Chapter 3
THE FEASIBILITY OF ADOPTING ANNUAL VERSUS ROTATIONAL PHOSPHORUS LIMITS FOR MANURE APPLICATION

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3.2 EXECUTIVE SUMMARY

The proposed EPA rule requires manure applications on phosphorus restricted fields be limited by the annual phosphorus requirements of the crop (annual phosphorus limits) (Federal Register, p 3142). We propose farmers be allowed to continue to apply manure on phosphorus restricted fields at the nitrogen limited rate and then refrain from further applications until subsequent crops use the applied phosphorus (rotational phosphorus limits).

We conclude that rotational phosphorus limits restrict phosphorus applications while allowing the farmer to:

- Rotate fields receiving manure and target crops that need both nitrogen and phosphorus.
- Continue to apply manure at the same rate and with the same equipment currently used for manure application in the years the field receives manure.
- Use manure to meet all fertilizer needs of the crop in the year manure is applied, eliminating the cost and time required to apply fertilizers other than manure to the crop.

We conclude that annual phosphorus limits will:

- Require farmers to reduce the annual, per acre application rate of manure by up to 90%.
- Result in slurry manure application rates that are infeasible with current manure application technologies and equipment.
- Require farmers with solid manure, slurry manure or other concentrated manure sources to invest in modifying existing, or purchasing new, manure application equipment.
- Require farmers with solid manure, slurry manure or other concentrated manure sources to reduce spreading discharge rate, thereby, increasing the time required for application of manure.
- Promote surface application of manure.
- Have the least impact on farms applying manure sources with high nitrogen to phosphorus ratios such as unagitated lagoon effluent.
- Have the largest impact on farmers who apply manure to crops that have high nitrogen to phosphorus ratios such as hay crops.
- Require farmers to apply supplemental nitrogen to all nitrogen-requiring crops that receive manure, thereby eliminating much of the incentive to use manure as a fertilizer.
- Have little water quality benefit compared to the rotational phosphorus limit.

We propose replacing the existing wording in Federal Register, p 3142, 412.37 (a)(2) *i* and *ii* with the following text:

"Multi-year phosphorus applications are permissible as long as they do not exceed the nitrogen limit for the current crop year. The phosphorus store should not exceed 5 years of crop need if there is a high or very high risk of phosphorus loss."

3.3 INTRODUCTION

Phosphorus is typically the most limiting nutrient in most freshwater aquatic systems (Sharpley et al., 1994). Excessive phosphorus entering a stream or lake will promote growth of aquatic flora and fauna and 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, and, in excessively eutrophic waters, water-born toxins from cyanobacteria.

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

Manure nutrients have been regulated based on the nitrogen content of the manure (Compendium of State Regulations published by EPA.). Manure application rates could not exceed the annual nitrogen need of the crop. Many manure sources contain more phosphorus and other nutrients than the crop requires when manure is applied based on the nitrogen requirement of the crop. Soil test phosphorus and other soil nutrient tests can increase rapidly when these sources of manure are applied every year in accordance with the nitrogen requirement of the crop.

The potential for water quality degradation due to mismanagement of manure phosphorus has resulted in voluntary and regulatory efforts to include phosphorus restrictions on manure application rates for agricultural fields. The NRCS agronomy standard (NRCS, 2000), (Federal Register, 01/12/2001), and the proposed EPA rules governing confined animal feeding operations include provisions that manure be applied based on the phosphorus removal rate of the crop. In both standards, the phosphorus status of the soil is assessed by one of three methods: the phosphorus index, the phosphorus threshold or the soil test phosphorus level. Manure can be applied every year based on the annual nitrogen requirements of the crop to fields with a low or medium phosphorous rating according to the chosen assessment method. Phosphorus and nitrogen application limits must both be observed on fields with a high phosphorus rating by the selected assessment method. No manure applications are allowed or recommended on fields rated very high in phosphorus.

3.4 PHOSPHORUS-BASED STRATEGIES FOR MANURE APPLICATION

There are at least two potential strategies for implementing phosphorus limits for manure application. Phosphorus rotation is the term we use to describe the practice of applying more than one year of phosphorus to a soil and then not applying manure until that amount of phosphorus has been harvested from the field by crops, meat or milk. In a nitrogen-based phosphorus rotation approach, manure is applied to the crop based on the nitrogen needs of the crop. A farmer using a nitrogen-based phosphorus rotation strategy will be able to use the same land-application equipment, pumping rates and application speeds as were previously used for nitrogen-based management. A nitrogen-based phosphorus rotation strategy allows the farmer to apply manure to a field at the same rate as in the past, but requires that the frequency of application to a specific field be reduced.

Alternatively, phosphorus could be limited to the annual crop needs of the crop. In this strategy, crop phosphorus removal capacity will be met each year with a manure application, but the manure will frequently provide insufficient nitrogen to meet crop needs. Additional fertilizer nitrogen may be required each year. Many farmers adopting annual phosphorus limits will likely need to reduce manure application rates.

The same number of acres of land will be needed for a manure plan based on the nitrogen-based phosphorus rotation strategy and the annual phosphorus strategy. Every acre in the plan will receive manure every year with an annual phosphorus-based plan. In contrast, a portion of the acres may receive manure in any given year with the nitrogen-based rotational phosphorus approach. Manure applications will be rotated from field to field until all acres receive manure.

Application rate is the gallons or tons per acre of manure that are applied to land. Manure application equipment is calibrated to provide a specific application rate by setting the rate at which the manure is discharged from the applicator, the equipment travel speed and the effective manure application width. Reducing the manure application rate will require increasing travel speed, increasing effective application width and/or reducing discharge rate.

Implementation of annual phosphorus limits may pose economic disadvantages that are not encountered in nitrogen-based phosphorus rotation strategies. When annual phosphorus limits require reducing manure application rates, the time and cost of land application may increase compared to phosphorus rotation strategies. The reduced manure applications rates may also be below those attainable by equipment available on the farm or currently available for purchase.

The NRCS agronomy standard does not specify how limits on the phosphorus applications are to be implemented. The effluent limitation guideline proposed by EPA explicitly prohibits multi-year phosphorus applications to meet phosphorus application limits (“Multi-year phosphorus applications are prohibited when either the P-index is rated high, the soil phosphorus threshold is between ¾ and 2 times the threshold value, or the soil test phosphorus level is high…” Federal Register, p 3142). However, the proposed rule acknowledges that, in at least some cases, annual phosphorus application strategies may be infeasible (“Manure application equipment designed for dry poultry manure or litter cannot obtain an application rate low enough to meet a phosphorus based application rate as determined by the PNP. In the event a phosphorus application occurs during one year which exceeds the crop removal rate for that given year, no additional manure or process water shall be applied to the same land in subsequent years until all applied phosphorus has been removed from the field via harvest and crop removal;…" Federal Register, p 3142).

Our primary objective was to compare the technical feasibility and cost of an annual phosphorus-based application strategy required by the proposed EPA rule to a phosphorus rotation strategy. This chapter does not assess the feasibility or impact of switching from nitrogen-based land requirements to phosphorus-based land requirements. Converting from a nitrogen land base to a phosphorus land base would be similar for both the phosphorus rotation strategy and annual phosphorus limit strategies. The costs and feasibility of converting from nitrogen to phosphorus-based management are evaluated in chapter 2. We instead evaluate the feasibility of two different phosphorus-based application strategies: annual limits and phosphorus rotation.

Our analysis has two parts. First, we assess the feasibility of applying annual phosphorus rates with currently available equipment. This assessment was done by comparing the annual nutrient content of selected crops with land application equipment technical specifications provided by several commercial equipment companies. The second part of the analysis compared the costs of adopting rotational phosphorus and annual phosphorus limits on 50 farms located throughout the U.S.

3.5 MATERIALS AND METHODS

Typical nutrient concentrations for selected crops and types of manure were developed through a literature review (Tables 3-1 and 3-2). Manure was divided into two categories: liquid (slurry and lagoon effluent) and solid. Nutrient concentrations in liquid manure were reported as lbs/1000 gallons and nutrient concentrations in solid manure were reported as lbs/ton.

Plant available nitrogen (PAN) was estimated by assuming 65% of the organic nitrogen (75% for poultry manure) was available to the crop, and 60% (surface applications) or 100% (injected manure) of the NH4-N was available to the current crop.

Manure application rate of selected land application technologies was calculated using the equation:

$$\text{Application Rate} = \frac{\text{discharge rate}}{(\text{travel speed} \times \text{effective swath width})} \times c \qquad \text{Eq. 3-1}$$

where c is a constant to adjust application rate to the units used for the specific manure source. For liquid manures, the application rate was calculated in gallons/acre; for solid manure, it was calculated in tons/acre. The phosphorus rule was assessed based on the assumption that the manure application rate would be limited by the capacity of the harvested crop to remove phosphorus on all land receiving manure.

3.6 RESULTS AND DISCUSSION

3.6.1 Plant and manure factors

Manure and the harvested crop characteristics determine the percent reduction in manure application rate if a farmer converts from a nitrogen-based phosphorus rotation application rate to an annual phosphorus-based application rate. The percent reduction in manure application rate required for a adopting an annual P rule (AP_{RED}) is a function of the $N:P_2O_5$ ratio of both the crop fertilizer need and the manure where:

$$AP_{RED} = \left(1 - \frac{\text{manure PAN} : P_2O_5 \text{ ratio}}{\text{crop fertilizer N} : P_2O_5 \text{ ratio}}\right) \times 100\% \qquad \text{Eq. 3-2}$$

Plant available nitrogen (PAN) is the fraction of the total nitrogen in manure that is available to the crop (Table 3-2).

The impact of annual phosphorus limits on the per acre manure rate is independent of the crop yield (Eq. 3-2). The adjustment of manure rates from nitrogen to annual phosphorus basis is purely a function of nitrogen and phosphorus ratios in the crop (removal in harvested portion of the crop or recommended fertilizer rate) and the manure.

An annual phosphorus limit will result in reduced manure rates when the $N:P_2O_5$ ratio of crops is greater than the $PAN:P_2O_5$ ratio of manure (Eq. 3-2). Harvested crops typically have a $N:P_2O_5$ ratio of 1.8 to 4.5 (Table 3-1). Manure $PAN:P_2O_5$ ratio ranges from 0.5 to almost 4 although most are below 1.5 (Table 3-2). Consequently, on most farms and fields, conversion to an annual phosphorus removal strategy will require lower manure application rates than the current nitrogen-based rates. For example, a farmer converting to an annual phosphorus limit would need to reduce broiler litter application rates to corn grain by up to 67% (using Eq.3-2, (1-(0.75/2.3)X100)).

Crops with the highest fertilizer nitrogen need compared to phosphorus need (highest $N:P_2O_5$ ratios) will be most affected by conversion to an annual phosphorus standard. The harvested components of all crops have a greater fertilizer nitrogen need or nitrogen removal capacity than phosphorus removal capacity ($N:P_2O_5$ ratio > 1; Table 3-1). Soybean, bermuda grass and alfalfa hay had the highest reported $N:P_2O_5$ removal ratios for the harvested portion of the crop (Table 3-1). Crops, with higher phosphorus need compared to nitrogen, and fields, with phosphorus need in excess of crop phosphorus removal rate, will be less affected by conversion to an annual phosphorus removal rate.

Manure types with the lowest $PAN:P_2O_5$ ratio will be more affected by conversion to an annual phosphorus standard. Manure nitrogen available to the crop (PAN), rather than the total nitrogen content of the manure, is the critical component. Consequently, surface applied manure is more affected by conversion to annual phosphorus application rates than injected manure because ammonia nitrogen volatilization losses during surface application of manure reduce the manure PAN:P_2O_5 ratio (Table 3-2).

Table 3-1. Nutrients removed in the harvested portion of selected crop[1].

Crop	Yield unit	N lbs/unit	P_2O_5 lbs/unit	N:P_2O_5 ratio	K_2O lbs/unit
Corn grain	bushels	0.9	0.4	2.3	0.3
Corn silage	Tons	8.4	3.8	2.2	8.9
Soybean	bushels	3.4	0.8	4.3	1.4
Wheat	bushels	1.3	0.7	1.9	0.4
Bermuda grass hay	Tons	49	11	4.5	42
Big bluestem hay	Tons	20	11	1.8	26
Tall Fescue hay	Tons	39	14	2.8	53
Alfalfa hay	Tons	50	12	4.2	50

Note: Values are reported as nitrogen (N), phosphate (P2O5) and potash (K2O).
[1]Sources:
NRCS. 1992. Agricultural waste management handbook. U.S. Department of Agriculture Soil Conservation Service, Washington DC.
Buholtz, D.D. 1992. Soil Test Interpretations and Recommendations Handbook, Department of Agronomy, University of Missouri, Columbia, MO.
Potash Phosphate Institute, Norcross, GA.
Agronomy Guide. The Pennsylvania State University, State College, PA.
North Carolina State University, AG-439-16
General Guide for crop nutrient recommendations. March 1999. Iowa State University, Ames, IA.
Atlas of nutritional data on US and Canadian Feeds. 1971. National Acad. of Sciences, Washington, DC.
Griffith, W.K. and L.S. Murphy. 1996.
Macronutrients in Forage Production. In (R.E. Joost and C.A. Roberts eds.) Nutrient Cycling in Forage Systems. Proc. of a conference held March 7-8, 1996. Columbia, MO.
PPI, Manhattan, KS

Only injected lagoon effluent consistently exceeded some crop N:P_2O_5 ratios. For example, injected lagoon effluent from grow-finish pigs has an PAN:P_2O_5 ratio of 2.0 (Table 3-2) which is greater than the N: P_2O_5 ratio of wheat and bermuda grass and almost as high as corn (Table 3-1). In these situations, nitrogen, not phosphorus, will limit manure application rates.

Adopting annual phosphorus application rates will require reducing manure application rates up to 90% (Fig. 3-1). Manure has a greater range in PAN:P_2O_5 ratios than crop N:P_2O_5 ratios (compare Tables 3-1 and 3-2). Therefore, differences among manure sources, collection systems, storage types and application management cause the greatest range of reductions required when adopting an annual phosphorus application rule. Highest reductions due to annual phosphorus application rate are associated with solid manure such as poultry litter (e.g. up to a 90% reduction when applied to soybean or hay). Reductions needed for surface applications of slurry manure and unagitated lagoon effluent can exceed 80% on the same crops. Annual phosphorus application rate for some injected lagoon effluents will only require a reduction in rate of 10 to 15% on soybean and hay ground.

Table 3-2. Typical nutrient concentration in selected sources of manure[1].

Manure Source	Units	Total N	NH_4-N	P_2O_5	K_2O	$PAN^2:P_2O_5$ Ratio Surface applied	Injected
Pigs							
Grow finish - deep pit	lb/1000 gal	50	33	42	30	0.73	1.04
Grow finish - wet/dry feeder deep pit	lb/1000 gal	75	50	54	40	0.86	1.23
Grow finish - earthen pit	lb/1000 gal	32	24	22	20	0.89	1.33
Farrow-finish pit	lb/1000 gal	28	16	24	23	0.73	0.99
Nursery pit	lb/1000 gal	25	14	19	22	0.82	1.11
Grow-finish unagitated lagoon	lb/1000 gal	4.0	4.0	2.0	3.0	1.20	2.00
Farrow-finish unagitated lagoon	lb/1000 gal	4.5	4.0	2.9	3.6	0.94	1.49
Grow finish - solid	lb/ton	16	6	9	5	1.12	1.39
Farrow finish - solid	lb/ton	14	6	8	5	1.10	1.40
Nursery - solid	lb/ton	13	5	8	4	1.03	1.27
Dairy cows							
Pit	lb/1000 gal	31	6	15	19	1.32	1.48
Unagitated lagoon	lb/1000 gal	4.1	3.6	1.7	2.9	1.46	2.31
Solid	lb/ton	10	2	3	7	2.13	2.40
Beef cows							
Finish - pit	lb/1000 gal	29	8	18	26	1.03	1.20
Finish - solid	lb/ton	11	4	7	11	0.99	1.22
Feedlot solid	lb/ton	24	-	16	3	-	-
Feedlot lagoon sludge	lb/1000 gal	52	-	18	14	1.88	1.88
Poultry							
Broiler litter	lb/ton	71	12	69	47	0.75	0.82
Broiler breeder litter	lb/ton	37	8	58	35	0.46	0.51
Turkey litter	lb/ton	55	12	63	40	0.63	0.70
Turkey breeder litter	lb/ton	35	8	47	18	0.53	0.60
Layer - solid	lb/ton	34	12	51	26	0.46	0.56
Layer - pit	lb/1000 gal	57	37	52	33	0.72	1.00
Layer lagoon liquid	lb/1000 gal	27	23	7.1	42	2.37	3.66
Layer lagoon sludge	lb/1000 gal	84	26	308	40	0.19	0.23
Layer under cage	lb/ton	28	14	32	20	0.59	0.77

Notes: All values are on an "as-is" or wet basis. Plant available nitrogen (PAN) estimates the fertilizer value of manure when surface applied or injected.

[1]Sources:

MWPS. 2000. Manure Characteristics. Midwest Plan Service, 122 Davidson Hall, ISU, Ames IA.

NRAES-132. 1999. Poultry waste management handbook. Natural Resource, Agriculture, and Engineering Service, Ithaca, NY.

NRCS. 1992. Agricultural waste management handbook. U.S. Department of Agriculture Soil Conservation Service, Washington DC.

[2]PAN – Plant Available Nitrogen.

The $N:P_2O_5$ ratios of the harvested portion of crops only vary by a factor of approximately 2 (Table 3-1). Consequently, potential application rate reductions from crop factors are less than those from manure factors. For example, among poultry litter sources, annual phosphorus rates would require a mean reduction in manure application rate from 70% (wheat) to 85% (alfalfa). Similarly, among unagitated swine and dairy lagoon manure sources, annual phosphorus rates would require a mean reduction in manure application rate from 43 to 74% (surface applied) and 8 to 59% (injected), depending on the crop.

In summary, annual phosphorus limits will have the largest impact on manure application rates in crops such as bermuda grass, alfalfa and other hays where the harvested portion of the crop has a high $N:P_2O_5$ ratio. Similarly, annual phosphorus limits will have the largest impact on manure types that have lower $PAN:P_2O_5$ ratios such as poultry litter and other solid manure types. Annual phosphorus rates will result in reductions in manure application rate for most types of manure.

3.6.2 Land application equipment factors

3.6.2.1 Travel speed

This section assesses the feasibility of attaining lower application rates for manure with current land application equipment. Manure application rate is controlled by adjusting travel speed, effective swath width and/or manure discharge rate (Eq. 3-1). Increasing travel speed provides one of two opportunities for reducing land application rate without increasing the time associated with land application. The potential for additional reductions in application rate through increasing travel speed (PR_{TS}) is a function of current travel speed (TS_c) and the travel speed at the minimum application rate (TS_{MAR}) where:

$$PR_{TS}(\%) = \frac{\left(\left(\frac{1}{TS_C}\right) - \left(\frac{1}{TS_{MAR}}\right)\right)}{\left(1/TS_C\right)} \times 100\% \qquad \text{Eq. 3-3}$$

The maximum possible reduction of application rate by adjusting travel speed for each piece of equipment is a function of the minimum and maximum travel speeds possible during land application. Typical minimum and maximum speeds and the associated application rate reduction potentials are reported for selected classes of land application equipment in Table 3-3. These represent the potential application rate reductions possible by increasing travel speed assuming the farmer is currently using the minimum travel speed.

Maximum application speeds are a function of equipment capabilities and safety concerns. Tractor-pulled spreaders have a lower maximum travel speed than truck-mounted spreaders because they have no suspension system. Injection requires lower speeds than surface application because of the greater stress and power requirements associated with pulling an implement through the soil. Traveling at higher speeds increases power requirements of the tractor; doubling the travel speed will more than double the power requirements for land application of manure (ASAE, 1998).

Table 3-3. Minimum and maximum travel speeds for selected types of manure application equipment.

Equipment Type	Travel Speed[1] (Min-Max)		Potential Reduction[2]
Tractor-pulled, injected	1 – 5	miles/hour	80%
Tractor-pulled, surface applied	1 – 6	miles/hour	83%
Truck-mounted, injected	2 – 7	miles/hour	71%
Truck-mounted, surface applied	5 – 15	miles/hour	67%
Traveling gun, water drive	1 – 5	feet/min	80%
Traveling gun, engine drive	1 – 10	feet/min	90%

[1]Travel speed can be varied within range given based on the capabilities of the equipment.
[2]Potential reduction is defined as the percentage reduction possible for application rate by reducing travel speed from the maximum speed to the minimum speed.

Travel speed alone will not provide sufficient reduction in application rate to make the change to annual phosphorus application rates for some methods of land application. For example, truck-mounted surface applications used for poultry litter have the potential to reduce application rates up to 67% through travel speed (Table 3-3) but most annual phosphorus application rates for poultry litter will require reducing application rates by 60 to 90% (Figure 3-1).

The maximum potential reduction in manure application rate attainable by increasing travel speed is typically greater than or equal to reductions in manure application rate needed for annual phosphorus application rates (compare Table 3-3, Figure 3-1). Travel speed has the potential to reduce land application rate of tractor-pulled spreaders by 80 to 83% and traveling guns by 90% (Table 3-3). These reductions are equal to or greater than the reductions needed for most crops receiving manure slurry (Figure 3-1).

The maximum attainable reduction based on equipment capability may not be the maximum achievable reduction for an individual farmer. Unless a farmer is presently traveling at the minimum speed, the maximum achievable reduction cannot be attained. Time incentives typically warrant a producer traveling at greater than the minimum speed.

Farmers seeking to minimize the time required to empty a manure storage structure will maximize the discharge rate of the land application equipment. To maximize the discharge rate, farmers will apply manure to the widest possible swath and travel at the maximum safe speed.

For example, a farmer who has a target application rate of 6,600 gallons/acre will reduce application time by purchasing equipment that has a discharge rate of 800 gallons/minute requiring a travel speed of 4 mph and a swath width of 15 ft compared to selecting equipment with a discharge rate of 400 gallons/minute requiring a travel speed of 2 mph. By increasing target application speed, discharge time is reduced 50% as shown in this example. This incentive makes it likely that manure application is being carried out at higher speeds than the specified minimum rate when there is an opportunity to select higher discharge rates.

We estimated travel speed of land application equipment on 15 farms (17 pieces of equipment) based on farmer reported swath width, discharge rate and/or type of equipment, manure characteristics and crop yield (Table 3-4). For slurry-based systems (tractor-pulled or truck-mounted spreaders), predicted travel speeds were near or at the maximum in 6 of 13 cases. Average travel speed was 4.0 miles/hour for tractor-pulled spreaders and 4.7 miles/hour for truck-mounted slurry spreaders (Table 3-4). This implies that most farmers are currently applying manure at speeds well above the minimum. A farmer using a tractor-pulled spreader traveling at 4.0 miles/hour can further reduce land application rate by 20% using travel speed. This is insufficient for converting to annual phosphorus application rates (Fig. 3-1). Consequently, most farmers applying slurries and solid manure will need to change other application rate variables in addition to travel speed to convert to annual phosphorus application rates.

Table 3-4. Discharge rate, swath width and travel speed used to model land application on U.S. swine farms.

Presentation Code	Discharge Rate (gallons/minute)	Swath Width (feet)	Travel Speed (miles/hour)
Tractor-pulled spreader			
IA-1	600	15	4.9
IA-2	1,000	15	2.8
IA-3	800	15	4.3
IA-4	350	15	4.8
IA-5	650	15	4.9
IA-6	800	30	2.7
MO-2	425	12	4.8
PA-4	1,000	40	2.7
PA-5	800	25	4.5
Mean	714	20	4.0
Truck pulled spreader			
PA-1	725	16	6.8
PA-2	1,000	30	3.3
PA-3	850	20	5.4
PA-6	800	40	3.1
Mean	844	27	4.7
Dragline system			
MO-3	520	15	5.0
MO-4	750	12	1.1
MO-6	650	12	1.6
Mean	640	13	2.6
Box spreader			
IA-3	800	15	4.7

Note: Travel speed was estimated from farmer reported swath width and discharge rate.

We estimated travel speed of three operations using dragline-injection systems. Two of these operations were applying manure while traveling near minimum application speeds. These two operations were applying unagitated lagoon effluent through a network of six-inch pipes. Pumping rate was a function of the pump and limited by specifications (diameter, length, elevation change) of their pipe network. These operations have the potential to meet a phosphorus application through travel speed only. The third operation was traveling at maximum speed while applying pit slurry.

Traveling guns and other irrigation-based manure application systems are unique in that many farmers make multiple passes to meet the target manure application rate. Single pass application rates are often a function of soil infiltration rate, not of crop nutrient need. Under these conditions, the viability of annual phosphorus application rates is difficult to assess using the reduction ratio concept.

Using travel speed to reduce land application rate has the benefits of having no effect on land application time and requires no investment for changes in land application equipment. Operations that cannot fully attain the reduced manure application rates required by annual phosphorus application rates will need to adjust swath width and/or manure discharge rate (Equation 3-1).

3.6.2.2 Swath width

Swath width is the effective width of the manure application pattern and equal to the distance between travel lanes across a field. The impact of swath width on application rate is analogous to travel speed; application rate is inversely related to swath width (Equation 3-1). Changing swath width is the second opportunity to reduce application rate without affecting the amount of time required for land application of manure.

Farmers who use manure injection equipment are resistant to reducing application rate by increasing swath width because it is likely to require purchase of a new, wider application tool bar. A wider injector bar will increase power requirements and may also require a larger tractor for land application. Doubling the width and number of injectors will approximately double the power requirements for the tractor for pulling it through the soil (ASAE, 1998). Maximum swath width of injection equipment may also be limited by road width if the manure application equipment needs to travel on public roads. Increasing swath width also may pose a problem for maneuvering in smaller and irregularly shaped fields. Most injection equipment currently is 8 to 15 feet wide.

Swath width for surface application equipment can be more easily adjusted. For example, poultry litter application trucks can change swath width by adjusting the spinner speed that distributes the manure as it is discharged from the conveyer. A typical range in swath width capabilities for this type of equipment is 20 to 45 feet. Surface applications using a slurry tank can be adjusted with the splash plate. Swath width is not as easily adjusted on box spreaders because they use beater paddles rather than spinners to distribute manure out the back of the spreader. Adjusting swath width is difficult in pivot irrigation systems. Swath width in traveling gun systems is a function of pump pressure and nozzle type.

Typical swath widths for land application equipment range from 8 to 15 feet for injection tool bars to several hundred feet for traveling guns. Potential reduction in application rate from increasing swath width is likely to be less than 50% because of the challenges associated with doubling swath width for most pieces of equipment.

3.6.2.3 Discharge rate

Discharge rate in gallons per minute or tons per minute is the rate at which manure is expelled from the land application equipment. Reducing application rate through discharge rate also directly affects the amount of time required for discharging the volume of manure to be spread (Equation 3-1). Maximizing the discharge rate based on the capabilities of the land application equipment will minimize the application time. Adjusting discharge downwards to reduce application rates has the added cost of increasing the time required to apply a set volume of manure.

The potential for additional reductions in application rate through decreased discharge rate (PR_{DR}) is a function of current discharge rate (DR_c) and the discharge rate at the minimum application rate (DR_{MAR}) where:

$$PR_{DR}(\%) = \frac{(DR_C - DR_{MAR})}{DR_C} \times 100\% \qquad \text{Eq. 3-4}$$

The maximum possible reduction through adjusting discharge rate for each piece of equipment is a function of the minimum and maximum discharge rates possible during land application. Typical minimum and maximum discharge rates and the associated application rate reduction ratios are reported for selected classes of land application equipment in Table 3-5. These represent the potential reductions in discharge rates possible assuming current discharge rate is at the maximum.

Engineering characteristics of specific equipment impact the maximum discharge rate and the ability to adjust discharge rate. Many tanker injection spreaders have a set discharge rate that can only be altered by placing restriction devices in the lines. This method of reducing discharge rate increases the potential for clogging of the lines and may not be recommended by the manufacturer. The potential discharge rate for dragline systems is dependent on the pump and the hydraulic characteristics of the distribution network. Factors such as pump size, pipe diameter, distance from source to applicator and elevation differences all impact the maximum discharge rate and the potential for adjusting discharge rate. Dry litter truck-mounted spreaders typically control discharge rate based on the size of the discharge opening (controlled by an adjustable gate), the speed of the conveyer belt that delivers manure to the opening, and the revolutions per minute of the impeller.

3.6.3 Feasibility of annual phosphorus rates

The total potential reduction in application rate (PR_{TOT}) available to a producer for a specific piece of equipment is a function of potential reduction from increasing travel speed (PR_{TS}), potential reduction from increasing swath width (PR_{SW}) and potential reduction from decreasing discharge rate (PR_{DR}) where:

$$PR_{TOT} = \left(1-\left(\left(1-\frac{PR_{TS}}{100}\right)\times\left(1-\frac{PR_{SW}}{100}\right)\times\left(1-\frac{PR_{DR}}{100}\right)\right)\right)\times 100\% . \qquad \text{Eq. 3-5}$$

All reductions are entered and reported on a percent basis.

3.6.3.1 Slurry with truck or tractor-pulled spreader

Farmers injecting slurry manure with tractor-pulled or truck-mounted spreaders are unlikely to meet the requirements for annual phosphorus application rates using their current equipment. Travel speed often provides limited opportunity to reduce application rate because they often are traveling closer to maximum than minimum travel speed (Table 3-4). Most producers are traveling at the median application speed or faster. This implies PR_{TS} = 0 to 40%. Tankers often have little inherent capacity to adjust discharge rate (Table 3-5); PR_{DR}=0 for many tankers and is unlikely to exceed PR_{DR}=50%. Expanding swath width with injection equipment usually cannot be accomplished without investment in new equipment (PR_{SW}=0). For most producers using a tanker with an adjustable discharge rate, we anticipate PR_{TOT} for their existing equipment will range from 0 to 40%, and 0 to 70%. The best-case scenario (PR_{TOT}=70%) is sufficient if the farmer applies slurry manure to corn, corn silage and wheat land; however, this potential reduction in application rate is likely to be insufficient for soybean and hay crops. This scenario assumes use of the current tractor, although doubling travel speed more than doubles power requirements. All other scenarios require investment to modify or purchase equipment needed for adoption of an annual phosphorus application rate.

Table 3-5. Discharge rates and reduction ratios for an application rate while changing discharge rate from moving from the maximum to minimum.

Equipment Type	Units	Common Discharge Rates (min-max)	Reduction Potential	Comments
Tankers (Tractor-pulled & truck-mounted)	gallons/ minute	530, 650, 800, 1000, 1300, 1700	0 to 50%	Pump speed fixed by PTO resulting in fixed discharge rate. Rates can be reduced using restrictors to other fixed rates. May not be recommended by manufacturer. May increase plugging from fibrous materials.
Dragline & Traveling gun	gallons/ minute	300 - 1000 200 – 800, 100 – 300	70% 75% 66%	Maximum: function of pump capacity and pipe network. Discharge rate adjusted through orifice restrictors or, in some cases, pump rpm.
Truck-mounted litter	tons/ hour	15 - 100	85%	Discharge rate: a function of belt speed and gate opening.

In many cases, annual phosphorus application rates may be difficult to attain or technically infeasible, even with the purchase of new equipment. A farmer who currently injects slurry manure at the median travel speed (PR_{TS}=40%) must increase travel speed, double swath width and halve discharge rate to attain annual phosphorus rates for soybean and hay crops (PR_{TOT}=85%). The farmer will need to invest in a new injection tool bar and will probably need new metering equipment to control the discharge rate of manure from the tanker. A more powerful tractor will be needed because power requirements are estimated to increase by a factor of four for this land application scenario.

All three modifications are required to make the annual phosphorus application rate feasible in the example above. Failure of any modification will result in failure to meet the limit. Many farmers already are applying manure near the maximum travel speed and will be unable to capture any appreciable travel speed reduction. Others farmers will not be able to expand swath width because of an existing wide injection tool bar, restrictions on allowable road width or field maneuverability problems.

Farmers who surface-apply slurry manure from a tractor-pulled or truck-mounted spreader will have the same challenges adopting an annual phosphorus rule as farmers injecting manure. The reductions needed for surface applied manure are greater than those needed for injecting manure (Figure 3-1). Significant increases in swath width may be difficult because farmers already have an incentive to use a wide swath width for surface applications. They face the same challenges as farmers injecting manure for altering travel speed and discharge rate.

Some farmers who are currently injecting slurry manure may choose to adopt surface application techniques. Transitioning from injection to surface application would provide opportunities to reduce the application rate through increased travel speed and swath width. Travel speed can be greater for surface application equipment (Table 3-3) so farmers who are injecting manure at the highest possible speed could obtain a 17% additional application rate reduction from travel speed by moving from the maximum speed for injection to the maximum speed for surface application. Converting from an injection swath width to a surface application swath width also provides an opportunity to at least double swath width.

3.6.3.2 Solid manure with truck-mounted spreaders

Farmers surface applying solid manure using a truck-mounted spreaders may be able to meet the requirements for annual phosphorus application rates using their current equipment by adjusting all three application rate variables. Travel speed alone will provide insufficient opportunity to reduce application rate (Table 3-5) and, as with slurry spreaders, farmers are likely to be traveling closer to maximum than minimum travel speed. If applicators are traveling at the median application speed or faster, PR_{TS} = 0 to 33%. Poultry litter applicators have a large capacity to adjust discharge rate (PR_{DR}=85%, Table 3-5). Litter applicators have an incentive to use the highest possible discharge rate so most farmers will have most of the potential discharge rate reduction available. Lower discharge rates have the liability of greater potential for bridging and clogging, in addition to increased application time compared to standard application rates. Swath width is unlikely to provide much opportunity for reducing application rates because applicators have incentives to use the widest swath width that is technically feasible (PR_{SW}=0). For most producers applying solid manure with truck spreaders we anticipate PR_{TOT} for their existing equipment will approach 90% ((1-((1-0.33)X(1-0.85)X(1-0))X100% from Equation 3-4). However, many crops receiving solid manure require nearly a 90% reduction in application rate (Figure 3-1). Under a best case scenario there is sufficient reduction potential available to the applicator. But if the travel speed is near maximum for the application equipment or, if more stringent discharge rate limits are imposed, the annual phosphorus application rate will be infeasible.

3.6.3.3 Lagoon effluent with irrigation equipment

Farmers land applying lagoon effluent with irrigation equipment (e.g. traveling gun) or dragline systems should be able to attain annual phosphorus rates. The needed reductions are lower for lagoon effluent than for slurry and solid manures (Figure 3-1). At one extreme, nitrogen, not phosphorus controls injected lagoon effluent rate on corn. Either travel speed (Table 3-3) or discharge rate (Table 3-5) can provide sufficient reduction potential to meet annual phosphorus application rates.

Many lagoon effluent distribution systems have limited discharge capacities because of pump, distance, elevation and pipe diameter limitations. Consequently, operators of dragline injection systems must reduce application speed to attain desired discharge rates. They are often traveling at the minimum travel speed (Table 3-4), so they can often attain annual phosphorus rates through increasing travel speed. Traveling guns frequently limit single pass manure rates to soil infiltration rates. Infiltration rate limits require multiple passes with a traveling gun to reach the nitrogen or phosphorus banking effluent application rate. Infiltration limits have thus forced producers to use equipment that is more compatible with an annual phosphorus application rate.

In summary, producers applying anaerobic lagoon effluent can probably achieve annual phosphorus application rates by using irrigation equipment or dragline systems. Applicators using tractor-mounted spreaders to surface apply solid manure are likely to attain annual phosphorus application rates by reducing manure discharge rates. Manure applicators who surface apply litter at travel speeds close to the maximum for their equipment are the most likely to be unable to attain annual phosphorus rates. Most farmers who land apply slurry manure will need to invest in new equipment and will realize an increase in land application time to attain an annual phosphorus application rate.

3.6.4 Time Effects

3.6.4.1 Tractor-pulled and truck-mounted spreaders

Total time needed for land application of manure with tractor-pulled and truck-mounted spreaders (T_{TOT}) is a function of loading time (LT), road travel time to the field (TT_R), in-field travel time to the point where application begins and after application ceases (TT_F), and discharge time (DT) where:

$$T_{TOT} = LT + TT_R + TT_F + DT \qquad \text{Eq. 3-6}$$

Transitioning from a nitrogen-based phosphorus rotation to an annual phosphorus limit will only significantly affect DT of the four variables included in T_{TOT}. Annual phosphorus limits frequently require reducing discharge rate with a corresponding increase in DT (see section 3.5.3).

The same numbers of loads of manure are hauled with the annual phosphorus and nitrogen-based phosphorus rotation strategies so there is no effect on LT. There will be little difference in TT_R between the two approaches to phosphorus limitations. The same number of acres receives manure under both phosphorus strategies. The annual phosphorus strategy requires visiting all fields every year. The nitrogen-based phosphorus rule allows manure application to a fraction of the fields in a given year; however, those fields will require more trips to supply manure nutrients needed in the year of application. Over the course of the manure rotation all fields will receive the same amount of manure and the same number of trips. Consequently, on average over time, TT_R for the two phosphorus strategies will be the same. With the nitrogen-based phosphorus rotation rule, some years TT_R may be lower if application is predominantly close to the manure storage. These years will be offset by years with higher than average TT_R when the manure application area is predominantly on fields further from the manure storage system.

There is likely to be little difference between the two approaches to phosphorus limits on TT_F. Every load of manure will need to be transported from the road to the starting point for manure application in both approaches.

3.6.4.2 Irrigation-based systems

Total time needed for land application of manure (T_{TOT}) for traveling guns and dragline systems that use an irrigation piping network to transport manure is a function of irrigation network setup time (INST), between pull setup time (BPST) and discharge time (DT) where:

$$T_{TOT} = INST + BPST + DT \qquad \text{Eq. 3-7}$$

Many operators will do much of the work associated with INST while manure is being applied at another location to reduce the duration of manure application activities. This does not reduce the total man-hours required to accomplish the task.

There are potential effects of converting to an annual phosphorus limit from a nitrogen-based phosphorus rotation limit on all three variables of T_{TOT}. A prerequisite for time differential time effects among the two phosphorus strategies is that the annual phosphorus rule will usually decrease the per acre manure application rate and increase the number of acres needed for manure application compared to the nitrogen-based phosphorus rotation limits. This is not always the case (see section 3.5.1).

The nitrogen-based phosphorus limit will allow the irrigation network to be assembled to deliver effluent to the subset of fields scheduled to receiving manure in that year. The annual phosphorus limit will require the farmer to setup the irrigation network to all fields in all years. Requiring annual phosphorus limits will likely increase INST because more extensive irrigation networks must be setup every year.

With nitrogen-based phosphorus rotation application rates, fewer acres are irrigated each year, requiring fewer set-ups and reducing BPST. The annual phosphorus limit would require irrigation of all fields maximizing the time required for BPST.

Operations that need to decrease discharge rate to meet annual phosphorus rates will increase DT. Existing irrigation operations applying unagitated lagoon effluent will meet phosphorus application requirements through increased travel speed and/or fewer passes through the field (section 3.5.3). These irrigators will not need to reduce discharge rate to achieve an annual phosphorus application limit. If an annual phosphorus application limit is implemented, operations using traveling gun irrigation will experience an increase in T_{TOT} because both INST and BPST will increase. This contrasts with T_{TOT} increases for road-based systems such as tractor-pulled tanks and truck-mounted applicators where the impact of annual limits is primarily due to changes in discharge rate. This analysis assumes manure is currently being applied with the assumption that the nitrogen requirements of the crop and manure characteristics remain constant among options.

3.6.5 Fertilization Effects

One value of manure is the compete elimination of commercial fertilizer need in the year of manure application. In contrast, annual phosphorus limits ensure that supplemental commercial fertilizer will need to be applied on most acres receiving manure. The nitrogen-based phosphorus rotation limit allows the farmer to meet the nitrogen need of the crop receiving manure in the year manure is applied. Annual phosphorus limits typically reduce manure application rate below the crop nitrogen need (section 3.5.1). Supplemental nitrogen must be applied on all non-legume crop acres receiving manure with an annual phosphorus limit. The need to apply supplemental nitrogen fertilizer increases the cost and time required for crop production if annual phosphorus application limits are implemented. An additional field operation to apply nitrogen on all fields requiring supplemental nitrogen must be performed. This will increase application time (to apply supplemental fertilizer), fuel use, equipment requirements and costs to implement annual phosphorus limits.

Implementing annual phosphorus limits makes it more difficult to extract the nitrogen value from the manure. The nitrogen-based phosphorus rotation allows the farmer to apply manure on phases of the rotation that have a nitrogen need and then not apply manure in years when there is no fertilizer nitrogen need. For example, manure could be applied only to the corn phase of a corn-soybean rotation with a nitrogen-based phosphorus rotation. In the year manure is applied it would supply all the nitrogen needed for corn production and also the phosphorus requirement of the soybeans to be produced the following year. Applying manure to comply with an annual phosphorus limit requires the producer to apply manure to all acres every year. Manure applied to soybeans provides no nitrogen value to the crop. The operation could double its land base to ensure it has sufficient acres to apply manure only to corn at the annual phosphorus rate. No production incentive exists for this approach because the manure will not provide sufficient nitrogen for the corn crop when applied at the annual phosphorus limit.

3.6.6 Water quality effects

Long-term manure application is not dependent on whether a nitrogen-based phosphorus rotation or an annual phosphorus limit strategy is implemented. The difference is that smaller rates of manure are applied to every acre each year with the annual phosphorus limit whereas larger manure application rates are applied less frequently with the phosphorus rotation strategy.

Manure and other surface-applied fertilizer sources initially cause high concentrations in runoff if rainfall occurs soon after application (Edwards and Daniel, 1994; Shreve et al., 1995). Within days the phosphorus reacts with the soil and becomes less vulnerable for loss as water-soluble phosphorus. Injected phosphorus also rapidly reacts with the soil. Factors affecting the reaction rate of phosphorus with soil include temperature and soil type (Barrow, 1986).

The concentration of phosphorus in runoff soon after a surface application of manure is linearly related to the rate of application (e.g. Edwards and Daniels, 1993). Any increase in the amount of manure applied to a field will result in a similar increase in phosphorus concentration in runoff from the field until the phosphorus attaches to the soil.

As a consequence of the linear nature of this relationship, there is little difference in the water quality impact of an annual phosphorus limit versus a nitrogen-based phosphorus rotation limit. For example, if under the annual phosphorus limit, every acre in the watershed would receive phosphorus, when runoff occurred all acres would lose phosphorus in the runoff water. In the nitrogen-based phosphorus rotation, a proportion of the acres would receive manure each year, for example 50%. Runoff concentrations from those acres receiving manure would be double those observed with the annual phosphorus rule but the losses would only be from 50% of the watershed. No difference in phosphorus load to the watershed would exist between the two approaches for the same runoff event.

3.6.7 Summary

Two potential approaches exist for implementing a phosphorus rule. The annual phosphorus limit approach proposed by the USEPA would require the producer to limit manure application rate to the current crop requirement for phosphorus. Alternatively, a nitrogen-based phosphorus rotation approach would permit manure to be applied to meet the nitrogen needs of the crop. Manure would not be applied until subsequent crops utilized the excess phosphorus from the original manure application.

Annual phosphorus limits will force farmers to reduce manure application rates in the year they apply manure for almost all cropping systems and manure types (section 3.5.1). This reduction in application rate will frequently require reducing discharge rates from the manure application equipment, particularly with solid and slurry type manures (section 3.5.2). In some cases, implementing annual phosphorus limits will require the producer to modify existing equipment or purchase new equipment to attain the reduced manure rates (section 3.5.3). Achieving annual phosphorus limit rates with slurry manure may not be feasible with currently available application equipment (section 3.5.3).

Annual phosphorus limits will frequently increase the time required for manure application (section 3.5.4) by mandating that producers reduce discharge rates (which increase discharge time) with road-based systems such as tractor-pulled tankers and truck-mounted spreaders. Land application time is increased for traveling gun and dragline manure application systems because setup time increases as all acres must be irrigated each year to comply with an annual phosphorous limits approach. Time requirements can also be affected by reduced discharge rates in irrigation systems.

Applying manure to achieve annual phosphorus limits also reduces the value of manure to the farmer (section 3.5.5). Annual phosphorus limits compel farmers to use manure as an incomplete fertilizer; non-legume crops receiving manure applied at annual phosphorus rates will require supplemental nitrogen fertilizer in addition to the manure supplied nutrients. This limits the value of manure because the farmer must perform additional field operations on those fields receiving manure to supply supplemental nitrogen.

The two approaches to phosphorus limits will have little difference in their impact on the phosphorus load reaching surface water bodies (section 3.5.6). With annual phosphorus limits, smaller amounts of phosphorus may be lost from more acres; nitrogen-based phosphorus rotations may allow larger amounts of phosphorus to be lost from fewer acres. The estimated total phosphorus loss from a watershed implementing an annual phosphorus limit rule or nitrogen-based phosphorus rotation rule over an extended period of time is expected to be insignificant.

3.6.8 Conclusion

We propose replacing the existing wording in Federal Register, p 3142, 412.37 (a)(2) *i* and *ii* with the following text:

“Multi-year phosphorus applications are permissible as long as they do not exceed the nitrogen limit for the current crop year. The phosphorus store should not exceed 5 years of crop need if there is a high or very high risk of phosphorus loss.”

3.7 REFERENCES

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3.8 FIGURES

Figures for Chapter 3 are on the following pages.

Figure 3-1. The percent reduction in manure application rate required if adopting an annual phosphorus rate for manure application for selected crops and manure sources. Values of 0% will continue to be restricted by nitrogen limits.