Phosphorus-Based Applications of Livestock Manure and the Law of Unintended Consequences

F. Bailey Norwood and Jan Chvosta

The application of manure phosphorus at rates above crop uptake has resulted in water pollution for some regions. In response, new manure management standards will require some farms to match manure phosphorus application rates with crop uptake. For some regions, this will lead to more crop acres and a shift toward crops with greater nutrient uptake, both of which will increase nitrogen runoff. The greater nitrogen runoff could offset the lower phosphorus runoff to result in greater water pollution. This demonstrates the law of unintended consequences, which results when policy does not consider how economic agents respond to incentives.

Key Words: best management practice, eutrophication, manure management, nutrient runoff, phosphorus standards, pollution control, water pollution

JEL Classifications: D6, Q1, Q2

During the 1800s, the predominant sources of fertilizer were human manure, livestock manure, and Chilean guano. Technological advancements have since yielded more efficient means of fertilizing crops. After we learned to create superphosphate by applying sulfuric acid to phosphate rock, phosphorus could be mined cheaper than it could be obtained through manure. Perhaps the greatest breakthrough was the discovery of ammonia synthesis, in which nitrogen could be extracted directly from the atmosphere. Because of these breakthroughs, chemical fertilizer use has risen from almost nothing to 40 million tons in 1965 and 150 million tons in 1990 (McNeil).

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In fact, chemical fertilizer prices are now so low that many livestock farms find it more expensive to apply manure to fields adjacent to where the manure is generated than to fertilize those fields with chemical fertilizers. Because of chemical fertilizer prices, farmers think of livestock manure less as a fertilizer and more as a burden.

Because of large manure transportation costs, production costs on many farms can be reduced by overapplying manure close to where the manure is generated. Overapplications of manure mean that some manure nutrients go unused by the crop. This has resulted in water quality problems in some areas. Excess nutrients (nutrients applied but not harvested) have the potential to leave the field and enter surface waters, where they encourage algae and bacterial growth. As the populations of these microorganisms rise, they can eventually consume all of the water's dissolved oxygen, causing the aquatic ecosystem

to collapse in what is referred to as eutrophi-cation. Even before eutrophication occurs, the algae can produce a toxin that makes the water undrinkable without expensive treatment.

The microorganisms causing eutrophica-tion, like all life forms, require both nitrogen and phosphorus for growth. If waters contain plentiful phosphorus but little nitrogen, nitro-gen is said to be the limiting nutrient. This means that additional nitrogen will cause more pollution, but additional phosphorus will not. For some waters, nitrogen is the limiting nu-trient and water pollution policies only man-age nitrogen. In the North Carolina Neuse River Basin, proposed regulations would re-quire each county to reduce their nitrogen loads to surface waters by choosing among various best management practices, such as conservation tillage, controlled drainage, and filter strips (Schwabe 1996, 2001). Phosphorus loadings to the basin, however, would not be regulated.

In other waters, phosphorus is the limiting nutrient. In the 1960s, Lake Erie was deemed a dead lake. This led to a series of studies that concluded that Lake Erie and 10,000 other U.S. lakes suffered from high phosphorus loadings. Regulations banning phosphate-based detergents and upgrading waste treat-ment plants later restored some health to these waters (U.S. Geological Survey 1999).

As another example, the Eucha-Spavinaw watershed, shared by Oklahoma and Arkansas, has received massive loads of phosphorus from the overapplication of poultry litter, mak-ing the water undrinkable. As a result, the City of Tulsa has sued Tyson Foods to receive com-pensation for the expensive treatment needed to make the water drinkable again. As a rule of thumb, phosphorus tends to be a problem in upstream and freshwaters, whereas nitrogen is a larger problem in downstream, brackish, and salty waters. The reason is that phospho-rus tends to settle close to where it enters wa-ters, whereas nitrogen is water soluble and moves easily with the current (Department of Water Quality 2002d).

Recently proposed federal and state regu-lations have sought to minimize phosphorus runoff from applications of manure. Although

the regulations vary, their central focus is pro-moting a practice referred to as phosphorus-based applications of manure (PBAs). It will later be shown that PBAs reduce phosphorus runoff by ensuring that all (plant-available) phosphorus applied is removed at crop har-vest. Two ways this can be achieved are by spreading the same amount of manure over a greater number of acres, utilizing different crops, or the use of both methods. Under cer-tain conditions, the U.S. Environmental Pro-tection Agency will soon require large con-fined operations to employ PBAs. Moreover, Natural Resources Conservation Service (NRCS) standards now state that livestock producers should consider the potential for phosphorus runoff in their nutrient manage-ment plan (NRCS 2002).

Specifically, the NRCS standards encour-age the use of a phosphorus index for each field, where a higher index value refers to higher potential phosphorus runoff. For high index values, it is recommended that manure be applied on a phosphorus basis. For very high index values, NRCS recommends no ma-nure or chemical phosphorus should be ap-plied. Some states, such as North Carolina, re-quire concentrated livestock facilities to follow these standards, essentially making them regulations.

Many applaud the new phosphorus stan-dards as a best management practice that will accrue environmental benefits. In this paper, we use a secondary survey in which North Carolina swine producers were asked how they plan to respond to the new phosphorus standards. A water quality model is then de-veloped for two North Carolina counties. The model results suggest that if the producers pro-ceed with their stated plan, phosphorus-based applications could have the unintended con-sequence of causing greater pollution. We fur-ther show that if water quality improves in these counties, the environmental benefits might not stem from PBAs being the best management practice, but from lower hog pro-duction levels because of the added costs of PBAs. Of course, producers might not respond to regulations as they say they will. Also, tech-nological advancements could present new,

more desirable options. Although we cannot say exactly how producers will respond to PBAs, that they are projected to degrade water under a single plausible scenario suggests that policy makers should use caution in encouraging the adoption of PBAs. When policy changes economic agents' incentives, and policy does not account for these incentives, policies with good intentions could lead to unintentional and undesirable outcomes.

The next section describes North Carolina swine farms, with particular attention to how producers responded to a survey asking how they plan to comply with the phosphorus regulations. A model is then constructed that predicts changes in field-edge runoff if producers follow their stated strategy. This model is applied to swine farms in Duplin and Sampson Counties of North Carolina. The third section tracks field-edge runoff to surface waters, demonstrating the effect on water quality. Results show that if hog production remains constant, PBAs will lead to an increase in demand for chemical nitrogen, which increases nitrogen runoff. Consequently, the greater nitrogen runoff could offset the lower phosphorus runoff to degrade water quality. If water quality does improve, it is because of lower hog production levels. Thus, even if water quality is enhanced by PBAs, there is little doubt that for the region of interest, better waste management solutions exist.

Phosphorus Regulations, North Carolina Swine Farms and Nutrient Runoff

The new regulations managing phosphorus runoff from manure applications are not yet finalized. Various aspects of the regulations are still being debated, but it is only a matter of time before they are enforced and swine producers will have to start applying manure on a phosphorus basis. Some farms could find the compliance costs prohibitive and might decrease their herd size. In a recent survey, 85 swine producers in North Carolina were asked how they would respond to regulations requiring PBAs of manure. The survey results, shown in Table 1, show that approximately one-third of farms would cease hog produc-

Table 1. Survey Responses on Effect of Phosphorus-Based Manure Application Regulations (Recreated from Carter-Young et al.)

Response to Stricter Phosphorus-Limiting Regulations on North Carolina Swine Farms	Respondents (%)
Would buy/lease more land for application	23.5
Would clear existing woodland	14.1
Would convert row crops to forage	15.3
Would plant different crops	17.6
Would decrease number of animals on farm	27.1
Could not continue hog production	36.5
No effect	1.2
Other	7.1

Notes: Represents responses from 85 North Carolina swine producers. The percentages do not sum to one because the respondent could select multiple responses.

tion, and 25% would decrease their production level. Because respondents could select multiple categories, some of those who selected "would decrease production level" might have also selected "cease hog production." For those farms that would continue to raise hogs, 15% said they would convert from row crops to forage, 24% said they would clear bordering woodlands, and 14% said they would lease more land for manure applications. Less than 2% of farms said the PBA regulations would have no effect on their farm.

Whether producers will actually follow these strategies when the PBA regulations are binding is uncertain. Faced with high compliance costs, new technologies might become available that reduce the regulation burden. Plus, this survey presented questions about topics in which producers possess incomplete information. Once faced with the reality of a binding regulation, producers might discover other strategies preferable to those listed in Table 1. Despite the uncertainty surrounding the effects of phosphorus regulation, projecting the consequences of regulations on the basis of how farmers say they will react is a useful exercise. We conducted this exercise for two
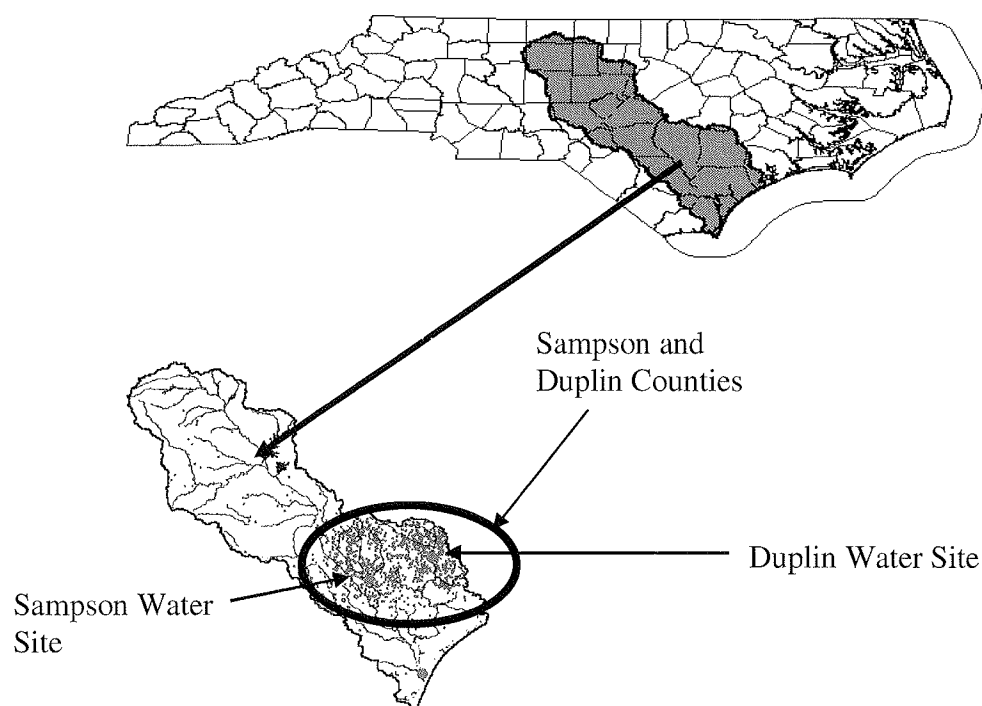
Figure 1. The North Carolina Cape Fear River Basin. Sources: Department of Water Quality (2002a,c). Notes: The numerous small dots represent 1,121 hog farms of known location. An additional 117 farms are in the Cape Fear area but do not have geographic coordinates. The three big dots refer to three water quality monitoring points

North Carolina counties, Sampson and Duplin, the two largest counties in the United States in terms of hog and pig inventories, litters farrowed, and feeder pigs sold (Figure 1).

This section projects effects by constructing a model that predicts nutrient runoff as farmers adapt to PBA regulations according to their survey responses. The model is constructed by first grouping all farms as (1) limited-land farms and (2) ample-land farms. Limited-land farms have little surrounding cropland on which to apply manure. Most apply manure to Bermudagrass, which has a large nutrient uptake, requiring few acres for manure application. North Carolina is the second largest state in terms of hog inventory and the first in terms of feeder pigs sold, and over half of all North Carolina hogs are in these two counties. Between 1990 and 2001, hog inventories in Sampson and Duplin Counties quadrupled (Department of Water Quality 2002a), which in turn increased hay acreage

by nine times (National Agricultural Statistics Service). So much hay is produced in these counties that most producers give the hay away for free. Hay production is seen more as a cost of raising hogs on limited-land farms than a crop. Ample-land farms almost universally apply manure to row crops, which either returns a profit or at least yields smaller losses compared with hay production (Frontline Farmers; Smithfield Foods).

Other limited-land farms have just enough land that they can raise row crops. However, if forced to apply manure on a phosphorus basis, they must convert those row crops to forage because of their higher per acre nutrient uptake.[1] Table 1 shows that 15% of farms fall

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[1] On average, a row crop rotation of wheat/corn/soybean can assimilate 90 lbs. of nitrogen and 13 lbs. of phosphorus, whereas a forage mixture of Bermuda grass and rye grass used for hay can utilize 290 lbs. of nitrogen and 34 lbs. of phosphorus.

into this category. Although there are no hard numbers to determine what percentage of farms are limited-land farms, a commonly held belief is that 70% of land receiving swine manure is on limited-land farms (Smithfield Foods; Frontline Farmers). This implies that at least 70% of hogs are raised on limited-land farms.[2] A survey of water quality permits revealed that this 70% is a reasonable estimate (Department of Water Quality 2002a, 2002b). Furthermore, in the survey from which Table 1 was recreated, 73% of respondents stated that they own no additional land that is usable for manure applications (Carter-Young et al.). On this basis, we assume that at least 70% of all hogs are raised on limited-land farms, the remaining being raised on ample-land farms.

Virtually all swine farms in North Carolina use a lagoon-sprayfield system for manure management. First, manure is delivered to an anaerobic lagoon that maintains a population of bacteria. Digestion by the bacteria releases about 60% of the nitrogen into the air as ammonia and elemental nitrogen gas. Of the remaining nitrogen, 5% settles as sludge and the rest is suspended or dissolved in lagoon effluent. Of the phosphorus generated by hogs, 34% settles as sludge and 20% is suspended in effluent. The remaining 46% is unaccounted for and is likely caked onto the lagoon walls and not easily removed with the sludge (Barker; Bicudo, Safley, and Westerman).

After digestion by the lagoon bacteria, the lagoon effluent (lagoon effluent is a form of manure) is applied to crops via spray irrigation. The nutrients in lagoon effluent are then removed from the field at crop harvest. The sludge that settles on the bottom of the lagoon has to be removed and applied to the land every 10 to 20 years. This study concentrates solely on lagoon effluent, but the main conclusions are unaffected if both lagoon effluent and sludge were accounted for.

Before discussing the model in detail, we must make a distinction between total nutrients and plant-available nutrients. Of all the nutrients in manure and chemical fertilizer, only a portion is available to the plant. These are referred to as plant-available nutrients. The portion that is not plant-available is either not in the proper chemical form for plant uptake or leaves the field through runoff or volatilization before it can be used. Approximately 50% of all nitrogen and 70% of all phosphorus is plant-available, and this portion is roughly the same for manure and chemical fertilizers (Barker; Gilliam).[3] For the remainder of this study, plant-available nutrients are referred to simply as nutrients. That is, if we state that 100 lbs. of nitrogen (phosphorus) are applied, we are implicitly stating that 100 lbs. of plant-available nitrogen (phosphorus) are applied, and that 200 (143) lbs. of total nitrogen (phosphorus) are applied.

Ample-land farms should have little problem complying with PBA regulations because they can simply extend spray irrigation onto bordering cropland. Manure that was overapplied on a phosphorus basis is now applied according to crop need, with little reason to think that the aggregate use of nitrogen will change. Figure 2 illustrates the change in excess nutrients when a farm moves from nitrogen-based applications (NBAs) to PBAs. Let N_H denote the nitrogen contained in lagoon effluent and assume the phosphorus-to-nitrogen ratio in effluent is fixed at θ. Assuming a fixed proportion of Leontief production function as in Feinerman, Bosch, and Pease, the ratio of phosphorus to nitrogen consumed by the crop is given by γ. Figure 2 depicts the scenario of

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[2] Most limited-land farms use forage because of the higher nutrient uptake. This means that one acre of forage assimilates manure from more hogs than one acre of row crops. Thus, if 70% of land receiving swine manure is in forage, more than 70% of hogs are raised on limited-land farms.

[3] For example, an acre of wheat with a yield of 30 bushels per acre will result in 15 lbs. of nitrogen removed at harvest (Shaffer; Zublena). However, a typical fertilizer recommendation for wheat with a 30-bushel-per-acre harvest is 32 lbs. of nitrogen applied per acre (Kansas State University). On a per acre basis, about half of the total nitrogen applied is not removed at harvest and can potentially become runoff. On average, the total nitrogen applied will equal 1/0.5 = 2 times the nitrogen removed at harvest, and the total phosphorus applied will equal 1/0.7 = 1.43 times the phosphorus removed at harvest. These numbers represent conditions for most crops in North Carolina by traditional application methods.
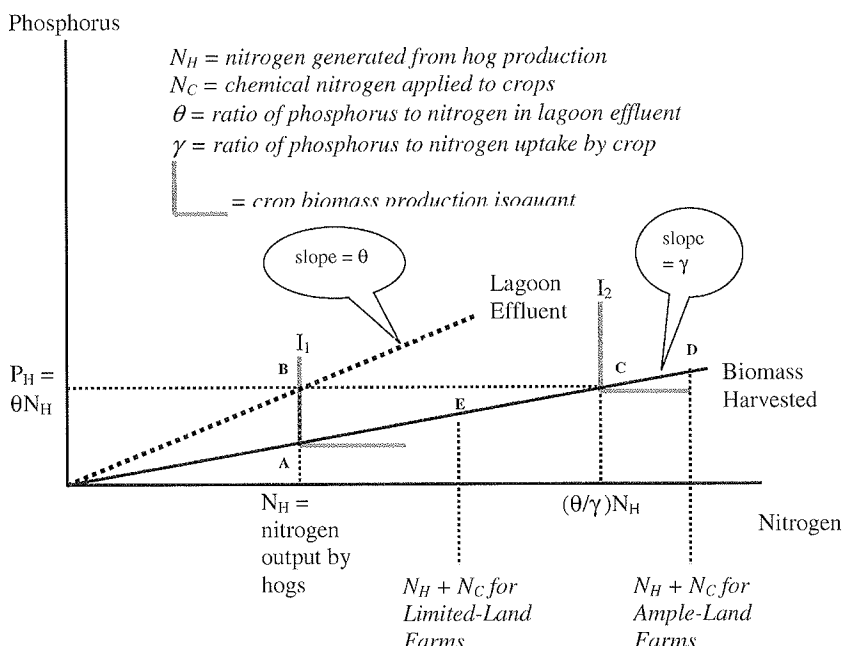
Figure 2. Phosphorus Versus Nitrogen-Based Manure Applications

$\theta > \gamma$, which is the norm. When applied on a nitrogen basis, lagoon effluent is applied to just enough acres that the nitrogen application equals the crop uptake, as given by Point A. The biomass assimilating this nitrogen and harvested is given by the isoquant I_1. The phosphorus applied to these acres equals θN_H, which is given by Point B and exceeds the phosphorus uptake by $(\theta - \gamma)N_H$ (the length of the Segment AB).

When the manure is applied on a phosphorus basis, ample-land farms will extend their irrigation onto more acres, ensuring the manure phosphorus applied on these acres equals crop uptake. This amounts to applying manure phosphorus to crop acreage with biomass production given by the isoquant I_2, or Point C. The nitrogen required to reach I_2 is $(\theta/\gamma)N_H$, which is greater than N_H, so the nitrogen deficiency must be made up with chemical nitrogen. However, ample-land farms are defined as those with enough surrounding cropland to meet PBA regulations. This naturally implies that the sum of all manure and chemical nitrogen in the surrounding area was greater than $(\theta/\gamma)N_H$ before PBAs (Point D, e.g.). Thus, although excess phosphorus declines, aggregate

nitrogen use on and near the farm is unchanged. For this reason, we assume the adoption of PBAs on ample-land farms does not result in any change in aggregate nitrogen use.

Another reason ample-land farms will have little problem adjusting to PBAs is that they have greater control over their crop mix. The nutrient ratio θ in lagoon effluent will be between 0.27 and 0.38, depending on how the lagoon is managed (Chastain et al.; Shaffer; Zublena). Although the phosphorus-to-nitrogen uptake ratio for crops is usually less than 0.20, some crops have a higher ratio. Wheat for grain, for example, can take 0.40 parts phosphorus for every part nitrogen, which is more consistent with the nutrient ratio in lagoon effluent. However, wheat has a small per acre nutrient uptake, so one must have ample land to begin with, making this option unavailable for limited-land farms.

Next, consider the effect of PBAs on limited-land farms. Most limited-land farms are built on tracts with just enough land for nitrogen-based applications. As mentioned previously, most of these farms use Bermudagrass for manure applications, which takes up 0.14 parts phosphorus for every part nitrogen (i.e.,

$\gamma = 0.14$). How will these farms comply with PBA regulations? One option would be to decrease the herd size. As Table 1 indicates, a large proportion of farmers prefer this option. Other limited-land farms (approximately 14%) indicate they would clear bordering woodlands, which would likely be planted in Bermudagrass. Figure 2 illustrates the consequence of converting woodlands to crops. Initially, biomass production is consistent with NBAs and is at the isoquant I_1. After adoption of PBAs, the farm clears enough bordering woodland to reach I_2. Although there is enough additional phosphorus in the effluent to supply the additional acres, crops require both nitrogen and phosphorus. To harvest the biomass given in I_2, it is necessary that the nitrogen deficiency $[(\theta/\gamma) - 1]N_H$ be made up for with chemical nitrogen. Hence, the sum of chemical and manure nitrogen use must increase by $[(\theta/\gamma) - 1]N_H$, increasing excess nitrogen by the exact same amount.[4]

Table 1 shows that some farms will convert from row crops to forage because forage can assimilate more nutrients per acre than row crops. We consider these limited-land farms as well because they are converting to a crop with negative returns because of land constraints. The implications for nitrogen runoff are exactly the same as if the farm cleared bordering woodlands. The biomass harvested from the row crops before PBAs equals I_1 (Figure 2). Harvested biomass equals the nutrient uptake per acre times the number of acres. When converting row crops to forage, the number of acres remains constant and the per acre nutrient uptake rises. As biomass rises

from I_1 to I_2, total nitrogen use on these acres must increase from N_H to $(\theta/\gamma)N_H$, leading to a rise in aggregate nitrogen use and therefore greater nitrogen runoff.

We now develop a model projecting how nutrient runoff changes when all farms in Sampson and Duplin Counties adopt PBAs. The level of hog production is assumed to be affected by PBA adoption, but the exact change is unknown. Regulations requiring PBAs are assumed to have only a minor effect on ample-land farms, so we leave their production level unchanged. The production level for limited-land farms is expected to change, but insufficient data are available to predict this change. The nitrogen output from hogs is assumed to be a fixed percentage of hog inventories, so N_H is a proxy for the number of hogs. Let $N_{H,AL}$ and $N_{H,LL}$ refer to hog inventories on all ample-land and limited-land farms, respectively. The decrease in hog production from PBA regulations is then given by $\Delta N_{H,LL}$, assuming $\Delta N_{H,AL} = 0$. Because the value of $\Delta N_{H,LL}$ is not estimated, changes in nutrient runoff will be calculated for various levels of $\Delta N_{H,LL}$.

Later, it will be shown that adoption of PBAs can degrade surface waters in Duplin and Sampson Counties. The reason is that the decrease in phosphorus runoff is outweighed by an increase in nitrogen runoff. To ensure robust results, the model is constructed to overpredict reductions in phosphorus runoff and underpredict increases in nitrogen runoff for any given value of $\Delta N_{H,LL}$, thereby serving as a conservative estimate of the unintended consequences of PBAs in North Carolina. Notice that in Figure 2, when moving from NBAs to PBAs (from I_1 to I_2), the reduction in excess phosphorus for the farm equals $(\theta - \gamma)N_H$, so long as hog production on the farm remains constant. This allows us to calculate the reduction in excess phosphorus across all ample-land farms as $(\theta - \gamma)N_{H,AL}$. Similarly, the reduction in excess phosphorus across limited-land farms is calculated as $(\theta - \gamma)(N_{H,LL} - \Delta N_{H,LL}) + (0.43)\theta\Delta N_{H,LL}$, where the second term refers to the decrease in excess

phosphorus from a decline in hog population.[5]

The adoption of PBAs by ample-land farms will not affect total nitrogen use or nitrogen runoff. For limited-land farms, evidence suggests that the current sum of chemical and manure nitrogen use (before PBAs) on land near the farm is close to N_H, which means most limited-land farms have just enough land for nitrogen-based applications. We make a liberal assessment of land availability and assume that chemical and manure nitrogen use of limited-land farms equals $(1/2)(1 + \theta/\gamma)N_H$, which assumes land available for manure applications equals the average of land required under PBAs and NBAs (Point E in Figure 2). This assumption ensures that we underestimate the increase in nitrogen runoff resulting from adoption of PBAs.

Those farms that will still exist after PBA regulations are enforced have indicated they will clear bordering woodlands or perhaps convert row crops to forage. Previously, it was shown that this will increase the farm-level chemical and manure nitrogen use to $(\theta/\gamma)N_H$. Thus, if hog production remained constant, excess nitrogen on the farm would increase by $(1/2)N_H(\theta/\gamma - 1)$.[6] If a single farm decreases its hog production by ΔN_H, then excess nitrogen would decrease by the exact amount. This leads to the conclusion that PBA regulations will change excess nitrogen by the amount $(1/2)(N_{H,LL} - \Delta N_{H,LL})(\theta/\gamma - 1) - \Delta N_{H,LL}$.

Water pollution does not stem from excess nutrients, but rather from the portion of those excess nutrients that reach surface waters. To

reach surface waters, excess nutrients must first be transported from the field to the field edge and then across land to the surface waters. On the basis of soil permeability in Sampson and Duplin Counties, it is estimated that 90% of all excess nitrogen reaches the field edge. Because of the soil type, slope, and cropping practices, it is estimated that 9% of excess phosphorus applied to forage and 27% of excess phosphorus applied to row crops reaches the field edge. However, to ensure that we overestimate the reduction in phosphorus runoff for PBAs, we assume 27% of excess phosphorus reaches the field edge regardless of the crop. These estimates are based on runoff measurements on North Carolina soils (Gilliam; Norwood and Chvosta; Schwabe 1996).

Because we assume that 70% of all hogs in Sampson and Duplin Counties are raised on limited-land farms, if ΣN_H is the total nitrogen emitted by all hogs in a county, the change in field-edge runoff (excess nutrients that reach the field edge) is calculated as

(1)   annual change in field-edge phosphorus runoff

$$= -(\theta - \gamma)(0.3)\left(\sum N_H\right)(0.27)$$
$$- (\theta - \gamma)\left[(0.7)\left(\sum N_H\right) - \Delta N_{H,LL}\right](0.27)$$
$$- (0.43)\theta\Delta N_{H,LL}(0.27), \quad \text{and}$$

(2)   annual change in field-edge nitrogen runoff

$$= (1/2)\left[(0.7)\left(\sum N_H\right) - \Delta N_{H,LL}\right](\theta/\gamma - 1)$$
$$- \Delta N_{H,LL}.$$

The values of γ and θ are assumed to be 0.15 and 0.25, respectively, and ΣN_H refers to the baseline lagoon effluent nitrogen across all hogs, which is 4.9 million lbs. for Duplin County and 4.1 million lbs. for Sampson County (Department of Water Quality 2002a; Natural Resources Conservation Service 1996).

The effects of PBA adoption on total field-edge runoff are shown in Figure 3. When production on limited-land farms falls by less than 25%, the reduction in phosphorus runoff is met with an increase in nitrogen runoff at the field edge. It is possible that this increase

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[5] The term $(\theta - \gamma)(N_{H,LL} - \Delta N_{H,LL})$ refers to the reduction in excess phosphorus from phosphorus still generated after PBAs but applied differently. If hog production falls by $-\Delta N_{H,LL}$, then total phosphorus generated falls by $-\theta\Delta N_{H,LL}$. Of the total phosphorus applied, 70% is plant-available and 30% is not, and "phosphorus" in this paper refers to plant-available phosphorus. Hence, when plant-available phosphorus falls by $-\theta\Delta N_{H,LL}$, excess phosphorus falls by $-(0.3/0.7)\theta\Delta N_{H,LL}$, or $-(0.43)\theta\Delta N_{H,LL}$. This makes the total excess phosphorus reduction for limited-land farms equal to $(\theta - \gamma)(N_{H,LL} - \Delta N_{H,LL}) + (0.43)\theta\Delta N_{H,LL}$.

[6] If the current nitrogen application is $(1/2)(1 + \theta/\gamma)N_H$ and this increases to $(\theta/\gamma)N_H$, nitrogen use increases by $(\theta/\gamma)N_H - (1/2)(1 + \theta/\gamma)N_H = (\theta/\gamma)N_H - (1/2)N_H - (1/2)(\theta/\gamma)N_H = (1/2)N_H(\theta/\gamma - 1)$.
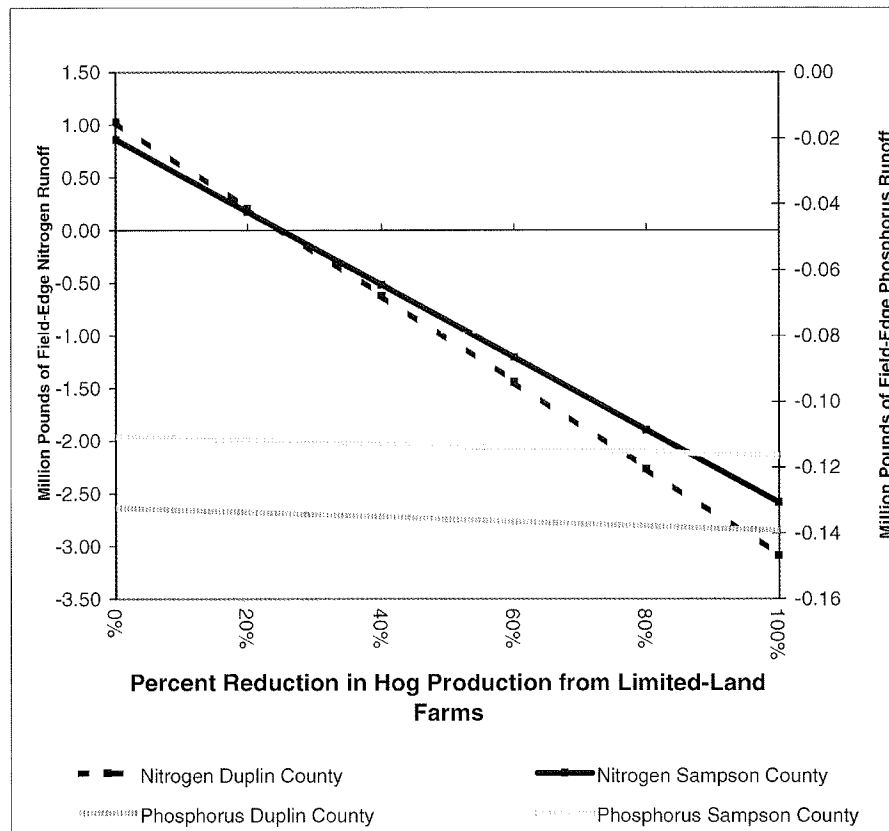
Figure 3. Change in Field-Edge Runoff from Adoption of Phosphorus-Based Applications of Swine Manure

in nitrogen runoff could offset the lower phosphorus runoff to create a net increase in water pollution. This is contrary to what PBAs are intended to accomplish. Only when hog production on limited-land farms falls by more than 25% do both nitrogen and phosphorus runoff decrease, unambiguously decreasing water pollution.

Still, depending on the landscape and current nutrient loadings, water quality could improve from lower phosphorus runoff despite the larger nitrogen runoff. Water pollution is a complex process depending on nutrient transport from fields to surface waters, past loadings to surface waters and the rate at which microorganisms consume nitrogen and phosphorus. The next section develops a water quality model that is used to track field-edge nutrient runoff to surface waters and determine the welfare effects of PBAs in the two counties of interest.

Effects on Water Quality

Nutrient runoff only causes environmental damage if it travels to water sources and leads to greater microorganism growth. This section takes the field-edge runoff estimates in Figure 3, estimates the percentage of runoff reaching surface waters, and combines this with a water pollution function to determine the water quality effects at two water sites in the Cape Fear River Basin. These sites are shown in Figure 1 with the large number of hog farms surrounding the sites.

Field-edge runoff describes excess nutrients that have left the field and reached the field's edge. Not all of these nutrients will reach the water sites. Estimating the portion of field-edge runoff that reaches surface water sites is difficult because very little is known about nutrient transport between fields and surface waters. Schwabe (1996) assumes that

50% of all field-edge runoff reaches surface waters. McMahon and Roessler use regression analysis to estimate that 7.7% of field-edge nitrogen will reach surface waters. This study takes an average and assumes that 29% of field-edge runoff in Sampson (Duplin) County reaches the Sampson (Duplin) water site.

Water pollution depends on the annual nitrogen and phosphorus loadings (NL and PL, respectively) to surface waters. The microorganisms causing pollution require a relatively fixed amount (about $\frac{1}{16}$) of phosphorus for every unit of nitrogen for growth (Vesiland, Peirce, and Weiner). Because water pollution increases with microorganism growth, we use the water pollution (WP) function

(3) $WP = min(NL/16, PL)$.

Baseline values of NL and PL were collected and then used in conjunction with the results in Figure 3 to calculate new nutrient loadings to the watershed. For example, loadings of nitrogen to the Duplin water site are 13.8 million lbs. per year. This is the baseline NL. We then use Equation (2) to calculate the change in field-edge nitrogen runoff from widespread adoption of PBAs and multiply that by 0.29 to get the change in nitrogen loadings to the Duplin water site. This provides a new value of NL. After performing a similar calculation for PL, we are able to calculate the water pollution function value before and after PBA adoption.

The effects of PBA adoption on water pollution are shown in Table 2. If hog production for limited-land farms falls by 20%–25% or less, water pollution will worsen from full adoption of PBAs. This is because at low levels of supply shocks, the increase in nitrogen runoff offsets the decrease in phosphorus runoff, to provide a net increase in water pollution. When hog supply disruptions are large, both nitrogen runoff and phosphorus runoff decline with the hog population, eventually leading to a net increase in water quality. The conclusion is that if pollution abatement occurs, it is not because of the direct effect of PBA adoption, but PBAs' indirect effect of reducing hog populations. This is akin to low-

Table 2. Effect of Phosphorus-Based Manure Applications on North Carolina Cape Fear River Basin Water Quality

Reduction in Hog Production From Limited-Land Farm (%)	Water Pollution at Duplin Water Site[a]	Water Pollution at Sampson Water Site
Before Adoption of Phosphorus-Based Manure Applications	864,162	880,763
After Adoption of Phosphorus-Based Manure Applications		
0	882,813	896,369
20	867,892	883,884
40	852,972	871,400
60	838,051	858,915
80	823,131	846,431
100	808,210	833,946

[a] Sources on baseline nutrient loadings are Department of Water Quality (2002a) and U.S. Geological Survey (2002). These estimates account for nutrient loadings from all sources, agricultural and nonagricultural. Baseline loadings to the Duplin water site is 13.8 million lbs. of nitrogen and 2 million lbs. of phosphorus, and baseline loadings to the Sampson water site is 14 million lbs. of nitrogen and 1.3 million lbs. of phosphorus. Water pollution is given by the function min(annual nitrogen loadings/16, annual phosphorus loadings).

ering water pollution by taxing hog production, without returning that tax money to society in the form of public goods. From this we conclude that, in the area of interest, if producers respond to PBAs as they indicate in surveys, PBAs are not environmentally friendly or best management practices, and much better pollution control policies exist and should be used.

Policy Implications

We first want to stress that the results of this study are only applicable to Sampson and Duplin Counties in the North Carolina Cape Fear River Basin and that readers should use caution in transferring these results to other watersheds and manure types. We do not intend to imply that PBAs are never best manage-

ment practices, only that they should not be considered best management practices without some analysis. The implication is that policy makers should use caution in promoting PBAs as a universal best management practice.

This study assumes that producers will respond to phosphorus regulations exactly as they stated in a survey, which implicitly assumes no technological change. Private firms and governments are making large investments to discover better manure handling technologies. The North Carolina Attorney General's Office, Smithfield Foods, and Premium Standard Farms are currently collaborating to evaluate 18 alternative technologies. More than $18 million have been invested in this project. It is possible that an affordable phosphorus management technology could emerge that makes the results of this study irrelevant. However, at the time this article was written, such a technology had not been developed.

It is well known that policy changes can change economic incentives, and if these incentives are not accounted for, policies can have unintended and undesirable outcomes. PBAs have been labeled best management practices because they almost always reduce runoff on a per acre basis. Pollution, however, is the result of all acres under production. As this study shows, mandating practices like PBAs could change the number of acres under crop production, leading to more pollution.

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