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Feasibility and Costs of Phosphorus Application Limits on 39 U.S. Swine Operations

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ABSTRACT

Concerns about manure P and water quality have prompted new regulations imposing P limits on land application of manure. Previous research established that P limits increase land needs for animal feeding operations. We evaluated the effect of N, annual P, and rotation P limits on the feasibility of manure management. A mechanistic model characterized manure management practices on 39 swine operations (20 unagitated lagoon and 19 slurry operations) in five states (Iowa, Missouri, North Carolina, Oklahoma, and Pennsylvania). Extensive information collected from each operation was used to determine effects of manure storage type, ownership structure, and application limits on attributes of manure management. Phosphorus limits had substantially greater effect on slurry operations, increasing land needs 250% (0.3 hectares per animal unit [AU]) and time for manure application 24% (2.5 min AU^{-1}) for rotation P limits and 41% (4.4 min AU^{-1}) for annual P limits. Annual P limits were infeasible for current land application equipment on two operations and had the greatest effect on time and costs because they required all but three slurry operations to reduce discharge rate. We recommend implementing rotation P limits (not to exceed crop N need) to minimize time effects, allow most farmers to use their current manure application methods, and allow manure to fulfill crop N and P needs in the year of application. Phosphorus limits increased potential manure value but would require slurry operations to recover at least 61% of manure value through manure sales. Phosphorus limits are likely to shape the U.S. swine industry through differential effects on the various sectors of the swine industry.

ANIMAL PRODUCTION has been a key component of American agricultural production, providing an average $90.5 billion in farm sales or 49% of total farm sales from 1990 through 1999 (USDA National Agricultural Statistics Service, 1999). Swine production accounted for an average of 12% of total farm sales from animal production during this 10-yr period. Negative effects from a poorly designed P-based manure application limit could have substantial economic effect on the U.S. swine sector and U.S. farm economy.

Phosphorus is typically the limiting nutrient in most freshwater aquatic systems (Sharpley et al., 1994). Increasing the quantity of P reaching a stream or lake promotes growth of aquatic flora and fauna. Excessive P will degrade water quality through the process of eutrophication. Negative attributes of eutrophic water bodies include reduced water clarity, excessive algal growth, low oxygen content, altered fisheries, increased filtration costs, and objectionable taste for drinking water sources. In excessively eutrophic waters, waterborne toxins from cyanobacteria may be found.

Mismanagement of fertilizers such as manure increases the quantity of P in runoff from agricultural fields. Increasing soil test P in a field will increase the concentration of P in runoff from the field (Pote et al., 1999; Sharpley et al., 1994). Runoff from fields soon after a surface application of P as chemical fertilizer or manure also results in high P concentrations in runoff (Edwards and Daniel, 1993; Edwards and Daniel, 1994; Shreve et al., 1995).

Manure nutrients have been regulated by the USEPA based on the N content of the manure (USEPA, 2003). Under regulation, manure application rates could not exceed the annual N need of the crop. Many manure sources contain more P and other nutrients than the crop requires when application rates are based on the N requirement of the crop. Soil test P and other soil nutrient tests can increase rapidly when these sources of manure are applied every year based on the N requirement of the crop (Sharpley et al., 1999).

The potential for water quality degradation from mismanagement of manure P has resulted in voluntary and regulatory efforts to include P restrictions on manure application rates for agricultural fields. The NRCS agronomy standard (USDA Natural Resources Conservation Service, 1999) and revised USEPA rules governing confined animal feeding operations (CAFOs) (USEPA, 2003) include provisions that manure be applied based on the P removal rate of the crop. In both standards, P status of the soil is assessed by one of three methods: the P index, the P threshold, or the soil test P level. Manure can be applied every year based on the annual N requirements of the crop to fields with a low or medium rating in accordance with the chosen assessment method. Phosphorus and N limits must be observed on fields with a high rating by the selected assessment method. No manure applications are allowed on fields rated very high.

There are at least two potential strategies for implementing P limits for manure application. Phosphorus rotation is the term we use to describe the practice of applying more P than will be removed by crops or livestock in the year of application and then not applying manure until an equivalent amount of P has been removed from the field by crops or livestock. In an N-based P rotation, manure is applied to the crop based on the N needs of the crop. After a manure application based on N, no additional manure is applied until manure P has been harvested from the field as crops, meat,

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Abbreviations: AU, animal unit; ROA, return on assets.

or milk. An N-based P rotation strategy allows the farmer to apply manure to a field at the same rate as in the past, but will reduce the number of times manure is applied to a specific field.

Alternatively, P could be limited to the annual needs of the crop. In this strategy, crop P removal capacity will be met each year with annual manure applications. However, the manure will frequently provide insufficient N to meet crop needs and additional fertilizer N may be required each year. This strategy requires a farmer to apply manure to a field every year to meet its P removal capacity and may require the additional task of applying commercial fertilizer to meet N needs of the crop.

Confined animals produce 1.1×10^9 kg N and 0.6×10^9 kg P per year usable for crop production (Gollehon et al., 2001). Swine farms produced 11% of this N and 21% of this P. Gollehon et al. (2001) used county aggregate data to estimate that converting from N-based to P-based manure management would increase the number farms needing to apply manure on neighbors' land from 22 to 31%.

Attributes of manure management systems differ among swine farms based on operation size, type of manure management system, region of the U.S., and ownership structure (Boland et al., 1999; Gollehon et al., 2001; Fleming et al., 1998; Lory et al., 2004). Transition from N- to P-based manure management has the potential to affect many aspects of how the farmer manages land application of manure including land needs, equipment needs, cost and value of manure, and time requirement for manure application. Feasibility of the transition from N- to P-based manure application has been assessed for Iowa pig farms (Fleming et al., 1998). Fleming et al. (1998) concluded that slurry operations had the potential to pay for increased costs of accessing more land through the increase in fertilizer value of the manure. Their analysis was based on regional averages for all parameters including availability of land and crop nutrient need.

Understanding how the changing regulatory structure will affect U.S. swine operations requires more detailed information on the feasibility and costs of adopting P limits for manure application. Lazarus and Koehler (2002) considered the implication of applying low manure rates on application time and equipment selection. They evaluated the pricing structure of custom application to compensate for lower application rates and increasing application time. Previous research has not considered the time needed for manure application in terms of the time available for those activities nor has previous research considered the suitability of equipment currently owned by the farmer for P-based manure rates. The potential differential effect on contract versus independent operations also has not been considered. Manure management costs are a much greater percentage of gross income on contract operations (Lory et al., 2004), potentially making them more susceptible to economic hardship associated with adopting P limits.

Our objective in this paper was to evaluate the effect of a P rule on the farm-specific manure management practices of a wide range of U.S. swine farms. We assessed the effect of the P rule on farm-level indicators of feasibility such as the hectares required for manure application, the manure application rate, time required for manure application, and cost and value of manure management. We specifically compared the feasibility of annual P limits, rotational P limits, and N limits.

MATERIALS AND METHODS

Farm visits were conducted to gather data on current manure management on 39 farms in Iowa ($n = 7$), Missouri ($n = 6$), North Carolina ($n = 8$), Oklahoma ($n = 7$), and Pennsylvania ($n = 11$). We visited three additional farms in Oklahoma that had evaporative systems that had never pumped manure. These operations were not included in this analysis. All selected states were in the top 12 in pork production (USDA National Agricultural Statistics Service, 2000) and included at least one state in each of three of the regions responsible for most of the swine production in the USA. The central, mid-Atlantic, and midwest regions had 96% of the swine production in 1999 (USDA National Agricultural Statistics Service, 2000).

We met with representatives of each selected farm and extensively surveyed them about farm characteristics and management of crops, animals, and manure. The survey collected information about the location of the farm; the number, production phase, and size of swine on the farm; water use in the buildings; N, P, and K concentration in the ration; description of the manure handling and storage system including details of the type, size, cost, and age of all manure storages and manure handling equipment; estimates of annual manure volume; manure test results; description of crop rotations including yield goals; location of fields receiving manure; streams, wells, and other sensitive areas near the land application areas; equipment used for manure application; and estimates of the time required for manure application. Farmers were also asked for soil test P levels for each field. All information was not available on all farms. Key attributes of the farms are listed in a companion paper (Lory et al., 2004).

The collected data were used to develop the input and to validate the results of a simulation model used to estimate time requirements, land requirements, and economic indicators associated with manure management. The mechanistic simulation model used contains the following three modules: (i) a manure storage design module and nutrient generation module, (ii) a manure land-application module, and (iii) an economic simulation of swine production module (Massey et al., 2000). A more detailed description of the mechanistic simulation model is in a companion paper (Lory et al., 2004).

The total number of hectares, the hectares in crop production, and the crop hectares suitable for manure application were determined for each farm. Farmers were asked to identify controlled hectares defined as owned or rented fields. Farmers were also asked to identify other farms where they currently apply manure and to identify other fields and farms where they anticipated they could apply manure if they needed more land. Neighboring farms that were designated as potentially receiving manure were also mapped.

Animal units (AU) were calculated as follows: 1 AU equaled 2.5 pigs greater than or equal to 25 kg or 10 pigs less than 25 kg. Details of methods used to estimate manure volume, manure nutrient concentration, crop nutrient need, and prioritization of fields for manure application are presented in Lory et al. (2004).

Fields were prioritized for manure application based on farmer comments, proximity to storage (tanker technology),

or minimizing additional piping requirements (irrigation and dragline technology). Fields within a similar distance to storage were further ordered based on N fertilizer need (e.g., corn preferred over soybean because corn requires fertilizer N whereas soybean has no or limited fertilizer N requirement).

Distribution of nutrients was prioritized to favor controlled land (owned or rented by the operation). When farms needed additional land beyond controlled hectares we applied manure first to neighboring farms identified as being available for manure application by the farmer, then to other nearby farms on the assumption that the farms near the operation would accept the manure. This approach may have underestimated the distance to additional hectares because all neighboring farms may not accept manure. Distances to neighboring farms were determined with a geographic information system. We then assumed that the field layout and size of the farm were similar to the land base of the home farm. This approach also assumes that neighboring farms had similar productivity and density of agricultural land as the modeled farm. We evaluated manure value under two conditions: (i) manure potentially had value only if applied to controlled land and (ii) manure potentially had value on all land receiving manure.

Application rates based on N need were based on the plant-available N content of the manure. Manure plant-available N was estimated by assuming 62% of organic N was available to the crop; availability of ammonium N was assumed to be 60% for surface-applied manure and 100% for injected manure. Manure P and K were assumed to be 100% equivalent to other P and K fertilizer sources. A spreadsheet was developed and used to calculate the manure application rate and distribute manure to prioritized fields until all manure was distributed.

We also evaluated adopting either an annual P-based application strategy or a P rotation strategy. The annual P limit was based on the annual P content of the harvested portion of the crop. The P rotation strategy was based on the N needs of the crop but no further manure could be applied until excess P had been removed by crop harvest. Rotational P application rates were further limited to not exceed 4-yr P removal capacity of the crop rotation. Both the annual and the rotational P strategies resulted in similar amounts of manure and P being applied over a 4-yr period.

Feasibility of calculated application rates was assessed for equipment currently used for manure application. When a P rule required reducing manure application rate we attempted to meet the required rate with the farmer's current equipment with the least effect on application time. The first option for adjusting application rate was to eliminate multiple passes on the same field when they were previously needed for N-based rates. Increasing travel speed was the second option used to reduce manure application rate. The model was constrained by a permissible range of field speeds for each piece of equipment. We assumed maximum travel speed during manure application was 2.2 m s^{-1} (5 mph) for tractor-pulled spreaders and dragline systems and 2.7 m s^{-1} (6 mph) for truck-mounted tankers.

Swath width was considered a fixed characteristic of the injection equipment unless they converted to surface application. Slurry operations were assumed to be able to convert from current injection or surface application swath width to a 12-m (40-ft) surface swath width with no cost to the producer.

The last option for reducing application rate was reducing discharge rate of the manure application equipment. Lowering discharge rate often requires equipment modifications such as installing pinch valves and/or a manifold distribution system. The operation was charged $10 000 for retrofitting existing equipment or purchasing new equipment if discharge rate

had to be lowered to meet the requirements of a P rule on slurry operations. If adjustments in the number of passes across the field, travel speed, swath width, and discharge rate were insufficient to meet the P-based application rate the application rate was considered not to be feasible for that farm.

The USDA Agricultural Statistics Services in each of the five states visited except North Carolina track fieldwork days per week and progress of planting and harvest for grain crops (USDA National Agricultural Statistics Service, 2000). Reports from 1996 to 2001 were used to estimate the number of hours available for manure distribution in spring before planting corn. Preplant season was the number of fieldwork hours after the ground thaws and before the "most active planting season" begins based on 10 h of fieldwork per day.

We evaluated the feasibility of restricting all injected or incorporated manure applications on grain crops to the preplant period in spring. In this analysis only manure irrigation systems (center pivot, traveling gun, and spray field) could apply manure during the growing season. These restrictions are consistent with the intent of the revised rules for concentrated animal feeding operations (USEPA, 2003) that suggest timing of manure applications to periods close to active uptake of nutrients by the crop in humid regions of the USA. Our objective was to evaluate the feasibility of such a restriction on manure applications.

Time for nutrient management planning activities was estimated and included time for soil and manure sampling, getting a nutrient management plan, updating the plan, and record-keeping. For the N limit we assumed soil sampling (for N, P, and K fertilizer) was required according to the respective state-university-recommended sampling intensity. For the P limit, we used the USEPA soil sampling intensity of a 4-ha (10 acre) grid every 3 yr (USEPA, 2001).

Manure application costs were a function of the cost of owning and operating manure management equipment and the number of hours required for manure application (Lory et al., 2004). The economic simulation module estimated revenues and costs associated with pork production (Boessen and Zulovich, 2003). Manure fertilizer value is computed as an income to pork production. No crop revenue is considered in the module.

Manure nutrients were given value if they were needed for crop production (Lazarus and Koehler, 2002; Roka et al., 1995). Nitrogen had value of $0.44 kg^{-1} N when applied to nonlegume crops such as corn and wheat but no value was given to N when applied to legume crops that can fix their own N, such as soybean. Phosphorus and K were valued at $1.40 kg^{-1} P and $0.35 kg^{-1} K, respectively, based on the crop removal capacity of the crop(s) between manure applications. A $12.30 ha^{-1} custom application credit was given any year when manure provided either all of the N or all of the P and K needs of a crop because the manure application replaced a commercial fertilizer application expense. No application credits or fertilizer value were given for P or K if the farmer provided soil tests that indicated soil test levels of P or K were "very high" and no P or K fertilizer is recommended.

The economic indicators of after tax return on assets, net manure value, and manure cost to sales ratio were estimated for each farm. After tax return on assets was used as an estimate of the profitability of pork production and to evaluate the effect of manure management on pork profitability. The net manure value is the fertilizer value of the manure applied less the cost of land application. This indicator was used to evaluate different manure storages and business tenures on farm profitability. The cost to sales ratio was used as a benchmark to measure the importance of manure management on cost control. The USEPA (2003) used cost to sales ratio as

an indicator of feasibility of various policy changes in its analysis of revised regulations for concentrated animal feeding operations.

General linear models and linear regression procedures (SAS Institute, 1987) were used to evaluate the effect of farm attributes on selected indicators of the feasibility of manure management. In the analysis of variance manure storage type and ownership structure were treated as main effects and application limit was treated as a split-plot effect. Least significant difference (LSD) and paired t tests procedures were used for mean separation of main effects. The Tukey–Kramer procedure for multiple comparisons was used for mean separation of interaction terms. Effects were significant if the probability of a greater F statistic was less than or equal to 0.05.

RESULTS AND DISCUSSION

The 39 farms had a mean of 984 AU (range of 120–3200 AU), had an average density of 18.2 AU ha^{-1} (7.4 AU acre^{-1}) of land suitable for manure application and, on average, required 65% of their controlled land for manure application based on N need of the crop. Predominant manure management system was unagitated lagoon on 20 operations and either covered or open pit agitated slurry system on the other 19 operations. Detailed information about farm characteristics and current manure management practices is presented in a companion paper (Lory et al., 2004).

Land Needs

Manure type and application limit significantly affected land requirements for manure application and the interaction of these two effects was significant (Table 1). The significance of application limits was due to differences between N- and P-based management, not differences between the types of P-based management (Table 1). Two operations were not included in the analysis of variance because annual P rates were not feasible (see equipment feasibility for annual P limits). Subsequent comparisons of land needs for N versus P

limits were based on rotational P limits to facilitate comparisons of the 39 operations analyzed.

Changing N limits to P limits would significantly decrease mean animal density on land receiving manure from 49.2 (median = 12.3) to 20.9 (median = 8.9) AU ha^{-1} for these 39 operations ($P < 0.01$). On average, these operations would need 2.8 times the land required for N-based application and 2.0 times their current controlled land base to meet long-term P land needs. Phosphorus limits reduced the number of operations renting or owning sufficient land for all their manure from 82 to 56%. Gollehon et al. (2001) predicted that P-based management would reduce farms controlling sufficient land for manure application from 78 to 69% based on national county aggregated statistics. Operations that controlled sufficient hectares for P-based management increased the percentage of their owned and rented hectares needed for manure application from an average of 28 to 51%.

The significant interaction of manure type and application limit on land needs from manure application was due the greater effect of P limits on slurry operations (Table 1). Rotation P increased land requirement for slurry operations by 3.6 times their current land base but had little effect on lagoon operations. Lagoon operations needed, on average, to apply manure to 0.02 additional ha AU^{-1} (range of 0–0.07) to meet P-based land requirements compared with 0.31 additional ha AU^{-1} (range of 0.12–0.45) on slurry operations. The P limit had no effect on land needs for manure application on 6 of 20 lagoon operations; P limits would not affect these operations because crop demand for P was high and/or manure P concentration was low relative to manure N concentration. All but two lagoon operations (90%) controlled sufficient land to meet P-based land needs compared with only four slurry operations (21%). There was no relationship between slurry operation size (as determined by AU) and the amount of additional

Table 1. Analysis of variance (ANOVA) of the effect of storage type and manure application limit on the number of hectares used for manure application and the time needed for manure application activities.†

		Land used		Land used per animal unit (AU)		Time		Time per animal unit
	n	ha	n	ha AU^{-1}	n	h	n	min AU^{-1}
Lagoon effluent	60	35b	60	0.04b	54	142	54	7.6b
Slurry	51	266a	51	0.35a	51	155	51	12.9a
N-based	37	60b	37	0.07b	35	133c	35	9.0c
Annual P	37	188a	37	0.24a	35	163a	35	11.3a
4-yr P rotation	37	177a	37	0.22a	35	149b	35	10.2b
Lagoon N-based	20	28b	20	0.03c	18	139bcde	18	7.4d
Lagoon annual P	20	37b	20	0.04c	18	145bcde	18	7.8d
Lagoon 4-yr P rotation	20	40b	20	0.04c	18	142bde	18	7.6d
Slurry N-based	17	96b	17	0.13b	17	126de	17	10.6c
Slurry annual P	17	365a	17	0.48a	17	182a	17	15.0a
Slurry 4-yr P rotation	17	337a	17	0.44a	17	156bc	17	13.1b
				ANOVA				
Source of variation	df	$P > F$‡	df	$P > F$	df	$P > F$	df	$P > F$
Manure type (M)	1	<0.01	1	<0.01	1	0.67	1	<0.01
Application limit (A)	2	<0.01	2	<0.01	2	<0.01	2	<0.01
M × A	2	<0.01	2	<0.01	2	<0.01	2	<0.01
r^2		0.90		0.94		0.97		0.96

† Means in the same category and column followed by a different letter are significantly different ($P \leq 0.05$).
‡ Probability of getting a greater F statistic by chance.

land needed per AU for slurry-based operations ($P = 0.74$).

A high percentage of the P excreted by pigs is retained in the solids that settle to the bottom of lagoons and forms a P-rich sludge. This characteristic of lagoon systems allowed them to meet P limits with an average of 38.4 (median = 34.4) AU ha^{-1} compared with 3.0 (median = 2.2) AU ha^{-1} for slurry systems. At some point in the future these lagoons will need to apply sludge to a larger land base. Alternatively, they could be required to agitate periodically, which would result in manure P content and animal density similar to slurry operations. If the 20 lagoon operations, through agitation, needed to drop from 38.4 AU ha^{-1} (unagitated lagoons) to 3.0 AU ha^{-1} (slurry storage) then all but one would need more land than is currently controlled by the operation.

We used the P-removal capacity of the land to estimate land need for a P rule. This is an estimate of long-term land need for P-based manure application. We also assumed that all land currently receiving manure on the operation could continue to receive manure at the P removal capacity. Short-term land needs may be less, as some of the land may not be currently restricted by P needs. In some cases, land needs may be greater if the operation currently applies manure on land where a P rule would prohibit further applications of manure.

Equipment Feasibility for Annual Phosphorus Limits

Annual P limits required reduced manure application rates on 33 of the 39 farms compared with N-based land needs. Annual P limit application rates were feasible with the current equipment used on all operations applying unagitated lagoon effluent with traveling guns or pivot irrigation. Any adjustment in application rate for traveling guns could be met by reducing the number of passes by the irrigation equipment or by increasing the travel speed of the equipment. No lagoon operations would have to change discharge rate or swath width to meet annual P limited rates. Similarly, center pivot operations were mixing freshwater with lagoon effluent for irrigation purposes and making multiple passes. Any lower rates required by annual P limits could be accommodated by reducing the number of passes where lagoon effluent was mixed with the irrigation water.

We anticipate that two of the three operations that used solid-set sprinklers to apply unagitated lagoon effluent would probably change to traveling gun technology to facilitate reaching the added hectares required for a P rule. Application rates for annual P limits were feasible for solid-set sprinklers. Nitrogen-based acreage was relatively small but acreage requirements for an annual P rule increased two- to threefold on these operations. It was much cheaper to adopt traveling gun technology than to purchase more solid-set equipment. The reduced setup time and/or the increased discharge rate of traveling guns also reduced time needed for land application of manure for the added land compared with solid-set technology.

All slurry-based systems needed to reduce application rate to meet annual P limits. Mean minimum application rate required to meet annual P limits on the 19 slurry operations was 11.2 m^3 ha^{-1}, a 77% reduction from N-based minimum rates. We evaluated combinations of three options for obtaining the annual P limit application rate with current equipment: maximizing travel speed, increasing swath width to 12.2 m using surface application, and reducing discharge rate to 25.3 L s^{-1}. Maximizing travel speed (assumed to be 2.2 m s^{-1} for tractors and 2.7 m s^{-1} for trucks) reduced application rates an average of 30% among the 19 slurry operations. This reduction did not meet annual P rates on any operations (Table 2). Farmers currently have incentive to

Table 2. Minimum N-based and annual P-based manure application rate for 19 pig operations using slurry manure systems and the feasibility of selected options for meeting annual P limits.

ID†	Technology	Application rate		Annual P-limit adoption strategies‡				
		N-based	Annual P-based	Travel speed (TS)	Swath width (SW) + TS	Discharge rate (DR) + TS	DR + SW + TS	Infeasible
		m³ ha⁻¹						
IA-N-1	tractor, surface	38.2	9.5				1	
IA-N-2	tractor, surface	39.6	6.5					X
IA-FW-1	tractor, inject	168.7	25.5		1		1	
IA-FF-1	tractor, inject	55.0	9.6				1	
IA-WF-1	tractor, inject	22.4	4.8					X
IA-WF-2	tractor, surface	55.3	11.0				1	
IA-WF-3	tractor, surface	46.3	10.0				1	
MO-FF-1	tractor, inject	34.4	12.1		1		1	
MO-WF-1	dragline, inject	32.3	12.1		1		1	
PA-N-2	truck, surface	38.9	8.6				1	
PA-FW-1	truck, surface	100.7	9.5				1	
PA-FF-1	truck, surface	35.3	9.9				1	
PA-FF-2	tractor, surface	35.3	10.4				1	
PA-FF-3	tractor, surface	39.3	13.4			1	1	
PA-FF-4	truck, surface	39.1	14.7			1	1	
PA-WF-2	tractor, surface	33.2	12.0				1	
PA-FDF-1	truck, surface	36.3	9.5				1	
PA-FDF-2	tractor, surface	44.6	9.6			1	1	
PA-FDF-3	truck, surface	29.6	13.3			1	1	
Total		–	–	0	3	4	17	2

† The first two letters are state abbreviation.
‡ Operations with a 1 were able to meet annual P limits with the specified adoption strategy.

maximize travel speed to maximize discharge rate of manure spreaders thus minimizing application time. This limits their flexibility to lower application rates through increased travel speed.

Only three operations could meet annual P limits without reducing discharge rate. They met annual P limits through a combination of increasing travel speed and converting from injection to surface application (Table 2). Fourteen of the remaining slurry operations could meet annual P limits with reduced discharge rates, increased travel speed, and an increase in swath width (Table 2). Two operations could not meet annual P limits for slurry with any combination of adjustments. Annual P limits were considered infeasible on these operations with currently available equipment.

These results demonstrate that adoption of annual P limits would force farmers managing slurry manure to make substantial changes in their manure application strategies. All farmers injecting manure would need to convert to surface applications. Surface applications contradict other water quality best management practices for manure. Injecting manure reduces odor, maximizes N value of manure, and minimizes manure losses in surface runoff.

Operations where annual limits were infeasible with currently available equipment were characterized as having manure with significantly higher P concentration ($P = 0.06$); P concentration had a mean of 2.6 kg m^{-3} (22 lb 1000 gal^{-1}) P on operations where annual limits were infeasible compared with 1.8 kg m^{-3} (15 lb 1000 gal^{-1}) P on other slurry-based operations. Strategies to reduce P content of manure could mitigate some of the feasibility issues on operations managing slurry manure.

Rotation P limits would allow N-based application rates in the year manure is applied on 33 of the 39 operations. The remaining six operations were all slurry operations that were limited by the 4-yr P application restriction before the N content became limiting. These six operations would need to reduce manure application rate with a rotational P limit. Adjustments in application speed were sufficient to reach rotation P limits on four of these six operations. These farms and farms able to use an N-based rate could continue to apply manure at the same discharge rate and swath width as they are currently using for N-based rates. The remaining two operations could adjust swath width to meet 4-yr P limits. Alternatively, one of these slurry operations could reduce discharge rate to meet rotation P limits; the second operation was already using a low discharge rate so reducing discharge rate did not meet 4-yr P limits.

In summary, rotation P limits would allow all but one operation to continue to use current discharge rate to meet the requirements of a P rule. Injection of manure would still be feasible on most farms and most farmers would not need to invest in retrofitting old equipment or purchasing new equipment to meet the requirements of a P rule.

Time Requirements

Application limit had a significant effect on the time required for manure application and the interaction with manure type was significant (Table 1). Annual P limits required the most time for manure application activities, N limits required the least time, and rotation P limits were intermediate (Table 1). This analysis did not include two slurry operations where annual P limits were infeasible and two lagoon operations where P limits would probably force them to change from a solid set to a traveling gun system.

The significant interaction of manure type with application limit on time required for manure application activities (Table 1) was due to the greater effects of annual- and rotation-P limits on slurry operations. When comparing rotation P and N limits, mean increase in time for manure management activities was 30 h more for rotation P limits on slurry operations. Annual P limits required an additional 26 h on slurry operations compared with rotation P limits. Mean time increase for P limits compared with N limits on lagoon operations was 3.0 h.

Time effects were quite variable on slurry operations. Annual P limits required slurry operations to increase the time spent on manure application activities by 0.5 to 9.8 min AU^{-1} (mean = 4.4, SD = 2.8). Rotation P limits increased time for manure application activities by 0.1 to 6.6 min AU^{-1} (mean = 2.5, SD = 2.1) on the 17 operations where this comparison was appropriate. There was no significant effect of operation size on increased time needs per AU for annual ($P = 0.97$) or rotation P ($P = 0.60$) limits. This implies that for the range of sizes we evaluated, P limits are a size neutral regulation when time is considered the relevant indicator.

Phosphorus limits have the potential to increase the time required for manure application through three mechanisms. Operations that reduced discharge rates require more time to pump manure or empty a tanker during manure application. Operations that need more land may require more time to reach the additional land if that land is further from the manure storage; lagoon operations may need more time for pipeline setup and slurry operations may need more road travel time. Operations that need more land may also require more time for nutrient management planning activities such as soil testing and record keeping. This analysis considers the first two mechanisms: reduced discharge rate and increased travel time.

Operations applying unagitated lagoon effluent never needed to reduce discharge rate to attain annual P rates so the pumping time for emptying the lagoon was unaffected. Fourteen of 20 of lagoon operations did need additional land, and the need for more land was typically small on operations that needed additional land (mean = 16 ha). Time effects of P limits were the increased time to lay pipe to the small number of additional hectares. Consequently, the additional time needed to reach the added hectares was similarly small.

All slurry operations needed more land for P limits and all but three operations needed to reduce discharge rate to meet the requirements of an annual P rule (Table 2). The change in land requirements (Table 1) and the reduction in discharge rate for annual P limits
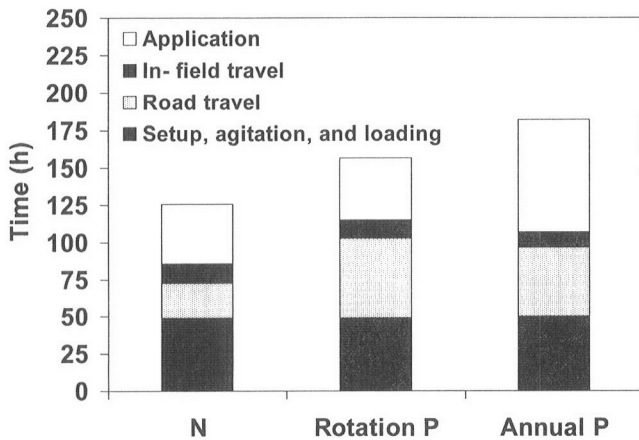
Fig. 1. Contribution of manure application activities to the duration of manure application as affected by manure application limits. Data are the mean of 17 U.S. swine operations managing slurry manure.
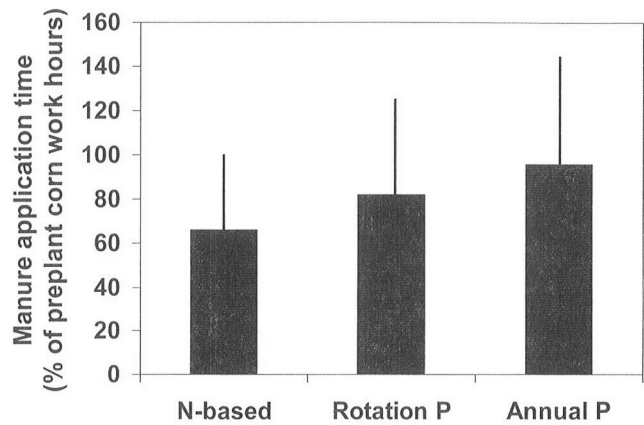

Fig. 2. Time for manure application activities as a percentage of preplant field work hours for corn as affected by manure application limits. Data are the mean of 17 U.S. swine operations managing slurry manure. The line above the treatment mean indicates one standard deviation.

(Table 2) result in the large predicted time effect of annual P limits (Fig. 1). Annual P limits substantially increased road travel time and application time over N limits, whereas the primary effect of rotation P limits was on road travel time (Fig. 1). Rotation P limits had less effect on application time because only one operation had to reduce discharge rate.

Time is often a major constraint for farmers. Regulations for animal feeding operations emphasize timing manure applications to match crop need for nutrients, particularly for N (USEPA, 2003). This would focus manure slurry applications into springtime after soils have thawed and before planting (preplant) for crops such as corn. We assessed regional effects of the increased time for slurry manure application by evaluating the time required for manure application as a percentage of preplant field work days. Times suitable for fieldwork in corn before planting vary significantly among the states (Iowa = 173 h, Missouri = 74 h, Oklahoma = 813 h, and Pennsylvania = 239 h; USDA National Agricultural Statistics Service, 2000).

Phosphorus limits increase the fraction of preplant work hours devoted to manure application on slurry farms (Fig. 2). Time for manure application activities exceeded spring preplant work hours on three operations with N limits, five operations with rotation P limits, and seven operations with annual P limits. There was insufficient time to apply manure as a preplant fertilizer to corn with the current equipment complement on these operations. The lower effect of rotation P limits on application time makes these more feasible than annual P limits.

Several options are available for managing the time pressure of land application of manure. Manure can be applied during the planting season if the farmer postpones planting or has sufficient pieces of equipment to simultaneously plant and apply manure. Operations could reduce time needed for manure application activities by using additional pieces of manure application equipment through purchase, leasing, or contracting with custom applicators. The producer could also change

cropping systems to include fall planted crops such as wheat to provide another window of preplant time. Increased time requirements for P-based manure application also may promote manure application during more marginal conditions such as wet soils or before heavy rainfall events. These options and their added costs were not assessed on this analysis.

The above assessment of manure application time did not include time needed for nutrient management activities such as soil and manure sampling, obtaining a nutrient management plan, and record-keeping activities. We estimated P limits would triple the time required for nutrient management activities from 31 to 101 h annually. The difference between slurry and lagoon operations was 15 h for N limits (24 vs. 39 h). Phosphorus limits increase time for nutrient management planning and record-keeping on lagoon operations to 54 h and on slurry operations to 154 h. This reflects the greater effect of P limits on the land requirements of slurry operations. The actual increase in nutrient management planning time is difficult to gauge because some nutrient management activities were already occurring on cropped land. These activities will represent new responsibilities when the farmer is seeking new land off the farm for manure applications.

Manure Application Costs Associated with a Phosphorus Rule

Annual P rule had the highest average manure application costs (Table 3). The interaction of manure type with application limit was always significant and due to the significant effect of application limit on slurry operations, whereas application limit effects were not significant on lagoon operation costs. On slurry operations the costs of manure application were highest with annual P limits. This analysis did not include the two slurry operations where annual P limits were infeasible and the two lagoon operations where P limits would probably force them to change from a solid set to a traveling gun system.

Manure value was affected by storage type, applica-

Table 3. Analysis of variance (ANOVA) of the effect of storage type and manure application limit on the costs of manure application and value of manure.†

	n	Cost	Cost per animal unit (AU)	Cost per m³	Manure value	Manure value per animal unit	Value per m³
		$	$ AU⁻¹	$ m⁻³	$	$ AU⁻¹	$ m⁻³
Lagoon effluent	54	8 490	8.14b	1.18b	3 663b	2.95b	0.41b
Slurry	51	9 538	14.10a	3.53a	14 400a	9.69a	2.56a
N-based	35	8 324c	10.06b	2.05b	6 700b	7.78c	1.89b
Annual P	35	9 910a	12.45a	2.67a	9 973a	11.61a	2.69a
4-yr P rotation	35	8 764b	10.60b	2.25b	9 962a	11.74a	2.73a
Lagoon N-based	18	8 461b	8.41c	1.20c	3 183c	2.67c	0.38c
Lagoon annual P	18	8 556b	8.18c	1.19c	3 870c	3.19c	0.44c
Lagoon 4-yr P rotation	18	8 454b	7.83c	1.15c	3 938c	3.27c	0.45c
Slurry N-based	17	8 178b	11.81b	2.96b	10 422b	13.19b	3.49b
Slurry annual P	17	11 344a	16.97a	4.21a	16 436a	20.52a	5.06a
Slurry 4-yr P rotation	17	9 092b	13.53b	3.41b	16 342a	20.71a	5.14a
ANOVA							
Source of variation	df	P > F‡	P > F	P > F	P > F	P > F	P > F
Manure type (M)	1	0.61	<0.01	<0.01	<0.01	<0.01	<0.01
Application limit (A)	1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
M × A	2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
r²		0.99	0.93	0.98	0.97	0.97	0.98

† Means in the same category and column followed by a different letter are significantly different ($P \leq 0.05$).
‡ Probability of getting a greater F statistic by chance.

tion limit, and their interaction (Table 3). Phosphorus limits increased the value of manure and manure value was not significantly different for both P strategies. The interaction effect of storage type and application limit on manure value was due to the greater increase in manure value with P limits on slurry operations. Net manure value was positive on slurry operations but not on lagoon operations. The net economic benefit of changing from an N limit to a P limit, defined as the incremental value of manure-supplied nutrients less the incremental cost of application, is positive.

Others have noted that potential manure value increases with P limits and suggested the increase in manure value will offset the cost of P requirements (Gollehon et al., 2001; Boland et al., 1999; Fleming et al., 1998). Potential manure value increases with P limits because this strategy has the potential to maximize the value of manure P and increases manure K value while typically maintaining the N value of the manure.

Significant barriers reduce the ability of farmers to realize the potential value of manure with P limits. Farmers have full control over recovering fertilizer value of the manure on controlled land (owned or rented). Lagoon operations had the potential to extract 99% of the value of their manure on controlled hectares with N limits and that decreased to 95% with rotation P limits. Slurry operations currently control about 78% of the land to which they apply manure and, therefore, could extract 78% of the manure value on controlled hectares with N limits. A P limit would mean applying manure to more uncontrolled land and possibly extracting only 39% of the benefits. To recover fertilizer value, slurry operations will need to convince farmers receiving manure to pay full fertilizer value for manure in addition to allowing the animal feeding operation access to the land for manure application. Paying full value provides the receiving farmer no incentive to use manure nutrients over fertilizer nutrients.

Another barrier to recovering fertilizer value of ma-

nure is that annual P limits do not provide all fertilizer requirements for the crop. Annual P rate provided sufficient N to meet crop needs on only 6 of the 37 operations where annual P limits were feasible. On all other operations, land that receives manure at the annual P rate will require supplemental fertilizer N for nonlegume crops such as corn and wheat. This requires two passes with fertilization equipment every year on both controlled and uncontrolled land that receives manure, one for manure application and one for supplemental fertilizer N. Rotation P limits allow manure to be used to meet the full N requirements of the crop in the year manure is applied plus the P requirements for 1 to 4 yr on most operations. This eliminates the need for any further fertilizer applications on fields that receive manure in years when manure is applied. This makes it easier for farmers selling manure to receive compensation for some of the manure value and reduces the potential for overapplication of fertilizer nutrients on fields receiving manure.

Our analysis may underestimate the cost of accessing more land for manure application on farms that do not control sufficient land for P limits. We assumed that neighboring farms that did not have an animal feeding operation would be willing to accept manure from the animal feeding operation. Competition for land and poor neighbor relations may require operations to travel further to locate additional land for manure application. The uncertainty associated with accessing more land will be much greater for slurry operations than lagoon operations because more slurry operations did not control sufficient land for manure application and the amount of land needed was substantially higher (Table 1).

We evaluated two indicators of the economic impact of P limits on U.S. swine farms. The return on assets (ROA) is a measure of the impact on farm profitability and the cost to sales ratio is a measure of the impact on financial feasibility. Ownership structure (contract versus independent) and application limits had a signifi-

cant effect on ROA and the interaction of storage structure and application limit also was significant (Table 4). Manure nutrient limits did not significantly affect ROA on lagoon operations but differences were significant on slurry operations (Table 4). Our analysis of ROA assumes farmers will obtain full manure value on controlled land.

This reduction in ROA associated with moving from an N limit to a P limit offers additional insight into why farmers currently do not apply manure according to P. While the net economic benefit of changing from an N limit to a P limit is positive, the ROA decreases with the change. Producers can make money on manure management but the return on assets invested in manure management is not as great as for those invested in pig production. Given the choice of investing limited time and financial resources into either pork production or manure nutrient management, they obtain a better return from pork production than from manure management.

The cost to sales ratio was used by the USEPA (2003) in evaluating the feasibility of various regulations of concentrated animal feeding operations. The cost to sales ratio gives an indicator of the relative significance of a particular expense and the degree of risk of associ-

ated with increases in the particular expense. A 20% increase in an expense category that represents 3% of sales is less important than a 20% increase in an expense category that represents 10% of sales. Cost to sales ratios are expected to vary by farm type, so no one indicator of financial stress can be offered for all agricultural enterprises (Farm Financial Standards Council, 1997).

All treatment effects on cost to sales ratio and their interactions were significant (Table 4). Manure management costs were a smaller component of total sales on independent and on lagoon operations (Table 4). The highest cost to sales ratio and the greatest increase in the cost to sales ratio were on contract slurry operations. Annual P limits also significantly increased cost to sales ratio on independent slurry operations ($P = 0.08$). Contract slurry operations are particularly vulnerable to cost increases associated with adopting P limits.

CONCLUSIONS

We recommend implementing proposed P rules using the rotation approach where farmers are allowed to apply manure based on N need and then refrain from further manure applications until excess applied P is removed by subsequent crops. Rotational P limits minimize the time impact of the rule, allow most farmers to use their current manure application methods, and allow manure to provide all crop N and P needs in the year of manure application.

Any P rule will significantly affect some segments of the swine industry. Most vulnerable are slurry operations, particularly contract slurry operations. Rotation P limits doubled cost to sales ratio of manure application activities of contract slurry operations. Slurry operations needed 0.30 ha AU^{-1} additional land for P limits and 79% would need to apply manure on land not controlled by the operation. Fertilizer value of manure could offset manure application costs but 61% of slurry fertilizer value had to be obtained through manure sales at fertilizer value. All of these factors contribute to greater challenges and greater uncertainty facing slurry operations implementing P limits.

Operations that apply unagitated lagoon effluent will typically see little effect from any form of a P rule. However, nearly all lagoon operations had insufficient land for manure application if they were required to agitate lagoons and meet P limits.

The average net manure value of manure applied according to a P limit is greater than the average net manure value of manure applied according to an N limit. Pork producers are still rational in not voluntarily adopting P limits because the additional investment required causes their ROA from pork production to decrease.

This analysis emphasizes that P regulations will not affect all U.S. swine operations equally. Phosphorus limits are likely to shape the U.S. swine industry through differential effects on the various sectors of the swine industry.

Table 4. Analysis of variance (ANOVA) of the effect of storage type, ownership structure (contract vs. independent), and manure application limit on the return on assets (ROA) and cost to sales ratio.†

	n	ROA	Cost to sales ratio
		%	
Lagoon effluent	54	16.1a	2.2b
Slurry	51	11.6b	6.9a
Contract	42	10.3b	8.6b
Independent	63	16.3a	1.8a
Contract lagoon	21	10.7b	4.4b
Contract slurry	33	10.0b	12.9a
Independent lagoon	21	19.6a	0.9b
Independent slurry	30	12.9b	2.8b
N-based	35	14.4a	3.0c
Annual P	35	13.5c	5.7a
4-yr P rotation	35	13.9b	4.9b
Contract lagoon N-based	7	10.8d	4.0de
Contract lagoon annual P	7	10.7d	4.6de
Contract lagoon 4-yr P rotation	7	10.7d	4.6de
Contract slurry N-based	7	11.2d	6.9c
Contract slurry annual P	7	9.0e	17.4a
Contract slurry 4-yr P rotation	7	9.6e	14.3b
Independent lagoon N-based	11	19.6a	0.8g
Independent lagoon annual P	11	19.6a	0.9g
Independent lagoon 4-yr P rotation	11	19.6a	0.8g
Independent slurry N-based	10	13.5bc	1.8efg
Independent slurry annual P	10	12.3c	3.5def
Independent slurry 4-yr P rotation	10	12.8c	3.1def

ANOVA

Source of variation	df	$P > F$‡	$P > F$
Manure type (M)	1	0.07	<0.01
Ownership structure (O)	1	<0.01	<0.01
M × O	1	0.16	<0.01
Application limit (A)	2	<0.01	<0.01
M × A	2	<0.01	<0.01
O × A	2	0.16	<0.01
M × O × A	2	0.19	<0.01
r^2		0.99	0.97

† Means in the same category and column followed by a different letter are significantly different ($P \le 0.05$).
‡ Probability of getting a greater F statistic by chance.

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