thornley). The linear programming ration formulation with the nutrient disposal cost function is defined as

$$(7) \quad \text{Minimize } C = \sum_{j=1}^n p_j x_j + \sum_{k=1}^m p_k d_k$$

Subject to

$$(8) \quad \sum_{j=1}^n a_{ij} x_j > (=, <) b_i$$

$$(9) \quad \sum_{k=1}^m \lambda_k d_k = 1$$

$$(10) \quad x_j, \lambda_k \geq 0, \quad \forall j, k.$$

The objective function is specified in Equation (7) where x_j represents quantities of feed ingredients with price p_j , and d_k represents quantities of excess phosphorus for the k th level of phosphorus intake (dependent on the phosphorus feed intake level) with a nutrient disposal price p_k . Equation (8) depicts the bounds of the nutri-

tional constraints, where a_{ij} is the nutritional content of the i th nutrient in the j th feed ingredient. The right-side variable b_i represents the bounds of the i th nutrient. Equation (9) specifies the constraint for the separable row, where λ_k is a row of ones. Therefore, $\lambda_k d_k$ is the proportion of the phosphorus disposal activity based on the k th level of phosphorus intake by the cow. Equation (9) must sum to one to ensure that all manure is disposed of. Equation (10) defines nonnegativity conditions. This LP program produces the least-cost combination of feed ingredients that meet the nutrient requirements for the specified performance level with the incorporation of the nutrient disposal cost function, therefore solving for a joint decision.

The modified LP was divided into three main sections: feed nutrient characteristics, nutrient requirements, and nutrient disposal cost function. In addition, there are bounds on nutrient ratios and a system to implement metabolizable protein requirements. The feed section was divided into four feed source categories: silage, hay, energy feeds, and by-product feeds. Only feedstuffs common to Michigan were included in the feed categories. The modified LP solved the feeding decision for lactating cows, dry cows, and heifers simultaneously, using a stacked LP (across lactating cows, dry cows, and heifers). The LP was solved using 15 constraints per animal group, of which 4 related to the metabolizable protein requirements. The nutrient disposal cost was incorporated into the modified LP with two additional constraints for the separable row and the excess phosphorus disposal cost. The nutritional constraints are presented and discussed in detail in the Appendix. Costs to dispose of excess phosphorus are calculated on a daily whole farm basis. The procedure for this calculation and its application to a representative farm are discussed in the following section.

Application to Representative Farm

The representative dairy farm from the 2004 Michigan Dairy Farm Business Analysis

Summary was used as an example for this study (Wittenberg and Wolf). The average dairy farm milked 200 cows and had 40 dry cows and 200 replacement heifers. (Summary farm characteristics are presented in Figure 1.) The ration for the lactating cows was based on a Holstein cow weighing 1,400 lbs. that was 120 days in milk and had a 3.0 body condition score and 3.5% fat-corrected milk with milk production of approximately 67 pounds per day. These assumptions result in a daily dry-matter intake of 52 pounds of feed per cow per day. The ration for dry cows was based on a cow 240 days pregnant weighing 1,550 pounds with a target average daily body weight gain of 1.32 pounds. The heifer ration was based on a heifer 12 months old weighing 717 pounds with an average daily target weight gain of 1.6 pounds in order to calve at 24 months of age.

Manure production for this representative herd totaled 1,799,466 gallons, with 96,522 pounds of nitrogen and 63,218 pounds of K_2O in the manure (Midwest Plan Service). The nutrient density of this manure was 31 pounds of N per 1,000 gallons and 36 pounds of K_2O per 1,000 gallons of manure.⁴ The P_2O_5 nutrient production and manure density change with the ration fed. The daily nutritional phosphorus requirement was 0.18, 0.05, and 0.04 pounds of phosphorus per lactating cow, dry cow, and heifer, respectively. The total herd consumed at least 46 pounds of phosphorus per day (16,787 pounds per year). At this feeding level, the total herd excreted 11,903 pounds of phosphorus (27,377 pounds of P_2O_5) per year, which corresponds to a P_2O_5 manure nutrient density of 15 pounds per 1,000 gallons of manure. Therefore, base nutritional requirements result in a minimum of 11,903 pounds of phosphorus in manure to dispose of. Manure disposal costs were estimated by increasing the phosphorus fed by three pounds (five grams) per herd per day. This increase was chosen to allow the incre-

⁴Phosphorus exceeds nutritional requirements when lower-cost DDGS is added to the ration. Nitrogen requirements are not exceeded with the inclusion of DDGS and nitrogen density in manure is held constant.

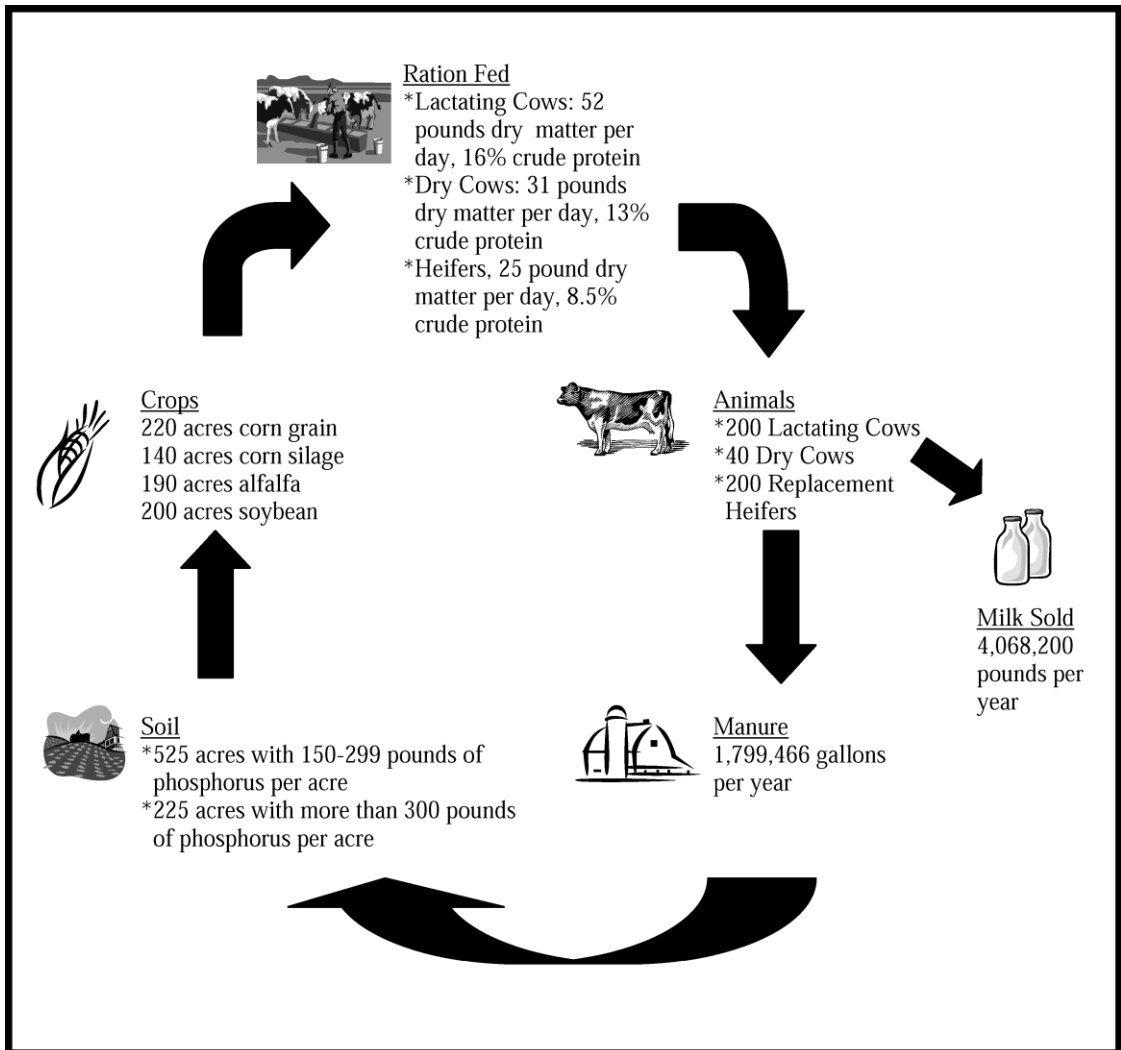


Figure 1. Whole Farm Phosphorus Cycle on Example Farm

ments between feeding decisions to be small enough for implementation of separable programming.

The representative Michigan dairy farm land base was 750 acres, with a cropping program of corn grain, corn silage, alfalfa, and soybeans. A continuous crop rotation was assumed for each crop category and the percentage of total acres devoted to each crop was determined using mean values from the Michigan dairy farm survey (Wolf et al.). The crops of corn grain, corn silage, alfalfa, and soybeans utilized 220, 140, 190, and 200 acres, respectively. It was assumed that the silage and alfalfa (forage) acreage was owned and

the corn grain and soybean acreage was rented. The rented acreage was assumed to be farther from the farmstead, indicating an increased nutrient disposal cost *ceteris paribus*. Owned acreage was available at a range of 1–3 miles round trip, and rented acreage was available at a range of 8–12 miles round trip. It was assumed that, if the owned and rented acreage was not sufficient for manure disposal, 200 additional acres of spreadable land were available for off-farm manure application at varying distances of 13–20 miles roundtrip. Nutrient removal for the different crops was calculated based on fertilizer recommendations for average crop yields from

Table 1. Manure Application Rates and Costs for Varying Levels of Phosphorus in the Dairy Ration

	Phosphorus Fed (Lbs./Herd/Year)					
	16,787 ^a	17,966	19,145	20,324	21,503	22,683
P ₂ O ₅ density of manure (lbs./1,000 gal)	15	17	18	20	21	23
Phosphorus excreted in manure (lbs.) ^b	11,903	13,082	14,261	15,441	16,620	17,799
Phosphorus excreted above base nutritional requirement (lbs.)	0	1,179	2,358	3,538	4,717	5,896
	Manure Application Rate (Gallons/Acre)					
Corn grain	3,608	3,282	3,011	2,781	2,584	2,413
Corn silage	4,719	4,294	3,939	3,638	3,380	3,156
Alfalfa	5,070	4,613	4,232	3,909	3,631	3,391
Soybeans	2,340	2,129	1,953	1,804	1,676	1,565
	\$/Herd/Year					
Manure disposal costs (MDC)	33,762	36,814	40,210	43,496	46,591	49,701
Manure disposal costs net of fertilizer ^c (NMDC)	30,131	33,183	36,579	39,865	42,960	46,070

^a Phosphorus fed based on minimum nutritional requirements.

^b Multiplying by 2.3 generates the P₂O₅ manure value.

^c A fertilizer credit is not given to manure applied off farm (rented and spreadable acres).

MSU Extension Bulletin E-2904 (Warncke et al.).

Manure was applied to the crop acres in accordance with Michigan Right to Farm guidelines for manure application. In Michigan, manure can be applied to land at nitrogen removal rates if the soil test level for phosphorus is less than 149 pounds per acre. If the soil test level for phosphorus is in the range of 150–299 pounds per acre, manure may be applied at phosphorus removal rates. If the phosphorus soil test level is 300 or more pounds per acre, manure may not be applied to the soil (Michigan Department of Agriculture).

Applying manure at the nitrogen removal rate increases phosphorus nutrient loading. Therefore, in future years, manure application rates will change from the nitrogen removal rate to the phosphorus removal rate. The application rate decreases with phosphorus fed, due to higher phosphorus concentrations in the ration and subsequently in the manure. Decreased application rates result in longer hauling distances and increased disposal costs. The manure application rates and associated costs are presented in Table 1.

For this representative farm, it was assumed that manure was applied at the crop

phosphorus removal rate for all acreage. This assumption is in accordance with the results from Fleming, Babcock, and Wang, which determined that applying manure at the phosphorus application rate for swine farms in Iowa was the most profitable manure application rate. To illustrate an example farm with a phosphorus problem, it was assumed that 30% of this acreage was in the no-manure application category (had greater than 300 pounds of phosphorus per acre). Under these assumptions, 525 of the 750 crop acres were available for manure disposal.

The farm used a 200-horsepower tractor with a 6,000-gallon manure spreader and operated a 70–90-horsepower manure pump with a 100-horsepower tractor. An average loading rate of 1,300 gallons per minute was assumed in filling the manure spreader, resulting in 4.6 minutes to fill a 6,000-gallon spreader. Agitation and maneuvering the spreader from the storage facility to the roadside was assumed to take 7.5 minutes (Harrigan 1997). It was assumed that the tractor traveled at a constant speed of 12 miles per hour with a full load of manure over distances less than a mile and at a constant speed of 14 miles per hour with full loads of

Table 2. Comparison of Feeding and Disposal Cost Models

	Cost/Unit	Ration Formulation Independent of Disposal Costs			Ration Formulation Joint with Disposal Costs		
		Lactating Cows	Dry Cows	Heifers	Lactating Cows	Dry Cows	Heifers
Feed Ingredient		Lbs./Animal/Day			Lbs./Animal/Day		
Corn silage	\$25/ton	6.98	13.83	15.31	8.20	15.07	15.31
Alfalfa	\$100/ton	20.67	3.50	3.53	20.57	6.17	3.53
Ground corn	\$2.50/bu.	12.36	–	–	13.53	–	–
Soybean meal, 48% CP	\$190/ton	0.10	2.48	0.58	2.11	3.44	0.58
DDGS	\$120/ton	11.79	3.83	–	7.48	–	–
		\$/Head/Day			\$/Head/Day		
Feed cost		2.82	1.16	0.80	2.84	1.17	0.80
		\$/Herd/Day			\$/Herd/Day		
Herd feed cost		770.47			775.60		
Herd disposal cost		31.20			12.70		
Total herd cost		801.67			788.30		

Note: This ration does not include mineral and vitamins.

manure over distances greater than a mile from the manure storage facility. Constant speeds of 14 and 17 miles per hour were used for return trips of less than and greater than a mile, respectively. The tractor traveled at a constant speed of 4 miles per hour while unloading the manure. The manure spreader width was 20 feet, which accounted for overlap of manure application. A 220-horsepower tractor was used for manure incorporation, traveling at a constant speed of 4 miles per hour. The tillage equipment incorporated the manure at a swath width of 45 feet. The hourly cost for manure disposal was valued at \$150.

The nutrient and mineral content of feeds used in the model were specified according to *Nutrient Requirements for Dairy Cattle* (NRC), with the additional support of the *Spartan Ration Balancer/Evaluator 3* model (Vandehaar et al.). Feed ingredients were limited to those typically available to dairy producers in Michigan and included corn silage, alfalfa hay, legume hay, corn grain, soybean meal, cottonseed, and DDGS. The feed ingredient prices were a three-month average (October 2006–December 2006) of Chicago feed prices, to represent current price relationships and decisions (LMIC).

Two least-cost rations were formulated.⁵ The first ration minimized feed cost without phosphorus disposal cost considerations. The second ration simultaneously minimized a joint feeding and nutrient disposal cost decision by incorporating phosphorus disposal costs. Ration results and cost comparisons for the two least-cost rations are presented in Table 2.

DDGS is a source of protein and energy, but it also contains large amounts of phosphorus. Therefore, including the phosphorus disposal cost in the ration formulation allows assessment of the consequences of including particular feedstuffs. As demonstrated in Table 2, including the excess phosphorus disposal cost reallocated the feed ingredients in the lactating and dry cow ration as the additional disposal costs became large enough

⁵ The nonseparable portion of the LP is linear by construction. The cost function incorporated into the LP using separable programming is convex, due to the economies of size in the disposal mechanism. When we initially solved the modified LP, the endpoints of the convex function were chosen, indicating that the second-order conditions were not met for the separable portion of the modified LP. Restricted-basis entry was used to iteratively solve the problem by selecting the points that are on both sides of the optimal solution.

to offset the cost savings of feeding cheaper sources of energy and protein. In particular, the quantity of DDGS fed to the lactating cows decreased 37% (from 11.79 to 7.48 pounds), whereas the quantity of soybean meal fed increased from 0.10 to 2.11 pounds per cow per day. DDGS that was originally fed in the ration without disposal cost considerations was eliminated for the dry cows, while soybean meal fed increased by 39%. This occurred because the cost of excess phosphorus disposal was greater than the value of the low-cost protein source. The protein and energy supplied in the base case was transferred from DDGS, with a feed cost of \$120 per ton and a phosphorus content of 0.0083 pounds per pound fed, to soybean meal, with a feed cost of \$190 per ton and a phosphorus content of 0.0070 pounds per pound fed (NRC).

Incorporating the phosphorus disposal cost increased the feed cost of the ration but lowered the aggregate feed and disposal cost. The ration formulation independent of disposal costs resulted in a daily total herd (200 lactating cows, 40 dry cows, and 200 heifers) feed and disposal cost of \$801.67, composed of total phosphorus disposal costs of \$31.20 per herd per day and feed costs of \$770.47 per herd per day. The ration formulation with phosphorus disposal costs jointly considered resulted in a daily total cost of \$788.30 per herd, composed of total phosphorus disposal costs of \$12.70 per herd per day and feed costs of \$775.60 per herd per day. Ration formulation independent of disposal costs fed 56 pounds of phosphorus to the herd, resulting in 43 pounds of daily excess phosphorus. The ration formulation with phosphorus disposal costs fed 53 pounds of phosphorus to the herd, resulting in 39 pounds of daily excess phosphorus. Incorporating the excess phosphorus disposal cost increased feed costs by 1% but decreased excess phosphorus disposal costs by 59%, resulting in total cost savings of \$4,883 per herd per year. This cost savings represented 6.1% of the five-year (2001–05) Michigan average dairy net farm income.

While the example farm is representative of a typical farm in Michigan, the results

highlight some general conclusions. The ration formulation results of the example make it clear that ration formulation determined jointly with nutrient disposal costs affects feeding decisions enough to matter on many farms. The farm characteristics most heavily affecting feeding decisions include herd size, land availability and proximity, crop selection, and existing soil nutrient levels. For operations with an adequate land base and existing soil nutrient stocks to dispose of manure, the feeding decision may not change with the inclusion of the nutrient disposal cost.⁶ In cases where disposal decisions are driven by nutrient content, we have demonstrated that it may be economical to trade off increased feed input costs for lower subsequent disposal costs.

Conclusions

Increasingly today, environmental regulations, and the cost of implementing them, are affecting farm management decisions. A standard economic result is that private costs should be modified to the social-cost level when externalities are present. Environmental regulations and the associated costs are assumed to represent the social-cost level in this analysis, as they are taken by individual farms as exogenous. Excess nutrient disposal costs are a function of herd size, land availability, manure management methods, and feeding decisions. These costs can be quantified and included in the ration formulation. In particular, manure disposal costs are highly sensitive to the amount and quality of land available for manure disposal and to manure application rates.

The results of this research are consistent with conditions in Michigan; however, the model can be used in various situations. This research demonstrated that it is possible, and

⁶Prices of feedstuffs may change the feeding decision. Recently, corn prices have risen to \$4 per bushel. Including this price for corn grain in our example ration formulation caused DDGS fed to increase while corn grain was dropped. This substitution may warrant concern, due to the high phosphorus content of DDGS.

relatively simple, to formulate rations to minimize the sum of feed and net nutrient disposal costs. A linear program approximating dairy nutritional requirements (NRC) was used to balance the ration and add the separable disposal cost. The inclusion of the phosphorus disposal cost reallocated feed ingredients to achieve lower levels of phosphorus in the whole farm ration to arrive at a joint least-cost decision. With the increasing availability of by-product feeds, animal nutritionists and producers need to be aware of the total cost of the ration rather than just the input cost of feedstuffs. The new modified linear program that included the phosphorus disposal cost function accomplished this goal by presenting the farmer with a decision-making tool that can be adapted to farm-specific situations. This method for including the phosphorus disposal cost could be incorporated into commercial ration formulation models. Making ration formulation decisions in this manner reflects the true farm cost of the feed decision, incorporating both feed input and nutrient disposal cost.

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Appendix

The nutritional constraints for the ration formulation are presented in Table A1. The protein system was of particular relevance, since the protein characteristics of DDGS are much different from feedstuffs in typical rations. The protein system was driven by metabolizable protein (MP). This system characterizes MP into ruminally undegraded pro-

tein, which was protein escaping ruminal degradation, and ruminally degraded protein (RDP), which is composed of two items: rumen degradable nonprotein (urea) and degradable true protein. RDP requires ruminally available energy for microbes to convert the degraded protein in microbial protein, which was modeled as an energy requirement per pound of microbial protein produced (NRC). The structure for modeling metabolizable protein is described by Black and Hlubik.

Table A1. Description of Nutrient Constraints for Dairy Herd

Constraint Coefficients	Unit	Sign	Lactating Cows	Dry Cows	Heifers
(1) Dry-matter intake	lbs./day	<=	51.92	31.37	24.91
(2) Neutral detergent fiber	lbs./day	>=	14.14	8.54	7.12
(3) Ruminally undegraded protein	lbs./day	=	3.88	1.74	0.18
(4) Ruminally degraded protein	lbs./day	=	4.57	2.22	1.94
(5) Metabolizable protein	lbs./day	>=	8.44	3.96	2.12
(6) Net energy	Mcal./day	>=	18.52	6.87	9.19
(7) Calcium	lbs./day	>=	0.32	0.07	0.08
(8) Phosphorus	lbs./day	>=	0.17	0.05	0.04
(9) Calcium:phosphorus lower bound	lbs./day	>=	0.00	0.00	0.00
(10) Calcium:phosphorus upper bound	lbs./day	<=	0.00	0.00	0.00
(11) Fat (ether extract)	lbs./day	<=	2.21	0.85	0.68