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The Economics of Manure Utilization: Model and Application

Keith O. Keplinger and Larry M. Hauck

A model of manure utilization is developed and applied to four types of transportable manure. Model results highlight important response differences among manure types and generally illustrate the diseconomies of manure production. For example, as manure production increases, manure value decreases and excess phosphate applications increase, thereby increasing the potential for phosphorus runoff. Policy scenarios limiting the manure application rate reduce manure value and excess phosphate application. Increasing the ratio of land using manure increases manure value while reducing excess phosphate application. Buildup of soil nutrients reduces manure value, but either increases or decreases excess phosphate application depending on the scenario.

Key words: linear programming, manure application, manure transportation, manure utilization, manure value, optimization

Background

Manure, although a by-product of animal production, has historically been considered a valuable resource as a fertilizer and soil amendment. While manure continues to be utilized as a resource—most is still applied on cropland as fertilizer [U.S. Department of Agriculture (USDA) and U.S. Environmental Protection Agency (EPA), 1999]—it is increasingly viewed as waste. Several historical trends are responsible for this fall in status. Prior to World War II, crop nutrients were provided primarily by local manure supplies (Sharpley et al., 1999). In the 1950s, commercial fertilizer became widely available as an inexpensive substitute for manure nutrients (Risse et al., 2001), thereby increasing the supply of nutrients and lowering the value of manure nutrients. This development promoted the separation of livestock from crop enterprises, since farmers no longer needed to rely on animal manure for crop nutrient requirements (Sharpley et al., 1999). In succeeding decades, technological advances on many fronts have favored larger and more specialized animal production units (see, e.g., Tweeten, 1998; Perry, Banker, and Green, 1999; Martinez, 1999; Risse et al., 2001).

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Although the agronomic value of manure application is well established, its per ton value is low compared to commercial fertilizer. The low value:mass ratios of manures result in higher application and transportation expense than for equivalent nutrient applications from commercial fertilizers. Like other commodities with low value:mass ratios, high transportation costs effectively limit the distance that manure can economically travel, resulting in localized manure markets. Consequently, demand for manure to supply crop nutrient requirements is spatially constrained and is a function of crop nutrient requirements. Manure *supply*, however, is largely tied to meat production decisions, because manure is a by-product of animal production. The by-product nature of manure in combination with structural changes in meat production has resulted in dramatically larger supplies of manure in production regions, irrespective of the capacity of crops in proximity to production to utilize manure nutrients. Economic theory indicates that the net value or disposal cost of manure (or other by-products) can affect production decisions (Schnitkey and Miranda, 1993). Empirical research, however, has shown the net benefits (or costs) of manure utilization to be insufficiently large, relative to meat production, to affect production decisions (Roka and Hoag, 1996).¹

When supplies of manure become large, its value falls and an incentive is created to apply manure at rates exceeding crop requirements or to otherwise dispose of manure as inexpensively as possible, despite negative externalities. Consistent with externality theory, degradation of public resources (air and water) has occurred in regions of the country with high concentrations of livestock. Thus, technological and structural changes leading to greater livestock concentrations (see Kellogg et al., 2000), while producing an abundant and low cost supply of animal protein to Americans, have also caused degradation of public resources, e.g., air and water pollution (U.S. EPA, 2002).

Environmental degradation resulting from manure application is largely attributed to applications of manure nutrients in excess of amounts recommended to meet crop requirements (agronomic rates) (Ogg, 1999). When applied at greater than agronomic rates, excess nitrogen (N) may leach into groundwater, causing potential human toxicity, or be transported to coastal waters, resulting in eutrophication (Vitousek et al., 1997), while runoff of phosphorus (P) from cropland can cause eutrophication of fresh waters (Sharpley et al., 1999; Sharpley and Rekolainen, 1997). Application of manure at agronomic rates is compounded by the fact that the manure nutrients come in fixed proportions, which do not match crop requirements. The N:P ratio required by crops is typically several times higher than the N:P ratio in manure. Manure application at a rate meeting crop N requirements (N-rate) provides more P than crops can utilize, resulting in soil P buildup and increased P runoff into surface waters. Most freshwater ecosystems are P limited; thus, aquatic vegetation, particularly algae, often responds to elevated ambient P levels, promoting a chain of events associated with eutrophication (Sharpley, 1995). Advanced eutrophication, in turn, may cause fish kills, unpalatability of drinking water, an increase of unsightly algae and aquatic weeds, and foul odors. For these reasons, state and federal regulatory changes portend a switch from nitrogen-based to phosphorus-based manure application policies (Yap et al., 2004; Kaplan, Johansson, and Peters, 2004).

¹ Nevertheless, the possibility always remains that the increased environmental regulation of manure could have sufficient economic implications to materially affect livestock production decisions.

Because of the economic importance of manure utilization and the environmental degradation that can result, numerous analytical studies have been performed. The objectives of this paper are (a) to present a generalized model of manure utilization that can be used and adapted to help inform the policy debate as changes in manure regulation are considered, and (b) to present the results of a few model applications that answer (and generally quantify) several important questions regarding manure utilization, especially with regard to its current status and contemplated policy changes.

The remainder of this study proceeds with a literature review of manure utilization research. Next, a generalized manure utilization model is developed, and some characteristics of the specification are explored. Model limitations are then discussed, followed by a section documenting the sources of data used in model applications. Selected model results of several relevant applications are then presented. The final section summarizes the analysis and highlights some key conclusions.

Literature Review

In studies published prior to the late 1980s (e.g., Henry and Seagraves, 1960; Matulich, Carman, and Carter, 1979; Ashraf and Christensen, 1974; Stonehouse and Narayanan, 1984), manure utilization is viewed largely as an aspect of farm production. While generally recognizing environmental concerns, these studies did not simulate specific environmental scenarios.

Consistent with the growing concentration and increased governmental involvement in the animal industry, economic analyses of manure utilization became much more numerous commencing in the late 1980s, and typically included scenarios designed to protect water quality. A key feature of many of these analyses is a transportation component. This feature is particularly true for broiler litter analyses, where high nutrient concentrations require greater land application areas, and consequently greater hauling distances than for other manure types. Bosch and Napit (1992), for instance, simulate the transfer of broiler litter from surplus to deficit counties employing a cost-minimization transportation model. Other quantitative analyses of broiler litter application include Vervoort and Keeler (1999); Jones and D'Souza (2001); Govindasamy and Cochran (1995, 1998); Xu and Prato (1995); Wimberly and Goodwin (2000); and Pelletier, Pease, and Kenyon (2001).

Recognizing manure and pork production as joint outputs of hog farming, Roka and Hoag (1996) incorporated a manure disposal component in a swine farm optimization model in order to determine if manure value influenced livestock management decisions. They found that the cost of manure disposal outweighed the value of contributed nutrients, but inclusion of manure value in their model did not affect pork production decisions because manure value was very small relative to net returns from pork production. Yap et al. (2004) also employed a hog-crop operation optimization model to assess the impact of switching to a phosphorus-based manure application rate.

Fleming, Babcock, and Wang (1998) employed a manure delivery cost formulation combined with a manure benefits function to estimate net returns to manure utilization for nitrogen- and phosphorus-based manure application standards. The inclusion of a variable indicating the proportion of cropland where manure is accepted (i.e., willingness to accept) is a significant aspect of their specification. Using Fleming, Babcock, and Wang's manure delivery cost formulation, Ribaudo et al. (2003) assessed

the costs to swine operations of meeting federal manure management proposals. They also performed a regional analysis of manure utilization (all types) for the Chesapeake Bay watershed utilizing a cost-minimization transportation model. An analysis by Lazarus and Koehler (2002) indicated that fertilizer savings resulting from lowering the application rate of swine manure could cover the costs of additional investments.

Studies of dairy manure utilization include McSweeney and Shortle (1989), Huang and Short (2002), and Huang and Christensen (2003), with the latter two employing a whole-farm optimization model. Osei et al. (2000) investigated the economic and environmental impact of implementing nitrogen- and phosphorus-based application rates at dairy farms, adopting environmental and farm economic simulation models. Oudendag and Luesink (1998) describe a manure model, which includes a cost-minimizing transport module, used by Dutch agriculture to provide insight into manure management decisions.

While the aforementioned studies are all empirical, two theoretical analyses (Schnitkey and Miranda, 1993; and Innes, 2000) that explored spatial patterns of manure application are noteworthy. As in these two earlier works, our study also analyzes but additionally quantifies optimal spatial patterns of manure utilization. In contrast, however, the model presented here does not attempt to quantify crop production functions; rather, it requires crop nutrient requirements to be satisfied, with no additional yield benefits to nutrients in excess of crop requirements. Although we acknowledge the importance of crop production functions, we believe they are not precisely known, and argue that crop farmers often base both commercial fertilizer and manure application decisions on published crop requirements.

The Model

The model developed in this section, while similar in some respects to other manure utilization models in the literature, is fairly unique in that the manure application rate is endogenous. Our baseline specification is as follows:

$$(1) \quad \text{Min } C = \sum_r \sum_c \left(\sum_i p_i F_{irc} + \left\{ \sum_k [s_{kc} + t_k(dis_r)] M_{krc} \right\} \right) a_{rc},$$

subject to:

$$(2) \quad \sum_i n_{ij} F_{irc} + \sum_k v_{kcj} n_{kj} M_{krc} \geq R_{cj} - S_{cj}, \quad \forall r, c, j,$$

and

$$(3) \quad \sum_r \sum_c M_{krc} a_{rc} = X_k, \quad \forall k,$$

where C is a variable representing the total cost of manure application, which is minimized; the variable M_{krc} is the application rate of manure k in region r for crop c ; and the variable F_{irc} is the application rate of fertilizer i in region r for crop c . The remaining notations are parameters, where p_i is the price of fertilizer i ;² s_k is the unit application

² Fertilizer prices (p_i) here are assumed to include application cost. All prices and costs presented in this paper are considered to be denominated in 2004 U.S. dollars and reflective of 2004 U.S. prices and costs. Recent increases in energy prices have undoubtedly increased certain expenses and prices.

expense of spreading manure k ; t_k is the cost of transporting one unit of manure k one distance unit; dis_r is the distance to region r ; a_{rc} is the land area planted in crop c in region r ; n_{ij} and n_{kj} indicate the macronutrient content ($j = \text{N, P, K}$)³ for commercial fertilizer i and manure k , respectively, for nutrient j ; v_{kcj} are nutrient availability coefficients for manure k , crop c , nutrient j combinations, which equate one unit of manure nutrient to a unit of commercial fertilizer nutrient; R_{cj} are nutrient j requirements for crop c , nutrient j ; and S_{cj} are soil-supplied nutrients (i.e., amounts by which R_{cj} can be reduced due to soil nutrient buildup and still meet crop needs).

The objective function [equation (1)] minimizes the cost of fertilization subject to crop nutrient requirements being met or exceeded [equation (2)]. The inequality in equation (2) allows excess applications of macronutrients which are assumed neither to harm nor benefit yields. Equation (3) is a manure availability constraint which specifies that *all* available manure (X_k) must be applied to crop fields.

This model is employed here in a general context, in that it assumes concentrations of available manure (and therefore livestock concentrations) at a single point, which is surrounded by crop fields in every direction. Regions (r) consist of concentric circular bands with an outer diameter of d_r and a common width of w surrounding the livestock concentration. Thus, travel distances are specified as:

$$(4) \quad dis_r = (d_r - 0.5w), \quad \forall r.$$

Land area of each concentric region is the difference between the areas of two circles with radius d_r and $d_r - w$, i.e., $[\pi d_r^2 - \pi(d_r - w)^2]$. Cropland areas for various crops (c) are specified as constituting fractions (ρ_c) of total land area, which, in this specification, are considered the same for all regions. Due to excessive slope and possibly other conditions, only a fraction (γ) of the cropland areas are suitable for manure application, which, in this general context, is considered invariant with respect to the crop and region. In practice, manure application is also limited by issues such as timing, odors, attitudes, etc.—factors that are difficult to model. Thus, a maximum adoption ratio for manure application (α) is also specified and is considered invariant with respect to the crop and region. Given this conception, manure application areas for (a_{rc}) in equations (1) and (2) are given by:

$$(5) \quad a_{rc} = \left\{ \pi [d_r^2 - (d_r - w)^2] \right\} \rho_c \gamma \alpha, \quad \forall r, c.$$

Organic fractions of manure nutrients become available over a multiple-year period in a manner consistent with theoretical decay functions. This analysis assumes repeated manure application; therefore, steady-state nutrient availability coefficients for all nutrients are appropriate. Nutrient availability coefficients for N are also affected by the manure application method (m). Manure applications may either be left on the surface of the crop fields or incorporated into it, either directly or by subsequent plowing or disking. Incorporating manure into the soil reduces ammonia N volatilization, which typically increases N availability by 10% to 15% (Peters and Kelling, 2002). The manure

³ When referring to manure or commercial fertilizer nutrient contents or to crop requirements, P indicates phosphate (P_2O_5) and K indicates potash (K_2O).

N availability coefficients used in this analysis ($v_{kc,j=N}$) are weighted averages (weighted by land area) of N availability for incorporated and unincorporated manure. The foregoing specification [equations (1)–(5)] is hereafter referred to as the manure transportation and application (MTA) model. The formulation is designed to simulate the application of specific manure types under very generalized conditions. The base formulation is unconstrained by policy in that it does not directly constrain the rate of manure application nor does it induce changes in manure utilization through incentives or penalties.

Simulating Environmental Policy

We consider the current baseline environmental policy regarding manure utilization to be the N-rate, with the exception that if the P-rate is higher than the N-rate, the higher P-rate is allowed. This ensures the simulated N-rate will always be greater than or equal to the simulated P-rate. Hence, the baseline N-rate scenario is simulated by adding the constraint:

$$(6) \quad M_{krc} \leq \max \left[\frac{R_{c,j=N}}{(v_{kc,j=N} n_{k,j=N})}, \frac{R_{c,j=P}}{(v_{kc,j=P} n_{k,j=P})} \right], \quad \forall k, r, c.$$

The additional constraint for the P-rate scenario is identical to equation (6) except that “max” is replaced by “min.”

Model Limitations

The MTA specification presented here incorporates the most easily quantifiable significant factors motivating manure transportation and application, i.e., the nutrient content of manure, nutrient availability ratios, crop requirements for nutrients, soil-supplied nutrients, manure application and transportation costs, and commercial fertilizer prices. Like similar models, MTA simplifies or ignores some potentially important agronomic, behavioral, and technological issues and relationships. First, we do not explicitly include an application cost for commercial fertilizer for practical considerations.⁴ This cost is small compared to equivalent nutrient applications from manure, and therefore would not be expected to materially change results.

We assume that manure value is entirely predicated on its plant-available macro-nutrient content. While organic matter and micronutrient content in manures may increase yields (Johnston, 1991), utilizing manure can also cause negative agronomic consequences due to soil compaction, weed seeds, rocks, and soluble salts, which can reduce yields (Risse et al., 2001). Thus, MTA does not completely define manure value, but this value can be either less than or greater than equivalent nutrient applications of commercial fertilizer, depending on whether the additional beneficial or negative agronomic characteristics of manure application predominate.

Other factors may likewise cause MTA model results to depart from empirical observation. The MTA specification, for instance, assumes that nutrient content, plant

⁴ The authors experimented with a nonlinear specification that allowed commercial fertilizer application expense to be specified on a \$/acre basis. In addition to much longer solve times, results that were strictly artifacts of the specification became serious when the nonlinear formulation was used.

availability, and rate of application are known with certainty. Yet these factors often are less well known for manure than for commercial fertilizer. For example, manure is frequently not tested, so nutrient content is sometimes not precisely known. Handling characteristics of manure can also result in uneven distribution, and the precise rate of application is generally less certain for manure than for commercial fertilizer. Less certainty in the amounts of plant-available nutrients applied may promote manure nutrient applications in excess of those for commercial fertilizer. For this reason, manure nutrient applications may generally exceed those from commercial fertilizer—a conclusion reached in the theoretical analyses of Schnitkey and Miranda (1993) and Innes (2000), but for different reasons.

As an artifact of the optimization procedure, MTA assumes perfectly efficient markets. Markets for manure, however, are often thin, and transfers of manure can involve a great deal of coordination on the part of livestock operators, custom manure applicators, and crop farmers, resulting in significant transactions costs. Lack of efficient and well-developed markets may cause low adoption rates and higher application rates than for commercial fertilizer. In some cases, livestock operators may be concerned about liability issues associated with manure transfers. For these reasons, there is sometimes a propensity for livestock operations to limit manure application to operation-owned land, even though manure nutrients may be more valuable when applied off-site. Objectionable odor also limits manure use, especially on land near residential development or public facilities. To some extent, these factors are handled in MTA by setting the maximum adoption ratio to only 0.50.

As noted by Roka and Hoag (1996), especially in areas of intense livestock production, changes in crop choice (to crops which utilize more nutrients) could significantly affect returns to manure. This MTA formulation assumes that crop choice is exogenously determined. Finally, as discussed earlier, this formulation of MTA does not simulate any particular region but assumes a surrounding crop distribution and other model inputs reflective of national averages.

Data

This paper reports results of MTA model simulations for national average conditions. Thus, where available, national average values were used to populate MTA model parameters. Where national average values were not available, literature values from several locations or regions were averaged, or values considered representative of national averages were used. In some cases, telephone interviews of academic experts, agency field personnel, and custom manure haulers and applicators informed parameter values.

Manure Characteristics

Four types of transportable manure, consisting of livestock type/production system combinations, were assessed: (a) dairy dry-scrape, (b) swine slurry, (c) broiler litter, and (d) layer high rise. Production of manure was estimated on a reference animal basis, where the term “reference animal” indicates the type of animal used to define the size of a livestock operation, i.e., finished broiler for broiler operations, layer for layer operations, finished hog for swine operations, and standing dairy cow (sum of lactating and dry cows) for dairy operations.

Table 1. Manure Production and Nutrient Content, by Manure Type

Description	LIVESTOCK TYPE / Reference Animal / Production System / Manure Collected As:			
	DAIRY	SWINE	BROILER	LAYER
	Cow	Finished Hog	Marketed Broiler	Layer
	Open Lot Dry Scrape	Covered Pit Slurry	Roofed Storage Litter	Roofed Storage Solid
Nutrient Content of Manure (lbs./ton):^a				
Nitrogen (N)	10.6	10.1	63.5	36.3
Phosphate (P)	5.9	9.3	52.7	51.5
Potash (K)	9.9	5.7	43.7	30.1
Manure Produced per Standing Reference Animal (tons/year) ^b	12.6	2.08	0.0082	0.0179
Plant Availability Coefficients (fraction):^c				
Nitrogen (N) (incorporated)	0.55	0.80	0.75	0.75
Nitrogen (N) (not incorporated)	0.45	0.65	0.65	0.65
Phosphate (P)	0.85	0.85	0.85	0.85
Potash (K)	1.00	1.00	1.00	1.00
Standing Reference Animals Needed to Produce:				
50,000 tons of manure/year	4,000	24,000	6,100,000	2,800,000
2,000,000 tons of manure/year	158,000	961,000	243,000,000	112,000,000

^a Calculations for manure nutrient content are based on averages of numerous literature sources.

^b Source for manure produced per standing reference animal: Keplinger, Tanter, and Hauck (2004).

^c Sources for plant availability coefficients: Motavalli, Kelling, and Converse (1989); Beegle (2003); Risse et al. (2001); and Peters and Kelling (2002).

Table 1 presents manure nutrient content (n_{kj}), production, and plant availability (v_{kmj}) data used in the analysis, by manure type. Nutrient content of animal manures at the time they are spread vary considerably, based on many factors, including nutrient content of the raw manure, type of storage, time since excretion, weather conditions, etc. Literature values reflect this variability. Nutrient content values in this analysis are averages of numerous literature sources. Manure produced per reference animal was estimated by a procedure outlined in Keplinger, Tanter, and Hauck (2004).

Consistent with many agronomic findings (e.g., Motavalli, Kelling, and Converse, 1989), steady-state plant availability coefficients for K are considered to have a value of one because most manure is available in inorganic forms (Beegle, 2003). The literature does not provide a clear consensus regarding the plant availability of manure P (Risse et al., 2001). Considerable portions of manure P occur in organic forms, which are eventually mineralized. We employ a P availability coefficient of 0.85 for all crops following Risse et al.'s judgment that 80% to 90% of manure P is currently considered plant available. Three-year plant availability coefficients for manure N are considered steady state, since very little N becomes available after the third year of application. N availability coefficients are considerably less than one, due to considerable volatilization of some manure N forms. We use the manure N plant availability coefficients reported in Peters and Kelling (2002).

Cropland Distributions

Cropland distributions (ρ_c) for each manure type were calculated from the *1997 Census of Agriculture* [USDA/National Agricultural Statistics Service (NASS), 1999] to reflect national average cropland distributions for the associated livestock-producing regions. We considered 11 crops covering the great majority of total cropland, plus permanent pasture and cropland used as pasture.⁵ Weighted average cropland distributions across all counties in the United States were calculated for each manure type to represent national average cropland distributions for the four manure types, where the weights were the estimated number of animals in each county associated with the manure type considered. Weights are therefore the products of the total number of animals in the county (e.g., dairy cows) (USDA/NASS, 1999) and the proportion of livestock falling into the selected production systems (e.g., dry scrape) (Moffitt, Kellogg, and Kintzer, 2002).

Cropland distributions for manure types (table 2) vary considerably, reflecting the spatial distribution of livestock types across the nation. Broiler litter regions, for instance, include the most permanent pasture, while swine slurry regions possess a greater percentage of "corn for grain" and soybean cropland than for the other manure types. These findings are consistent with broiler operations being concentrated in the southeastern United States, where permanent pasture is prevalent, and many swine slurry operations being concentrated in the Midwest, where "corn for grain" and soybean production predominate. Summation of cropland categories totaled 73% of total land area for swine slurry regions, but only 35% for broiler operations (table 2). Nutrient requirements for the four livestock regions are weighted averages of the nutrient requirements for the crops within each region, where weights are the percentages. Hence, differences in cropland distributions result in different nutrient requirements for land adjacent to the four types of livestock facilities considered. Per acre nutrient requirements for each crop were estimated by multiplying average yields (USDA/NASS, 1999) by nutrient uptake and removal values as reported in Lander, Moffitt, and Alt (1998).

Land Availability Factors

Land suitable for manure application (γ) is an important element in manure utilization but is very region- and site-specific. The ability of manure application equipment to access and fertilize cropland is often restricted by excessive slope or other physical factors. For this analysis, we employ a suitability factor of 0.60 ($\gamma = 0.6$) for all crops and regions based on Cook and Silberberg (1998).

The maximum adoption ratio for manure (α) is a very important consideration in simulating manure application behavior, but its value is not well established. Kaplan, Johansson, and Peters (2004) estimated that substitution rates of manure for commercial fertilizer are currently about 20% in the Chesapeake Bay area. Substantial cropland areas, however, are not conveniently located to manure sources and would most likely use manure if its price (including transportation) was economically viable.

⁵ These 13 crop categories (11 crops, permanent pasture, and cropland used as pasture) constituted 98% of the land area of the 26 categories considered in Kellogg et al. (2000).

Table 2. National Average Cropland Distributions and Nutrient Requirements, 13 Crop Categories

Description	LIVESTOCK TYPE / Manure Handling System:			
	DAIRY Dry Scrape	SWINE Slurry	BROILER Litter	LAYER High Rise
Cropland Distribution (% land area):				
Permanent Pasture	12.78	13.59	15.82	10.14
Corn for Grain	9.47	25.76	2.39	14.77
Soybeans	5.82	22.10	3.12	12.59
Cropland Used as Pasture	5.17	4.52	6.87	4.25
Other Tame Hay	2.49	1.21	3.25	1.87
Alfalfa Hay	3.95	2.34	0.39	2.45
Corn Silage	2.25	0.92	0.42	1.84
Cotton (lint and seed)	0.11	0.16	0.98	0.21
Grass Silage	2.36	0.44	0.23	0.83
Wild Hay	0.43	0.42	0.63	0.32
Oats	0.68	0.42	0.06	0.35
Sorghum for Grain	0.15	0.66	0.10	0.31
Peanuts for Nuts	0.03	0.01	0.26	0.04
Total (13 crop categories):	45.69	72.55	34.53	49.96
Average Nutrient Requirements (lbs./acre):				
Nitrogen (N)	23.38	36.19	14.75	25.24
Phosphate (P)	13.53	23.12	8.83	15.84
Potash (K)	20.78	24.38	10.31	19.36

Sources: Calculated from 1997 *Census of Agriculture* data (USDA/NASS, 1999) and information on the distribution of operation types (Moffitt, Kellogg, and Kintzer, 2002).

Anecdotal evidence, for instance, suggests that the extent of manure application on pasture and hayfields is currently around 50% in some intensive broiler production regions.⁶ Accordingly, we initially set the maximum adoption ratio at 0.50 ($\alpha = 0.5$). Policy efforts to promote manure use through education, provision of information, and marketing efforts, however, might substantially increase the maximum adoption ratio. Due to the importance of the value of α , its uncertainty, and the possibility that it can be raised, we also assess scenarios where α is set at 0.25 and 0.75.

Legacy Soil Nutrients

Nutrient requirements ($R_{c,j}$) can be met either from commercial fertilizer, manure, or from nutrients already present in the soil. The parameter $S_{c,j}$ in equation (2) represents soil-supplied nutrients, i.e., amounts by which nutrient applications can be reduced from recommended crop nutrient requirements and still meet crop needs. Profligate historical use of manure has resulted in elevated levels of P and K in many cropland areas adjacent to livestock facilities, which we refer to as legacy soil nutrients. In such cases, some or

⁶ This anecdotal evidence is based on conversations with custom manure haulers in intensive broiler production regions.

all of crop P and K requirements can be met from soil-supplied P and K. For our baseline specification, we consider that half of crop P and K requirements can be met through soil-supplied nutrients [$S_{c,j=P} = (0.5)(R_{c,j=P})$ and $S_{c,j=K} = (0.5)(R_{c,j=K})$]. However, because of the importance of soil-supplied nutrients to manure utilization and its great regional variation, we also consider scenarios where none and all of crop P and K requirements are met through soil-supplied P and K.

Fertilizer Prices

Three readily available dry fertilizers were used in the analysis as sources of nutrients in addition to the manures considered: ammonium nitrate (34% N), superphosphate phosphate (46% P), and muriate of potash (potassium chloride) (60% K). Prices used in the analysis for these fertilizers were \$206/ton, \$261/ton, and \$160/ton, respectively, which represent five-year averages (1996–2000) of national average U.S. farm prices (The Fertilizer Institute, 2000).⁷

Manure Application and Transportation Costs

Theory and data indicated declining *per ton* manure application costs (s_{kc}) for increasing application rates (M_{krc}). We developed schedules of *per acre* manure application expense ($peracre_{kc}$):

$$(7) \quad peracre_{kc} = f(M_{krc}),$$

from which per ton manure spreading costs (s_{kc}) were calculated:

$$(8) \quad s_{kc} = peracre_{kc} / M_{krc}.$$

Functions for per acre manure application expense ($peracre_{kc}$) were derived from three data points representing three manure application rates and a point at the origin, with straight line segments connecting each successive point. A positive but declining slope for each successive line segment of equation (7) resulted in generally declining per ton manure application expenses [s_{kc} in equation (8)] as manure application rates increased.

Application expense for three application rates of swine slurry was derived from a survey of custom applicators published in Schmidt (2001). Application expense for three rates of application for broiler litter and dairy manure were based on interviews with academic experts, agency field personnel, and custom applicators. Application costs for layer manure were assumed to be the same as for broiler litter based on its similar characteristics.

An investigation of manure application behavior revealed that manure was typically spread at the N-rate, but sometimes at multiple-year intervals in order to effectively achieve a lower annual average rate, e.g., an average annual P-rate. To approximate actual manure application behavior, per ton manure application expense (s_{kc}) was set to the rate mapping to the N-rate for all manure-crop combinations. Resulting per ton manure application expense for each crop as well as the underlying data points from which they were derived are presented in table 3.

⁷ Fertilizer prices translate into nutrient costs of \$0.302/lb. for N, \$0.279/lb. for P, and \$0.134/lb. for K.

Table 3. Manure Application Expense

Description	DAIRY Dry Scrape	SWINE Slurry	BROILER Litter / LAYER Manure
A. Manure Application Expense for Three Rates:			
▸ Rate 1: Application Rate (tons/acre)	15.00	12.50	1.00
Application Expense (\$/acre)	45.00	20.68	6.00
Application Expense (\$/ton)	3.00	1.65	6.00
▸ Rate 2: Application Rate (tons/acre)	25.00	20.90	2.00
Application Expense (\$/acre)	60.00	31.92	10.00
Application Expense (\$/ton)	2.40	1.53	5.00
▸ Rate 3: Application Rate (tons/acre)	50.00	37.60	3.00
Application Expense (\$/acre)	90.00	52.05	12.00
Application Expense (\$/ton)	1.80	1.39	4.00
B. Manure Application Expense for 13 Crops, N-Rate (\$/ton):			
Permanent Pasture	3.00	1.65	6.00
Corn for Grain	2.69	1.63	4.65
Soybeans	2.32	1.55	3.99
Cropland Used as Pasture	3.00	1.65	5.18
Other Tame Hay	3.00	1.65	6.00
Alfalfa Hay	2.12	1.49	3.59
Corn Silage	2.58	1.60	4.42
Cotton (lint and seed)	3.00	1.65	6.00
Grass Silage	2.93	1.65	5.07
Wild Hay	3.00	1.65	6.00
Oats	3.00	1.65	6.00
Sorghum for Grain	3.00	1.65	5.37
Peanuts for Nuts	2.68	1.62	4.65

Notes: For the three application rates and costs in section A, data for swine slurry were derived from a survey of custom applicators published in Schmidt (2001); data for broiler litter and dairy manure were based on interviews with academic experts, agency field personnel, and custom applicators; data for layer manure were assumed to be the same as for broiler litter based on its similar characteristics. Application expenses in section B were derived by the procedure outlined in the text.

Because we assume manure is actually spread at the N-rate, manure application rate variables [M_{krc} in equations (1)–(3) and (6)] are interpreted as *average annual* rates, which are often achieved by applying manure at multiple-year intervals. This interpretation is advisable given actual manure application behavior and because manure application equipment is typically not designed to apply manure at rates as low as MTA often selects (e.g., K-rates or P-rates).

Several published studies employ a transportation expense for broiler and dairy manure ranging from \$0.10 to \$0.13/ton per mile hauled (e.g., Ribaud et al., 2003; Pelletier, Pease, and Kenyon, 2001; Bosch and Napit, 1992). Based on this range, transportation expense for dairy dry scrape manure and broiler litter was set at \$0.12/ton-mile. Transportation expense for high rise layer manure was assumed to match that for broiler litter based on its similar characteristics. When converted from gallons to tons, transportation expense for swine slurry was found to be \$0.30/ton-mile when transported by tank, and \$0.25/ton-mile when transported by drag hose, based on Ribaud et al., Gollehon, and Agapoff (2003), and Lorimor (2001).

Application

MTA applications were chosen with the objective of lending insights to several important aspects of manure utilization and to assess the impacts of policy changes. MTA was applied to the four manure types considered (dairy dry scrape, swine slurry, broiler litter, and layer manure), using national average data and the N-rate policy as baseline. To illustrate important differences between manure types, each manure type was assessed independently, i.e., only one type of manure was considered for any given model run while other manure types were set to zero. To highlight the relevance of livestock concentration on manure utilization and associated environmental consequences, manure production (X_k) was incremented by 50,000 tons, starting at zero. Forty-one iterations were run for each manure type and scenario, resulting in a series of output values representing manure production ranging from zero to 2 million tons annually. The production of 50,000 tons of collectable manure annually represents small concentrations of livestock, while the production of 2 million tons of manure annually implies extremely large concentrations of animals (see table 1).

Is Manure a Waste or a Resource?

In general, we consider that resources (or goods) have positive value and are utilized, and wastes (or bads) have negative value and can only be disposed of at a cost. Manure application guidance published by university, state, and federal sources often espouses the traditional view—i.e., manure is a valuable resource and should be properly utilized on the basis of crop nutrient needs. On the other hand, many analysts conclude that manure is now largely a disposal problem (e.g., Letson and Gollehon, 1998) and that more land is needed to properly dispose of animal wastes (Ribaud, Gollehon, and Agapoff, 2003). Like other commodities, manure has a downward-sloping demand; its value declines as more is produced. At some level of production, the marginal value of manure reaches zero and becomes negative. The extension of the demand curve into the negative quadrant is caused by the model assumption that all manure must be spread at a cost. For ordinary goods, it would be uneconomic to produce a product beyond a level yielding net benefits. Because manure is a by-product, however, its production (or supply) is not greatly influenced by manure demand (Roka and Hoag, 1996). Thus, increasing livestock densities reduce manure value, sometimes causing it to become negative and transforming this potential resource into a waste where disposal becomes problematic and costly.

To generally quantify the waste/resource question, simulations were performed using average national data for the four types of assessed manure under the N-rate policy scenario—conditions which we consider baseline. Figure 1 presents the resulting marginal manure values [the negative dual values of equation (3)]. These manure values (or derived demands) decline with greater production for all manure types—a phenomenon due entirely to transportation expense. As livestock concentrations increase, more manure is produced, which must be hauled farther in order for it to be optimally utilized. In addition, increased transportation expense often induces manure to be applied at greater rates, thereby reducing its nutrient value and leading to excess nutrient applications. The particular shapes of the derived demands for manure largely depend on manure nutrient content, but are also influenced by nutrients demanded on surrounding crop fields, which are a function of the type and quantity of surrounding cropland (table 2).

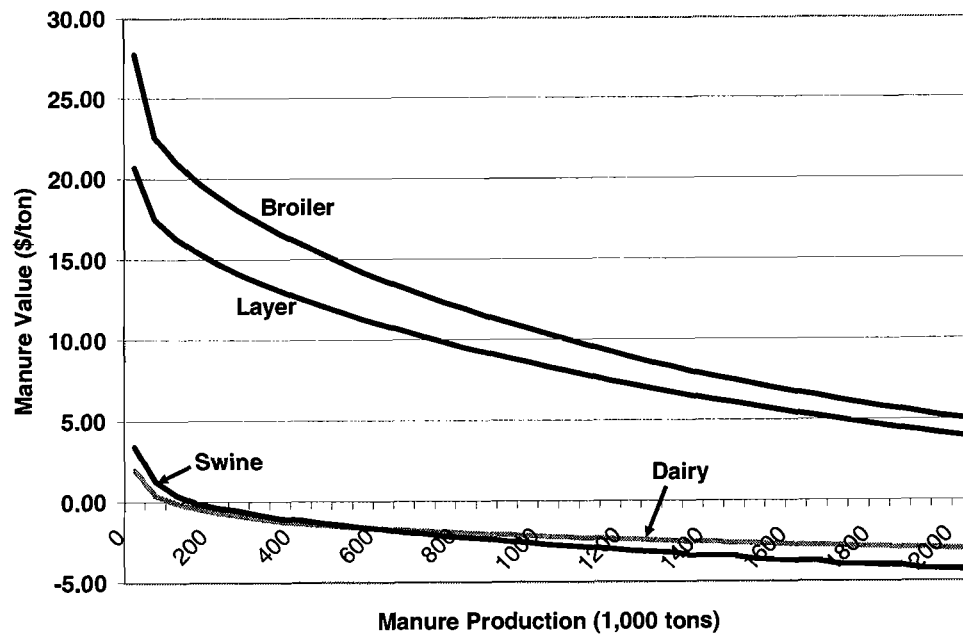


Figure 1. Marginal manure value, N-rate scenario

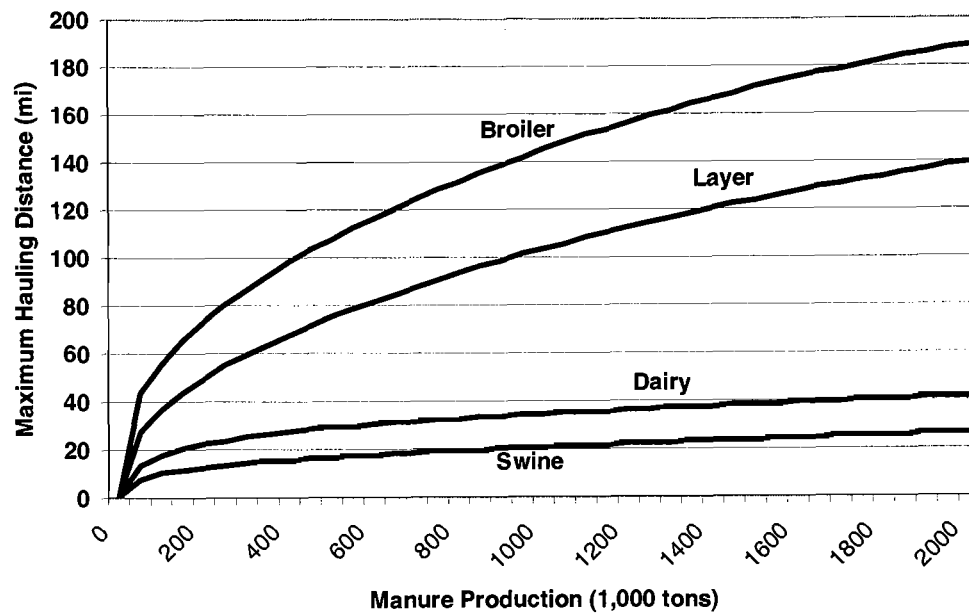


Figure 2. Maximum manure hauling distances, N-rate scenario

Figure 2 shows the maximum distance that each manure type would need to be hauled to optimally utilize manure nutrients while meeting environmental requirements. Maximum travel distances also largely depend on manure nutrient content, but are influenced by the type and quantity of surrounding cropland as well. Because the baseline specification constrains manure to be applied at no greater than the N-rate, manure must be hauled farther as more is produced, even though this sometimes forces marginal manure value to become increasingly negative (figure 1).

As readily seen from figure 1, broiler litter and layer manure are much more valuable than dairy and swine manure for all levels of manure production, which is mainly attributable to their much higher nutrient content (table 1). Thus, for the conditions simulated, these manures remain valuable resources for all levels of production considered. Figure 2 indicates that broiler litter and layer manure (high-value manures) can travel considerable distances and still remain valuable resources and, indeed, they must travel farther than manures with lower nutrient content when an agronomic rate restriction is applied because of their higher nutrient content. The value for broiler litter declines faster than for layer manure because crop nutrient requirements in broiler production regions are less than for layer production regions (see table 2). The marginal values for dairy dry scrape and swine slurry (low-value manures) remain positive only for low levels of manure production, since the expense involved in transporting these manures quickly exceeds their fertilizer value as manure production increases. The marginal value of swine slurry is initially higher than that of dairy dry scrape but quickly falls below it because its application expense is less than that for dairy dry scrape (table 3), but it is more than twice as expensive to transport.

Effect of Livestock Concentration on Excess Phosphate Application

We define excess phosphate application as the amount of phosphate applied in excess of crop requirements. Since commercial phosphate would not be applied if manure phosphate exceeded requirements, excess phosphate application consists entirely of excess manure phosphate applications:

$$\sum_k \sum_r \sum_c \left[(M_{krc})(n_{k,j=P})(v_{kc,j=P}) - R_{c,j=P} \right].$$

Figure 3 illustrates the amount of excess P applied to cropland as manure production increases. At fairly low levels of production, the low-value manures (swine slurry and dairy dry scrape) begin to be applied at the N-rate (the maximum allowed), causing excess phosphate application. In contrast, excess P application does not occur until much higher levels of production are attained for the high-value manures (broiler litter and layer manure), indicating that a P-rate or below is voluntarily chosen for the high-value manures until critical levels of production are reached. Excess phosphate application increases faster for swine slurry than for dairy dry scrape because the P:N ratio is higher for swine slurry (see table 1). When certain levels of production are reached, excess phosphate application for broiler litter and layer manure increases quite rapidly as application areas for these manures begin shifting to the N-rate.

Figure 4 indicates where, in relation to the livestock concentration, excess P is applied, using three levels of swine slurry production (200,000, 500,000, and 1,000,000 tons corresponding to 96,000, 240,000, and 481,000 standing swine, respectively) as an example.

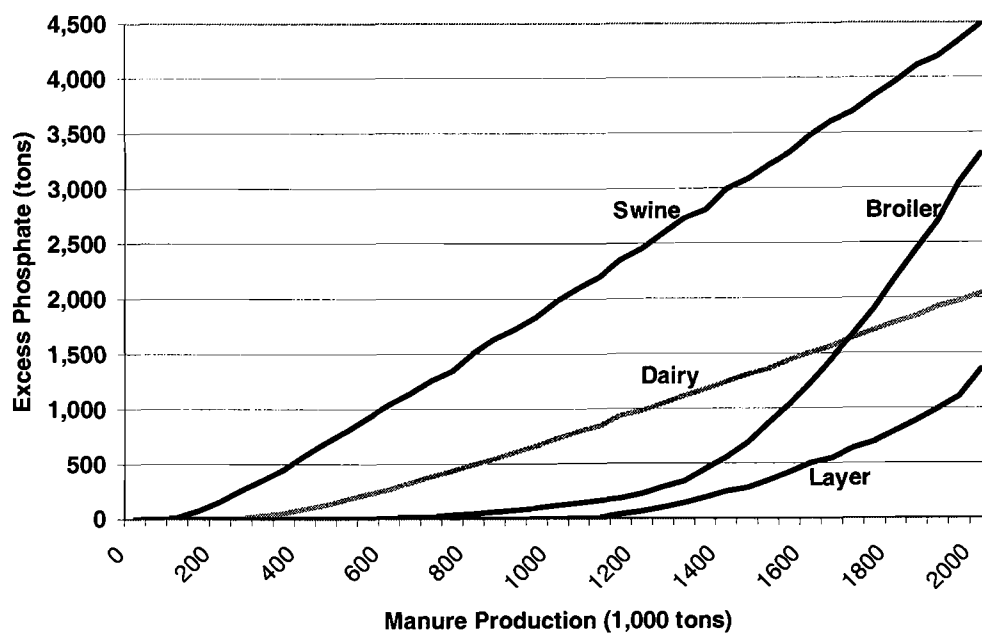


Figure 3. Excess manure phosphate application, N-rate scenario

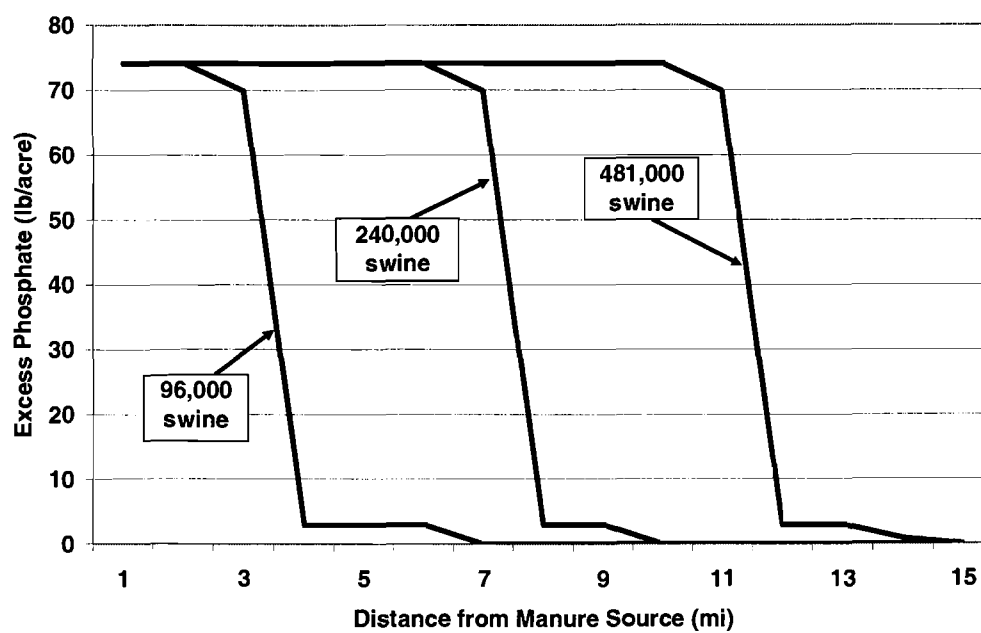


Figure 4. Amount and location of excess manure phosphate application for three levels of swine production, N-rate scenario

As shown by figure 4, excess P application occurs close to the manure source, and the area (radius from the manure source) of excess P application increases as the numbers of animals, and therefore manure production, increase.

Simulating Environmental Policy

Environmental policies are typically designed to improve an environmental measure (e.g., reduce excess nutrient applications), but can also greatly affect manure value and utilization. Here we investigate the impacts of manure application rate restrictions on manure value and utilization. Some researchers (e.g., Innes, 2000) have argued that implementing manure application rate restrictions is infeasible because they cannot be adequately monitored or enforced, and suggest incentives or penalties to achieve desired environmental outcomes. We argue that manure application rate restrictions can be largely (though probably not totally) effective because: (a) fields can and are tested for soil test P, which is a function of manure application rates; (b) awareness of the detrimental environmental effects of over-applying N and P is a deterrent and can be improved through outreach efforts; (c) growing numbers of livestock operators and crop farmers are adopting nutrient management plans and working closely with agency field personnel to implement those plans; (d) community pressure from within and without the agricultural community promotes compliance; and (e) the desire of most livestock operators and crop farmers is to “do the right thing.”

We consider four scenarios which include a base case simulating no environmental constraints plus three policy scenarios with increasing restrictiveness:

- SCENARIO 1. No environmental constraints.
- SCENARIO 2. Manure must be land applied but can be spread anywhere at any rate (“must spread”).
- SCENARIO 3. Maximum application at the N-rate (“N-rate”).
- SCENARIO 4. Maximum application at the P-rate (“P-rate”).

The impact of these policy scenarios on the marginal value of swine slurry is presented in figure 5.

The marginal value of swine slurry quickly reaches zero but never becomes negative for the “no environmental constraints” scenario. This implies swine slurry can be indefinitely stockpiled or dumped at no cost close to the manure source if it cannot be profitably utilized on crop fields. The shape of the derived demand schedule for the “must spread” scenario is similar in shape to that of the “no environmental constraints” scenario except it achieves a maximum negative value of \$1.64, which is the average per ton application cost for swine slurry (see table 3). According to this scenario, swine slurry in excess of that which can be profitably utilized on crop fields is spread at high rates on land close to the livestock facility, and not transported. These two scenarios are improbable given today’s environmental consciousness. The N-rate and P-rate scenarios require that all manure must be spread at no more than these rates, and successively reduce the value of swine slurry because each successive rate restriction imposes a lower maximum application rate, and therefore increases hauling requirements. An increase in environmental restrictions affects other manure types in a similar manner.

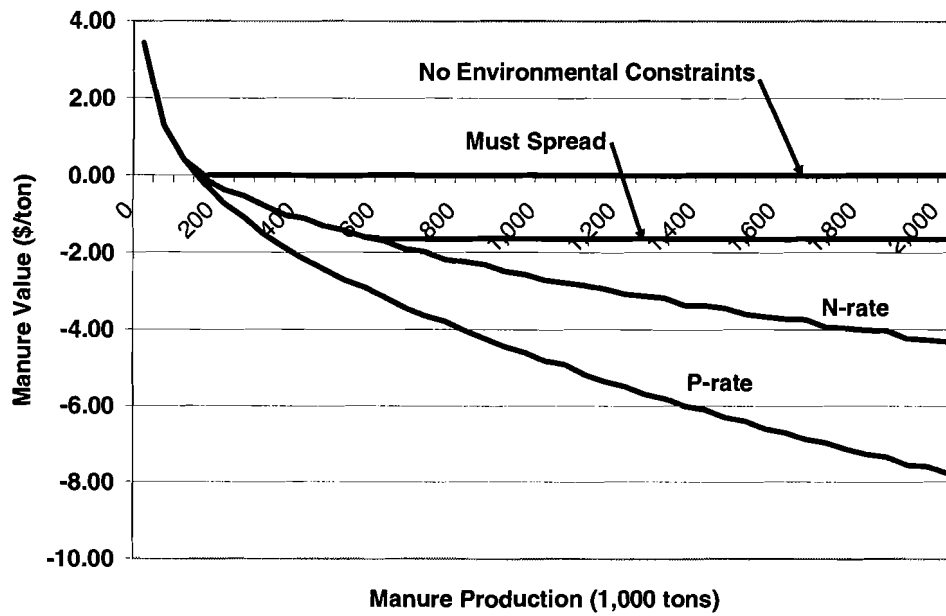


Figure 5. Marginal value of swine slurry for no environmental constraints and three environmental scenarios

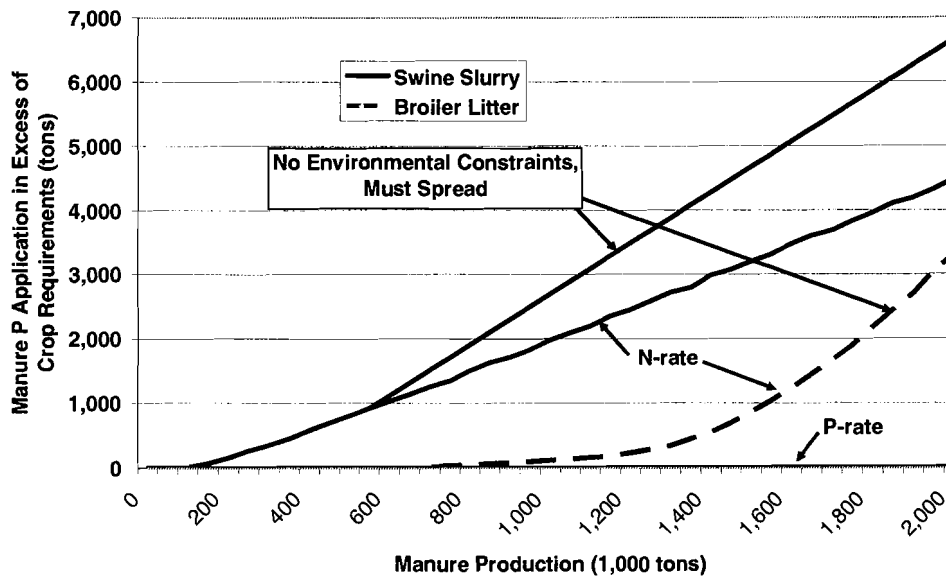


Figure 6. Manure phosphate application in excess of crop requirement (excess P) for swine slurry and broiler litter for no environmental constraints and three policy scenarios

Figure 6 illustrates the impact of the four scenarios on excess P for swine slurry and broiler litter. For both swine slurry and broiler litter, the excess P schedules for the “no environmental constraints” and “must spread” scenarios are identical since the only difference between these scenarios is whether manure which cannot be economically transported is dumped or spread at high rates adjacent to the facility. The N-rate schedule for broiler litter also tracks the first two scenarios, indicating that broiler litter is never applied at a rate greater than the N-rate for any level of manure production considered, even when the N-rate policy is not imposed. For swine slurry, the N-rate scenario reduces excess P application beyond a moderate level of manure production. The P-rate scenario, by definition, eliminates excess P application for both manure types.

Importance of the Maximum Adoption Ratio

A key determinant in the demand for manure nutrients is the amount of surrounding land area that accepts manure application—the product of the sum of cropland fractions ($\sum_c \rho_c$), the fraction of land that is potentially manure fertilizable (γ), and the degree to which owners of surrounding land would actually apply manure, i.e., the maximum adoption ratio (α). The foregoing analyses have assumed a maximum adoption ratio (α) of 0.5; the value of α , however, is not well known. In addition, the amount of surrounding cropland ($\sum_c \rho_c$) and the fraction of cropland suitable for manure fertilization (γ), can vary greatly between regions.

To determine how changes in the maximum adoption ratio impact manure value and utilization, MTA was run for three levels of α (0.25, 0.5, and 0.75). We believe the “true” value of α , in most instances, lies between 0.25 and 0.75. Because of the multiplicative relationship between γ , α , and ρ_c [see equation (5)], the selected levels of α also correspond to three levels of γ (0.3, 0.6, and 0.9) when we assume baseline levels for α and ρ_c .

The effects of varying the maximum adoption ratio (α) on swine slurry and broiler litter value for the baseline N-rate are presented in figure 7. Reducing α reduces manure value, especially for high concentrations of high-value manures (e.g., broiler litter). A maximum adoption ratio of 0.25 forces the value of broiler litter to become negative at very high production levels even under the baseline N-rate policy. Reducing the level of α has an even greater impact on manure value under the more constraining P-rate scenario (figure not shown). Reductions in manure value are caused by the greater hauling distances required when the amount of land potentially adopting manure fertilization is reduced.

Figure 8 shows that the application of excess P decreases as the propensity to utilize manure (α) increases. Consequently, promoting greater utilization of animal manure on cropland in livestock production regions induces more efficient use of manure nutrients, and therefore fewer nutrient losses to the environment. The reduction in excess P application as the maximum adoption ratio (α) increases is especially dramatic for large broiler concentrations (figure 8).

Given current trends in policy discussions and recent changes in regulations, the cost of moving manure utilization from the N-rate to the more restrictive P-rate is a relevant and timely issue. Figure 9 shows that the cost of moving to the P-rate policy (from the baseline N-rate policy) can be reduced, sometimes dramatically, by increasing the

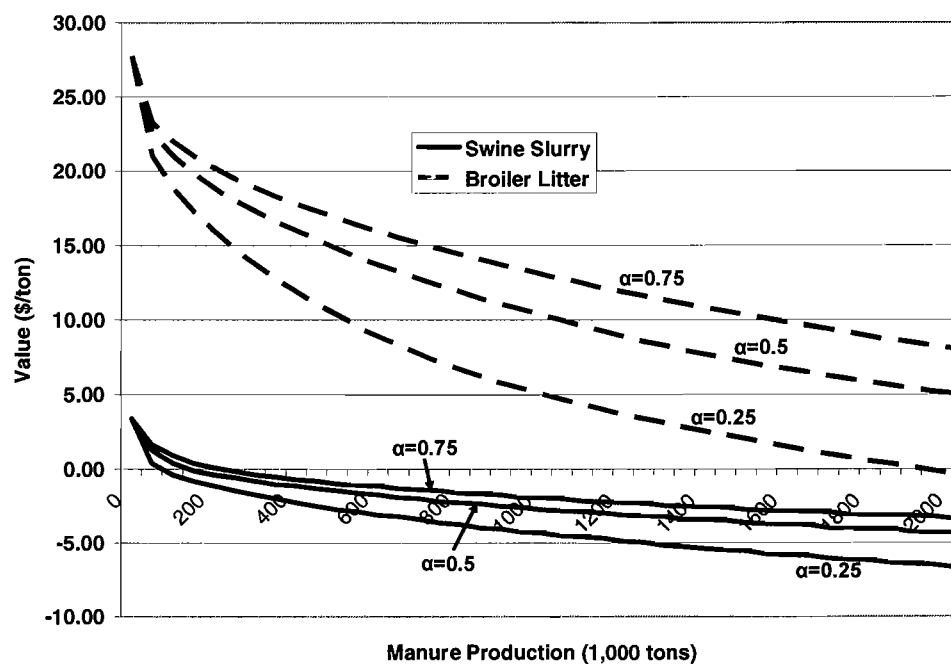


Figure 7. Marginal manure value for three maximum adoption ratios for swine slurry and broiler litter, N-rate scenario

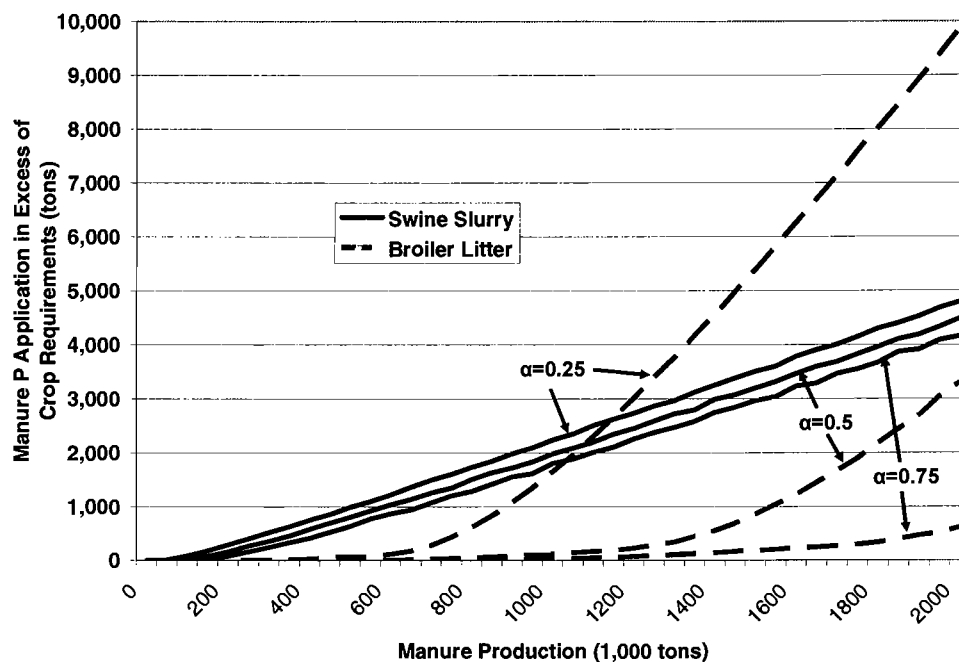


Figure 8. Manure phosphate application in excess of crop requirement (excess P) for three maximum adoption ratios for swine slurry and broiler litter, N-rate scenario

maximum adoption ratio (α). For all manure types, per ton savings increase for larger livestock concentrations. These results underscore the potentially great benefits of increasing the adoption of manure to fertilize cropland. Figure 9 also shows that the cost of moving from the baseline N-rate to the P-rate is much higher for swine slurry (a low-value manure) than for broiler litter (a high-value manure). For the very highest levels of manure production considered for the baseline maximum adoption ratio ($\alpha = 0.5$), shifting from the N-rate to the P-rate policy would involve a cost of about \$2/ton annually for swine slurry, but only \$0.15/ton annually for broiler litter.

Legacy Effects of Soil Nutrient Buildup

Due to historical manure applications greater than agronomic rates, nutrients (particularly P and K) have often accumulated in cropland soils adjacent to livestock operations. In some cases, soil P and K from these fields are more than adequate to supply all crop P and K requirements. In this case, any contributions of P or K from commercial fertilizer or manure are superfluous. The presence of soil-supplied nutrients can dramatically influence manure utilization.

Consider that all land in the vicinity of a livestock operation has more than adequate P and K to supply crop requirements. In this case, manure would always be applied at the N-rate, because no value would accrue from P or K application. The perverse result is that when less P and K are needed by crops, due to nutrient buildup, more is applied. This will always be the case if crop needs for P and K drop to zero for all land surrounding a facility. The direction of the effect, however, is indeterminate if only some land in the vicinity of an operation becomes built up with P or K, or if the nutrient buildup does not completely meet crop requirements. Consider, for example, that P and K buildup extends 20 miles from a manure source. The operator could attain greater nutrient value from the manure by hauling it beyond the 20-mile radius of nutrient buildup, but would incur greater hauling costs. If the higher nutrient value of the manure exceeded the extra hauling cost, the manure would be hauled beyond the 20-mile radius and less excess P and K would be applied.

To explore the impact of soil-supplied nutrients on manure value and utilization, we ran three scenarios each for broiler litter and swine slurry, described below, where all scenarios simulated the baseline N-rate policy:

- SCENARIO 1. No contribution of soil nutrients.
- SCENARIO 2. Soil P and K are assumed to supply *one-half* of P and K crop requirements within 20 miles of the source for swine slurry and within 50 miles of the source for broiler litter, with no contributions of soil P and K beyond these radiuses.
- SCENARIO 3. The same as scenario 2 except that soil P and K are assumed to supply *all* crop P and K requirements within 20 miles of the source for swine slurry and within 50 miles of the source for broiler litter.

Manure value is only marginally affected by simulated increases in soil-supplied P and K, due in large part to the relatively small radiuses of nutrient buildup chosen. Figure 10, however, indicates that excess P increases dramatically for swine slurry as soil-supplied nutrients increase, but decreases for broiler litter. Insight into this divergent behavior is provided by figures 11 and 12.

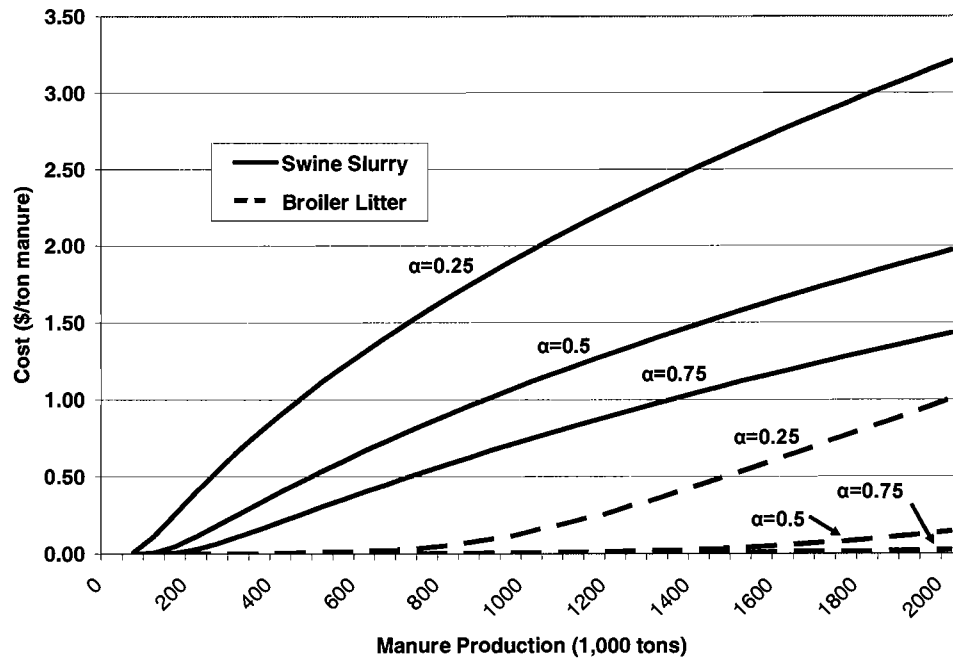


Figure 9. Cost of moving from the N-rate to the P-rate policy scenario for three maximum adoption ratios for swine slurry and broiler litter

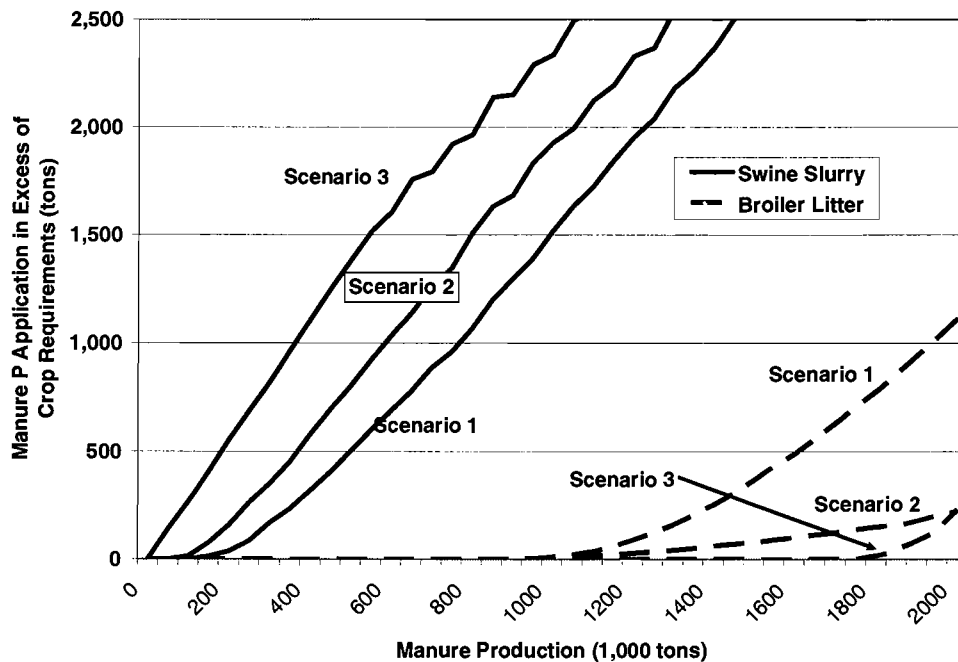


Figure 10. Manure phosphate application in excess of crop requirements (excess P) for three levels of soil nutrient buildup for swine slurry and broiler litter, N-rate scenario

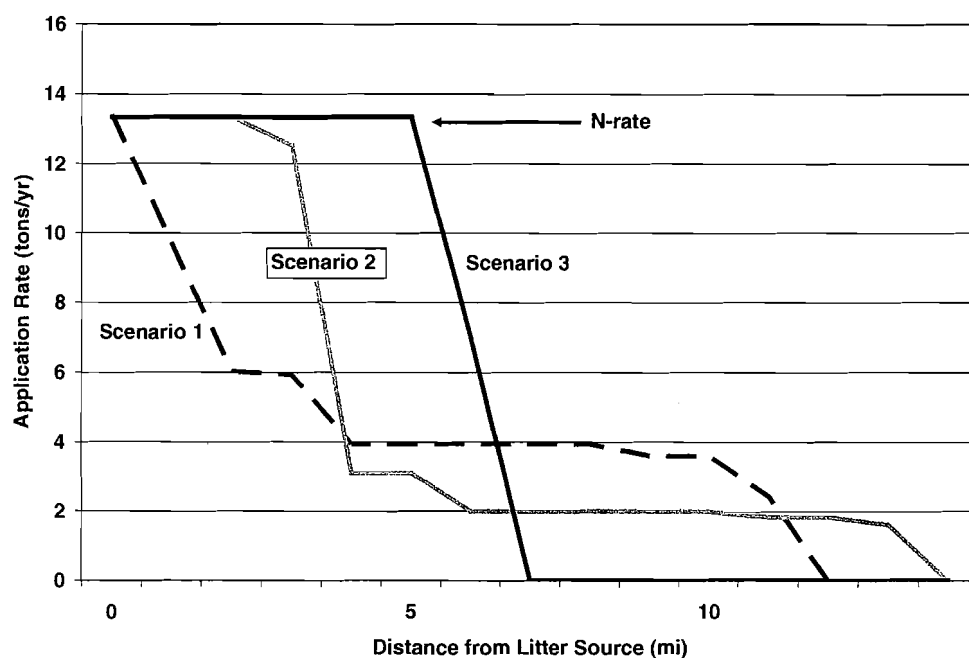


Figure 11. Swine slurry application rate for three levels of soil nutrient buildup, N-rate scenario

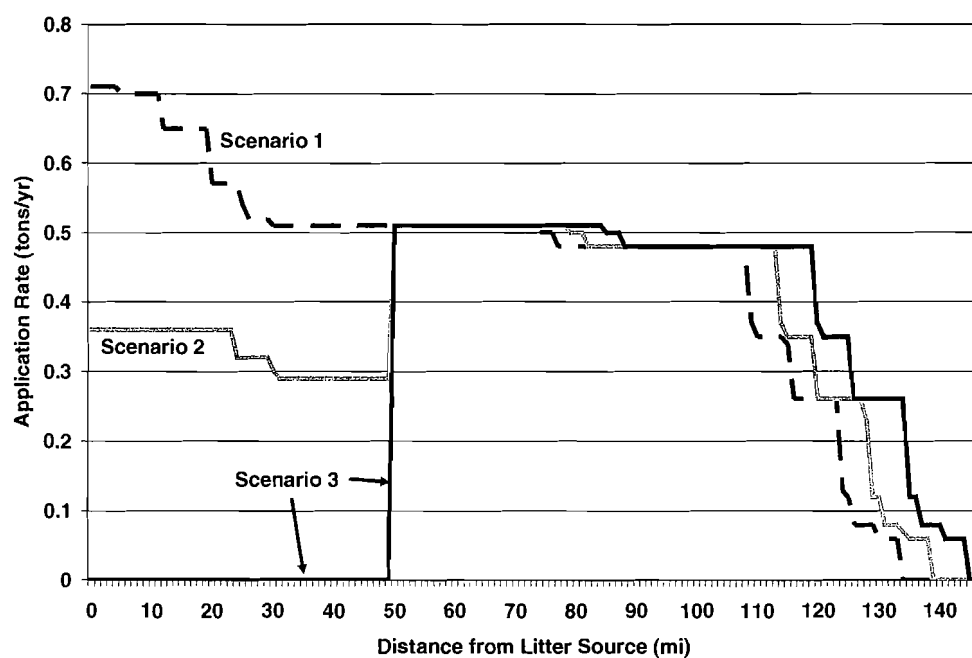


Figure 12. Broiler litter application rate for three levels of soil nutrient buildup, N-rate scenario

As shown by figure 11, as soil P and K increase, more swine slurry is applied at the N-rate, because the foregone value of applying at the N-rate is less than the increased cost needed to haul the slurry farther to capture the nutrient value. By contrast, figure 12 indicates that as soil-supplied P and K increase, less broiler litter is applied at greater than the P-rate (which averages 0.51 tons/acre across crops) close to the litter source; and that greater rates of litter are applied beyond the 50-mile radius of P and K buildup, in order to capture more nutrient value from the litter. Interestingly, while litter application exceeds the P-rate close to the litter source for scenario 1, it never exceeds the P-rate beyond the 50-mile radius of P and K buildup for any scenario. This is because the nutrient value of litter P value must be fully captured in order for the litter to possess a nutrient value greater than its application and hauling costs beyond the area of nutrient buildup.

We conclude that P and K buildup of soils surrounding livestock concentrations will always reduce manure value, will generally substantially increase excess P applications for low-value manures, but may leave excess P applications unchanged (or even reduce them) for high-value manures. Excess P application, however, would increase even for high-value manures if the radius of nutrient buildup was sufficiently large because the hauling cost of leapfrogging to areas of reduced nutrient buildup would at some point exceed the nutrient value of applying manure to this area.

Summary and Conclusions

A behavioral model of manure transportation and application was developed, which minimizes crop fertilization and manure disposal expense, subject to satisfying crop nutrient requirements and environmental constraints. Model output generally illustrated the diseconomies of manure production, i.e., marginal manure values decreased and maximum manure hauling distances increased as manure production increased. Derived synthetic demands for manure indicated that the value of swine slurry and dairy dry scrape (low-value manures) becomes negative at fairly low levels of manure production. Broiler litter and layer manure (high-value manures) were found to be much more valuable than dairy dry scrape and swine slurry, but also required greater hauling distances because of their greater nutrient content. Thus, the size of a concentration of livestock as well as the particular type of manure factor prominently in determining whether manure is a waste or a resource. As simulated manure production increased, the model also simulated increased rates of excess phosphate application, and therefore increased potential for environmental damage.

Buildup of soil P and K, which many livestock regions have experienced due to historical manure application, also significantly affected manure value and utilization. When present at sufficient quantities, soil P and K can supply some or all of crop P and K requirements. Manure value declined in all cases where buildup of soil P and K was simulated. The direction of the effect of soil nutrient buildup on excess P application, however, was not consistent. Excess P application from swine slurry application increased rapidly with increasing soil nutrient buildup, whereas no additional excess P was applied for low levels of broiler production, and less excess P was applied for high levels of broiler production as simulated buildup of soil P and K increased. The reason for these divergent results is that high-value manures are able to profitably leapfrog beyond the areas of high nutrient buildup in order to attain more nutrient value from manure application.

Environmental policies were simulated by imposing constraints on the maximum rate of manure application. Low-value manures were greatly affected by application rate restrictions; each successively tighter restriction caused a reduction in manure value. High-value manures were less affected by the policy restrictions because application rate constraints were often not binding, and therefore often did not affect results. Thus, the cost of moving from an N-rate policy to a P-rate policy was found to be much higher for low-value manures than for high-value manures.

Since the demand for manure nutrients is, to a large extent, predicated on the fraction of land area adopting manure fertilization in the vicinity of the livestock operation, varying the maximum adoption ratio had a significant effect on manure value and utilization. As the maximum adoption ratio increased, manure value increased, hauling distances decreased, excess P application decreased, and the cost of moving from the N-rate to the P-rate decreased for all manure types.

Tightening restrictions on manure utilization will impose costs on livestock operators, often in the form of increased transportation expense and reduced manure value. One way to reduce transportation expense and increase manure value is to increase the percentage of cropland willing to adopt manure for crop fertilization.

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