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# Are Phosphorus-Based Applications of Livestock Manure Environmentally Friendly?

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**Are Phosphorus-Based Applications of Livestock Manure Environmentally Friendly?**

Crop production typically entails applications of nitrogen, phosphorus, and potassium through chemical fertilizer or livestock manure. Regardless of the nutrient source, more nutrients must be applied than the crop can take up. This is because one portion of nutrients is said to be "plant available nutrients" while the other portion is "not plant available." The plant available portion can be applied to crops and harvested. Nutrients that are not plant available are either not in the proper chemical form for crop uptake, or leave the area they were applied via leaching or runoff (henceforth, runoff). Excess nutrients (nutrients applied to the crop but not harvested) can potentially leave the field, enter surface waters, and pollute waters through eutrophication.

Eutrophication is the process by which nutrient loadings to surface waters lead to large algae populations. When the algae die they sink to feed greater populations of bacteria. The large algae and bacteria populations eventually consume all available oxygen, thereby killing most of the aquatic life. Algae, like all life forms, require both nitrogen and phosphorus for growth, so water pollution is a function of nitrogen and phosphorus water loadings. If waters contain plentiful phosphorus but little nitrogen, nitrogen is said to be the limiting nutrient. This means that additional nitrogen loadings will cause more pollution, but additional phosphorus will not.

For some waters, nitrogen is the limiting nutrient and water pollution policies only manage nitrogen loads. In the North Carolina (NC) Neuse River Basin, proposed regulations would require each county to reduce their nitrogen loadings by choosing among various best management practices; such as conservation tillage, controlled drainage, and filter strips (Schwabe 1996; 2001). No phosphorus restrictions would be imposed.

In other waters, phosphorus is the limiting nutrient. In the 1960's, Lake Erie was deemed a dead lake. Investigation found Lake Erie and 10,000 other U.S. lakes suffered from high phosphorus loadings. Regulations banning phosphate-based detergents and upgrading waste treatment plants later restored some health to these waters (USGS 1999). As a rule-of-thumb, phosphorus tends to be a problem in upstream and fresh waters, while nitrogen is a larger problem in downstream, brackish, and salty waters. The reason is that phosphorus tends to settle upstream, while nitrogen is water-soluble and moves easily with the current.

Applications of livestock manure can contribute to water pollution through nitrogen and phosphorus runoff, but historically only nitrogen runoff received much attention. Most regulations require manure to be applied on a nitrogen-basis. This means that manure should be applied such that all plant-available-nitrogen is harvested. Nitrogen-based applications are sometimes deemed an environmentally sound practice because all the nitrogen that can be harvested from the field is harvested. This minimizes excess nitrogen, and thus nitrogen runoff. Excess phosphorus is not minimized though. This is because the ratio of nitrogen to phosphorus in manure is lower than plant uptake, leaving some phosphorus that could be harvested free to become runoff.

Recent proposed federal and state regulations have sought to minimize excess phosphorus applied to land. The EPA, in its proposed CAFO rules, would require large confined operations to apply manure on a phosphorus-basis instead of a nitrogen-basis. Moreover, National Resource and Conservation Service (NRCS) standards now require manure applications to consider excess phosphorus and potential phosphorus runoff (NRCS 2002). These standards require a phosphorus index for each farm to be created where a higher index value refers to higher potential phosphorus runoff.

For low index values, manure applications can be nitrogen-based. For higher values, manure must be applied on a phosphorus-basis. Very high index values imply no manure may be applied. Some states, such as North Carolina, require concentrated livestock facilities to follow these standards, essentially making them regulations. Currently, the new NRCS standards are expected to affect only 5-10% of NC swine farms, but if manure continues to be applied on a nitrogen-basis it will affect many more (Gilliam).

Many applaud the new phosphorus standards as an environmentally friendly practice. Across environmental groups and scientists, it has been taken for granted that phosphorus-based applications (PBA's) are environmentally superior to nitrogen-based applications. This study questions the conventional wisdom that PBA's of manure are environmentally friendly. True, on a *per acre* basis switching from nitrogen- to phosphorus-based manure applications usually reduces nutrient runoff. However, water pollution is a function of nutrients applied to *all acres*, and depends on the crop planted as well.

This paper argues that for swine manure in NC, PBA's will reduce phosphorus runoff but will increase nitrogen runoff. This argument extends to a lesser degree towards poultry manure. This is because more nitrogen (chemical and manure) will be applied under PBA regulations, and roughly half of all nitrogen is not crop-absorbed. While lower phosphorus runoff may enhance water quality, higher nitrogen runoff detracts from water quality. Thus, PBA's are not necessarily environmentally friendly practices.

The next section briefly describes a water quality model for Duplin and Sampson counties in the Cape Fear River Basin of North Carolina. The model tracks nutrients from the farm to three points within the basin. The third section simulates several farm responses to regulations requiring phosphorus based applications. The model illustrates the possibility that PBA's may reduce water quality. Though the authors believe in most cases PBA's will enhance water quality, this paper shows that whether PBA's are environmentally friendly is a question worth asking before costly regulations are set.

**Linking Swine Manure Applications and Water Quality in the Cape Fear River Basin**

As indicated in previous sections, this study questions conventional wisdom that phosphorus-based applications (PBA's) of livestock manure are always environmentally friendly. Though PBA's will reduce water pollution in most regions, it will not necessarily in all regions. Advocates of PBA's may have overlooked the fact that water pollution depends on nutrient runoff from all acres, not nutrient runoff on a per acre basis. This paper develops a model simulating farmer responses to PBA requirements in two North Carolina counties and estimates the impact on local waters. The simulations illustration that, under certain conditions, PBA's could cause an increase in water pollution. This section describes the simulation model.

Swine farms in NC can be grouped according to whether land constraints exist. It is believed that approximately 30% of farms are not land constrained, meaning there is ample cropland bordering the farm. These farms tend to apply lagoon effluent to row-crops. Should PBA's be implemented, these farms may extend their sprayfield to more row-crops or convert some row-crops to forages. If extended to row-crops, more nitrogen would be applied to soybeans than before. Since soybeans do not require nitrogen applications but will uptake nitrogen if provided, and roughly half of all nitrogen is not harvested, greater nitrogen runoff would ensue. Manure nitrogen is not substituted for chemical nitrogen because no chemical nitrogen was applied. The conversion of row-crops to forages will also require the import of more chemical nitrogen, leading to greater nitrogen runoff.

The other 70% of farms are land constrained, and have little land bordering the farm. To fully dispose of all the lagoon effluent nutrients, these farmers usually plant forages, due to their high nutrient uptake. Acres in forages have become so numerous that producers in concentrated areas rarely receive a positive price for hay. These farmers have indicated that the additional acres needed for PBA's would sometimes be obtained by clearing bordering woodlands and planting forages. New forage acres requires more chemical nitrogen which must lead to greater nitrogen runoff. If this is not an option, hog production may have to decrease until the current sprayfield acres are sufficient. A fall in hog production will lead to less nitrogen runoff. But notice the lower nitrogen runoff is not because PBA's are environmentally friendly, but because hog production is essentially taxed. If hog production levels remain the same after the introduction of PBA's, barring technological change, greater nitrogen runoff must result. If hog production falls due to greater manure disposal costs, that leads to less nitrogen runoff. The point is that the lower phosphorus runoff due to PBA's could correspond with a higher nitrogen runoff. It is possible this greater nitrogen runoff will increase water pollution, despite the lower phosphorus runoff.

Figure 1. shows the proximity of the Cape Fear River Basin in North Carolina, along with the hog farms in the basin. Notice virtually all the hogs are located in two counties: Duplin and Sampson. These are the top two counties in terms of hog and pig inventories, litters farrowed, and feeder pigs sold compared to all other U.S. counties. North Carolina is the second largest state in terms of inventory and the first largest in terms of feeder pigs sold, and over half of all NC hogs are in these two counties (NASS).

Only in the last decade has NC become a dominant hog state. The hog population has more than doubled since 1992, yet the hog industry and basin surface waters have existed peacefully. Waters directly downstream from Sampson and Duplin counties are among the purest in the state, with very little nutrient water loadings attributable to land applications of swine waste (University of North Carolina at Wilmington). However, concern still exists for the potential for water pollution, especially since a decade of nitrogen-based applications has caused a [sometimes enormous] buildup of phosphorus in sprayfields. Plus, these two counties do not have enough cropland to fully assimilate all nutrients produced by livestock, leading many to wonder where the excess is going (Kellogg et al.).

This paper simulates several responses to PBA regulations and estimates the impact to each three water sites in Figure 1. The Duplin and Sampson Water Sites are chosen because they are located within and slightly downstream from concentrated hog populations. Only excess nutrients from Duplin (Sampson) county are assumed able to reach the Duplin (Sampson) Water Site. The Estuary Site is chosen as a downstream recipient of nutrients reaching the Duplin and Sampson sites.

Not all excess nutrients applied to crops are transported to surface waters and become pollutants. One portion will remain on the field, decay, or volatize. The other portion will reach the field-edge. Nitrogen, being water-soluble, leaves the field primarily through subsoil leaching. Soils with a higher permeability carry more nitrogen to the field-edge. Soils in both counties are similar and highly permeable. Based on soil data and previous research relating soil permeability to nitrogen leaching, 90% of all excess nitrogen in Sampson and Duplin counties is assumed to reach the field-edge (Schwabe 1996; Gilliam; NCSU). This coefficient will be referred to in a subsequent equation as the nitrogen-edge-of-field delivery coefficient (NEOFDC).

Phosphorus is generally not water-soluble, but binds to soil particles. Thus, phosphorus reaches the field-edge primarily through soil erosion. Erosion potential is measured by the Universal Soil Loss Equation, which takes into account soil types, rainfall, tillage practices, and crop types. This equation was calculated for Sampson and Duplin counties separately for forages and row-crops. Since cropland in both counties is relatively flat, there is little erosion and only a small portion of excess phosphorus reaches the field-edge. Less phosphorus is transported with forages than row-crops because no tillage takes place and forages have a stronger hold on soils. The phosphorus-edge-of-field delivery coefficient is 9% for forages ($PEOFDC_F$) and 27% for row-crops ($PEOFDC_R$) (Gilliam; NCSU; Schwabe 1996; USDA SCS).

Less is known about the delivery of nutrients from the field-edge to surface waters. Nitrogen is delivered over land through continuous leaching, while phosphorus is transported by periodic flash floods. Schwabe (1996; 2001), based on expert opinion, assumes 50% of all nitrogen and phosphorus at the field-edge reaches surface waters. Using regression analysis, McMahon and Roessler estimate 7.7% of nitrogen reaches the field-edge. This model uses the average of 28% for nitrogen and phosphorus, and is referred to as the land-to-water delivery coefficient (LTWDC).

Water pollution is directly related to algae growth. Generally speaking, the algae required for eutrophication requires 16 parts nitrogen for every part phosphorus (Vesiland et al.), suggesting water pollution goes by the function: Water Pollution = WP = min(N/16,P). Other sources suggest the functions WP = min(N/12,P) or WP = min(N/4,P) (Tetra Tech). Algae growth is a complicated process and follows no specific formula, as different algae types consume nutrients in different ratios. The model WP = min(N/16,P) will be used here, but the sensitivity of results to alternative water pollution functions will be examined.

Let ($N_D$, $P_D$) and ($N_S$, $P_S$) be the initial nitrogen and phosphorus loadings to the Duplin and Sampson Water Sites. Then, let $\Delta EN_D$ and $\Delta EN_S$ be the change in excess nitrogen from lagoon effluent applications in Duplin and Sampson counties, ($\Delta EP_{D,F}$ , $\Delta EP_{D,F}$) be the change in excess phosphorus applied to forages in Duplin county, and ($\Delta EP_{D,R}$ , $\Delta EP_{D,R}$) be the change in excess phosphorus applied to row-crops. Water pollution at the Duplin Water Site can then be expressed as

$$\text{(1)}\quad \begin{aligned} WP_D &= \min\left\langle \frac{N_D + (LTWDC)(NEOFDC)(\Delta EN_D)}{16}, \; P_D + (LTWDC)\left[(PEOFDC_F)(\Delta EP_{D,F}) + (PEOFDC_R)(\Delta EP_{D,R})\right] \right\rangle \\ &= \min\left\langle \frac{N_D + (0.28)(0.9)(\Delta EN_D)}{16}, P_D + (0.28)\left[(0.05)(\Delta EP_{D,F}) + (0.27)(\Delta EP_{D,R})\right] \right\rangle \end{aligned}.$$

Pollution at the Sampson Water Site follows the same expression, substituting subscript “S” for “D.”

Initial nutrient loadings at the estuary are not available, so only the change in loadings will be discussed. The portion of nutrients at the Duplin and Sampson Water Sites entering the estuary depends on the stream flow rate, distance, and rate of nutrient decay. Based on percentages used by Schwabe (1996) for the Neuse River Basin, we provide rough estimates to be used more as a thought experiment than a forecast. Of the nitrogen entering the Duplin and Sampson Water Sites, 40% is assumed to reach the estuary. A lower percentage of 30% is assigned to phosphorus, since phosphorus is rarely water-soluble and tends to settle. If initial loadings at the Estuary Site were such that N/16 = P, the formula describing the change in water pollution in the estuary would then be

$$\text{(2)}\quad \Delta WP_E = \min\left\langle \frac{(0.4)(0.28)(0.9)(\Delta EN_D + \Delta EN_S)}{16}, \; (0.3)(0.28)\left[(0.05)(\Delta EP_{D,F} + \Delta EP_{S,F}) + (0.27)(\Delta EP_{D,R} + \Delta EP_{S,R})\right] \right\rangle.$$

Are phosphorus-based applications of livestock manure environmentally friendly? This section showed that decreases in excess phosphorus may be realized at the expense of more excess nitrogen. The water quality model in this section illustrates the tradeoff between each nutrient. It can be seen from expressions (1) and (2) that the higher nitrogen runoff could offset the lower phosphorus runoff to cause environmental damage, but the opposite is possible as well. It is also evident that decreases in both nitrogen and phosphorus runoff will unambiguously improve water quality. The next section simulates three farmer responses to PBA's, incorporating those changes in the water quality model developed here.

**Simulated Effects of Phosphorus-Based Applications of Swine Manure on Water Quality in the Cape Fear River Basin**

Based on an informal survey asking farmers how they would respond to the implementation of PBA's, and personal communication with farmers, we simulate three responses to PBA's. These should be thought of as "thought experiments" or "best guesses." The first two scenarios assume no change in hog production, while the third allows for supply disruptions. The scenarios require many assumptions that cannot be described here due to space constraints. A few important assumptions are (1) sludge is not considered in the analysis (2) all hay is exported out of the counties and (3) farmers do not stir up sludge when pumping lagoon effluent. Consider first a scenario where *some land constraints* exist. Those farms utilizing row-crops easily expand their irrigation onto existing row-crops, and those utilizing forages convert bordering woodlands into new forage acres. Table 1 shows the baseline nutrient loadings to the Duplin and Sampson Water Sites, and the simulated loadings under Scenario 1. Phosphorus loadings decrease, but nitrogen loadings increase through expanded acreage and manure nitrogen applied to soybeans. The water pollution function increases, signifying a degradation of water quality.

The second scenario assumes *many land constraints*. All farms must use forages because of their higher nutrient uptake. Otherwise, the plant-available-phosphorus from all farms would exceed cropland availability. Those initially using row-crops convert a portion of those acres to forages.[10] Those with forages haul excess lagoon effluent (or extend irrigation) to off-farm acres. These off-farm acres were formerly in row-crops. All effluent nutrients are now applied to forages and the total row-crop acreage is reduced. This results of this scenario is similar to the previous scenario, except that water pollution is made even worse.

Those hay acreage increases were realized during a period of great hog expansion. The implementation of PBA's could cause the opposite result: a contraction. The third scenario allows for these *supply disruptions*. Of those initially using forages, one-third of farms is assumed to cease production, and one-third decrease production until their current sprayfield size is adequate. The other third is not land constrained and expand their sprayfield onto bordering land, converting row-crops to forages. Producers originally using row-crops expand their sprayfield onto additional, existing row-crops. Water quality improves under this scenario, and PBA's appear environmentally friendly. However, water quality is enhanced not because PBA's are necessarily a better practice, but because the hog population declines. Under this scenario, PBA's behave less like best management practices and more like production taxes.

Without knowledge of baseline loadings at the Estuary Site, it is unclear whether water pollution increases or decreases in Scenarios 1 and 2. Since both nitrogen and phosphorus loadings decrease under Scenario 3, water quality improves. All results should be interpreted with caution as they are sensitive to model assumptions. For instance, had the water pollution function $WP = \min(N/4, P)$ been used, water quality would improve under all scenarios. Linking agricultural practices to water sites is a complex process and fraught with uncertainty. The exercise in this section should be considered a thought experiment, rather than a set of predictions. Put differently, the model showing PBA's can cause greater water pollution is not a prediction, but rather a possibility.

Are phosphorus based applications of livestock manure environmentally friendly? The answer is not clear cut. It depends largely on the region, initial water conditions, and how farmers respond to new regulations. Our belief is that, in most regions, the answer is "yes." This paper demonstrates the possibility that phosphorus based applications could be damaging to surface waters. Policy makers should keep this in mind when considering costly manure management regulations.

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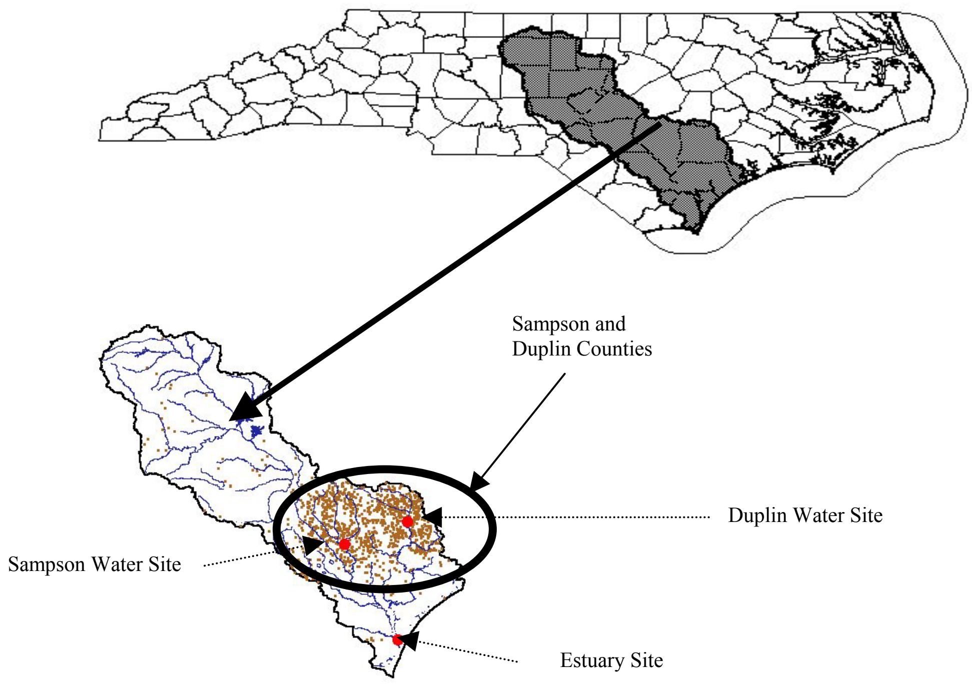
**Table 1.**
**Impacts of phosphorus-based manure applications to three surface water sites**

| | Annual Nitrogen (N) Loadings | Annual Phosphorus (P) Loadings | Water Pollution = min(N/16,P) |
|---|---|---|---|
| *BASELINE*[a] | | | |
| Duplin Water Site | 13,826,592[a] | 2,008,992[a] | 864,162 |
| Sampson Water Site | 14,092,210[a] | 1,312,246[a] | 880,763 |
| *SCENARIO 1: SOME LAND CONSTRAINTS*[b] | | | |
| Duplin Water Site | 14,258,840 | 1,986,278 | 891,177 |
| Sampson Water Site | 14,448,587 | 1,293,563 | 903,037 |
| *SCENARIO 2: MANY LAND CONSTRAINTS*[c] | | | |
| Duplin Water Site | 14,456,512 | 1,995,899 | 903,532 |
| Sampson Water Site | 14,611,407 | 1,299,916 | 913,213 |
| *SCENARIO 3: SUPPLY DISRUPTIONS*[d] | | | |
| Duplin Water Site | 13,496,881 | 1,997,088 | 843,555 |
| Sampson Water Site | 13,821,275 | 1,302,390 | 863,830 |
| *CHANGE IN LOADINGS TO ESTUARY FROM LAGOON EFFLUENT APPLICATIONS IN DUPLIN AND SAMPSON COUNTIES* | | | |
| Scenario 1: | 315,450 | -12,419 | not calculated |
| Scenario 2: | 459,647 | -7627 | not calculated |
| Scenario 3: | -240,258 | -6528 | not calculated |

a) Sources: DWQ 2002a and USGS 2002. The baseline refers to regulations allowing nitrogen- based applications of manure. The three scenarios assume phosphorus-based applications.
b) Hog production does not change. Those initially with row-crops easily expand onto other row-crops. Those with forages clear bordering woodlands to create new forage acres.
c) Hog production does not change. All lagoon effluent is applied to forages. Those with row-crops convert a portion of those acres to forages. Those with forages expand or haul to additional acres where row-crops are replaced with forages. Total acres do not change.
d) Of those initially utilizing forages, one-third of producers leave the market, one-third decrease their hog production until their initial sprayfield size is adequate, and one-third expands or hauls to additional acres where row-crops are replaced with forages. Those initially with row-crops easily expand onto additional row crops.

**Figure 2.**
**The North Carolina Cape Fear River Basin**




Sources: DWQ 2002a; 2002b
Note: The numerous small dots represent 1,121 hog farms whose locations are known. An additional 117 farms are in the Cape Fear but do not have geographic coordinates. The three big dots refer to three water quality monitoring points.