Impacts of Agricultural Nutrient Regulation in a Heterogeneous Region

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This paper examines the impacts of nutrient management regulations in a heterogeneous region. Nonpoint sources of water pollutants, in particular, nutrients like nitrogen and phosphorus, are increasingly a focus of US water pollution policy. In most cases, agriculture is the largest contributor of these pollutants, in part because, until recently, it has largely remained unregulated. Recently, however, a number of initiatives have targeted nutrient runoff and leaching from animal agriculture. Many states have promulgated new nutrient management regulations stipulating that manure be disposed of in ways that limit runoff and leaching to acceptably low levels. Stricter state regulations have been especially common in the Mid-Atlantic and Southeast, where excess nutrients have proven particularly problematic (Gollehon et al.). In 2003, the US Environmental Protection Agency updated its regulatory oversight of confined animal feeding operations. The new regulations apply to a larger subset of such operations than in the past, most notably large poultry producers. In addition, they require all such operations to create and implement nutrient management plans that restrict land application of manure such that the quantity of nutrients a crop needs are correlated with the amount of nutrients applied to the crop.

Several studies have examined the economics of nutrient management regulations. Fleming et al. assess the profitability of land application of swine manure for a single operation using data from Iowa. Innes presents a theoretical analysis for manure application in a region in cases where manure may be subject to both leaching and catastrophic spills into nearby water bodies in extreme weather events. Goetz and Zilberman present a theoretical analysis of optimal manure application and pollution taxes in a spatially differentiated region where phosphorus runoff is a stock pollutant. Feinerman et al. analyze least-cost combinations of manure and chemical fertilizer use at a regional level under nitrogen- and phosphorus-based nutrient management plans in the case of a linear-with-plateau von Liebig production technology both theoretically and empirically using data from Virginia.

All of the aforementioned studies, except Goetz and Zilberman, assume that land is homogeneous in terms of its potential for nutrient runoff and leaching. In most cases, however, there is substantial heterogeneity in pollution potential due to differences in such factors as proximity to water bodies, soils, topography, phosphorus status, and BMP implementation. In many parts of the US, for instance, nutrient management regulations are based explicitly on the phosphorus site index (PSI), which incorporates information about soil phosphorus levels, leaching potential, and indicators of potential environmental damage.

This paper extends existing frameworks in several ways that are crucial from the perspective of practical regulation. First, both nitrogen and phosphorus are potential sources of water quality degradation; thus, nutrient management regulation needs to take both nutrients into account. Second, manure contributes to stocks of nutrients held in soils and nutrients are released only gradually, i.e., carryover is significant. As noted above for the case of phosphorus, nutrient management regulations are often conditioned on these soil stocks. Third, land heterogeneity determines nutrient application rates as well as runoff and leaching rates. Fourth, the use of manure can involve extra application costs and, in some instances, significant costs of transportation to suitable sites. Fifth, manure may have other uses than application to cropland, e.g., composting, pelletization for export, energy production, and forest fertilization.

We develop a theoretical model of optimal manure application and chemical fertilizer use that incorporates all of these elements. Returns to crop production are modeled as a general function of nitrogen and phosphorus uptake. Available nitrogen is modeled as the sum of chemical fertilizer input plus releases from a stock of soil organic matter less land-type-specific losses to leaching and runoff. Changes in soil stocks of organic matter are assumed to equal additions from manure less releases to available nitrogen. Changes in soil phosphorus stocks are equal to additions from manure less crop uptake and losses to the environment at rates that depend on land type and existing stock levels. All soil phosphorus is assumed to be bioavailable. Environmental damage is assumed to depend on aggregate losses of nitrogen and phosphorus to the environment.

We use the model to derive field- (land-type-) specific nutrient management recommendations for both manure application and chemical fertilizer use. We distinguish conditions under which nutrient management leads to (a) reliance on chemical fertilizer only, (b) reliance on manure application only, and (c) simultaneous use of chemical fertilizer and manure. We discuss the evolution of those recommendations over time as manure nutrient levels change due to alterations in feed, and as soil phosphorus and organic matter stocks change. We also discuss steady state recommendations.

We apply the model empirically to the case of the Delmarva Peninsula, where regulators in Maryland and Delaware have introduced strict nutrient management regulations to address problems of phosphorus and nitrogen runoff into the Chesapeake Bay, with an emphasis on the management of poultry litter. This region has been identified as having large excesses of nitrogen and phosphorus relative to assimilative capacity, suggesting a need for long-distance export of much of the region's poultry litter (Gollehon et al.).

A Model of Nutrient Management in a Heterogeneous Region

Consider a region that contains J farms. Farm j contains A_j acres of cropland of quality θ_j, and generates a quantity of manure M_j each year. Crop production is a function of nutrient uptake, specifically, uptake of nitrogen and phosphorus from bioavailable stocks present in the soil, which the farmer manages by adding synthetic nitrogen and phosphorus fertilizers in per-acre quantities n_j and p_j, respectively, and by adding manure per acre m_j.

Soil Nutrient Dynamics

The soil is assumed to contain two stocks of nitrogen and one stock of phosphorus. One stock of nitrogen, Z_j, is present in undecayed manure and plant material and is not available for plant uptake. We refer to it hereafter as the organic matter stock of nitrogen. The other stock of nitrogen, N_j, consists of nitrogen in water soluble forms that are available for plant uptake. The entire stock of phosphorus, P_j, is assumed to be in water soluble forms that are available for plant uptake.

The stock of organic matter nitrogen, Z_j, can be augmented by adding manure. Organic matter decay also makes some of this stock available for plant uptake each year. Assume that the nitrogen and phosphorus content of manure are constant fractions (α_n and α_p, respectively) of the amount of manure applied per acre, m_j. A fraction β of the manure nitrogen is bioavailable immediately. The remainder enters the organic matter stock Z_j. The rate at which organic matter (and thus the stock of organic matter nitrogen) decays and thus becomes bioavailable is δ. The change in the stock of unavailable nitrogen at time t is thus

$$\dot{Z}_j(t) = (1-\beta)\alpha_n m_j(t) A_j - \delta Z_j(t)\,. \tag{1}$$

The stock of nitrogen available for plant uptake, N_j, is augmented by the bioavailable fraction of manure, by the addition of nitrogen fertilizer, and by the decay of organic matter in the unavailable stock. The crop takes up a fraction of the bioavailable stock that depends on soil quality, $\gamma_n(\theta_j)$. Losses of nitrogen into the environment come only from the bioavailable stock and depend on the stock and soil quality, $e_n(N_j,\theta_j)$. The change in the stock of nitrogen available for crop uptake at time t is thus

(2) $$\dot{N}_j(t) = \beta\alpha_n m_j(t)A_j + n_j(t)A_j + \delta Z_j(t) - \gamma_n(\theta_j)N_j(t) - e_n(N_j(t),\theta_j)\,.$$

The stock of phosphorus, P_j, is augmented by the phosphorus content of manure, $\alpha_p m_j$, and phosphorus fertilizer, p_j. The crop takes up a fraction of the phosphorus stock that depends on soil quality, $\gamma_p(\theta_j)$. Losses of phosphorus into the environment depend on the stock and soil quality, $e_p(P_j,\theta_j)$. The change in the soil phosphorus stock at time t is thus

(3) $$\dot{P}_j(t) = \alpha_p m_j(t)A_j + p_j(t)A_j - \gamma_p(\theta_j)P_j(t) - e_p(P_j(t),\theta_j)\,.$$

We assume that each soil has a finite nutrient holding capacity, which implies that losses to the environment quasi-thresholds, i.e., are roughly S-shaped and approach a 45-degree line in the limit as the stock of available nitrogen or phosphorus increases. When soluble nutrient stocks are low, nutrients tend to stay bound to the soil and neither leach nor run off readily. As soluble nutrient stocks increase, they take up a growing share of the soil's finite nutrient holding capacity. Losses to the environment remain low until soluble nutrient stocks approach the soil's nutrient holding capacity, at which point they rise rapidly. Increases in environmental losses cannot exceed increases in soluble nutrient stocks, however, which implies that losses to the environment approach a 45-degree line in the limit.

Crop Production

Output is assumed to depend on the uptake of nitrogen and phosphorus from bioavailable soil stocks. Specifically, output per acre is given by the production function $f(\gamma_n(\theta_j)N_j,\gamma_p(\theta_j)P_j)$, assumed increasing and concave in both arguments. Note that soil quality influences crop productivity through its effect of nutrient uptake rates.

Regional Distribution of Manure

If manure markets are well developed, farmers' nutrient management regimes will derive from free choices of combinations of manure and synthetic fertilizer applications. Farm j generates an annual amount of manure, M_j. Some of that manure, m_jA_j, is applied to crops on that farm. Some of that manure may be sold to other farms. Conversely, farm j may purchase extra manure to apply. Let b_{jk} be the amount of manure purchased by farm j from farm k and s_{jk} be the amount of manure sold by farm j to farm k. There may also be markets for manure for alternative uses such as composting, formulation of fertilizers for non-agricultural uses (or export from the region), bioenergy production, etc. Let y_j be the amount of manure farm j sells for these non-agricultural uses. Materials balance in the use of manure by farm j can be expressed by the constraint

$$M_j(t)+\sum_{k\neq j}[b_{jk}(t)-s_{jk}(t)]-y_j(t)\geq m_j(t)A_j\ . \tag{4}$$

Farm Profit

We assume that farmers in the region are risk neutral profit maximizers. Annual profit for farm j consists of the value of output plus revenue from net manure sales less expenditures on synthetic fertilizers less the cost of applying manure less expenditures on net manure purchases. For convenience, normalize the price of output to one, so that revenue equals the level of output and all prices are expressed relative to the output price. Let w_n and w_j denote the respective prices of nitrogen and phosphorus fertilizers. Let w_m denote the unit application cost of manure and v_e the market price of the highest value alternative use of manure. Assume that manure trades are arranged by a set of competitive brokers who charge a fixed price v_m plus the cost of hauling manure from the supplying farm to the purchasing farm. Assume that the cost of hauling a unit of manure from farm k to farm j, c_{jk}, is an increasing function of the distance between them. Farm j's profit at time t is thus

$$\begin{aligned}\pi_j(t)=&\left\lfloor f(\gamma_n(\theta_j)N_j(t),\gamma_p(\theta_j)P_j)-w_nn_j(t)-w_pp_j(t)-w_mm_j(t)\right\rfloor A_j\\&+v_ey_j(t)-\sum_{k\neq j}(v_m+c_{jk})b_{jk}(t)+\sum_{k\neq j}v_ms_{jk}(t).\end{aligned} \tag{5}$$

Environmental Damage

Socially optimal nutrient management depends on the damage caused by nutrient losses to the environment. We assume that environmental damage depends on total nutrient losses in the region. We allow for difference in the environmental damage arising from nutrient losses at different locations by weighting those losses according to location and soil quality. The social value of environmental damage is thus

(6) $$D\left(\sum_j \phi_{nj} e_{nj}(N_j, \theta_j), \sum_j \phi_{pj} e_{pj}(P_j, \theta_j)\right).$$

Nutrient Management with Competitive Manure Markets

If manure markets are well established and competitive, the nutrient management regime in the region will allocate synthetic fertilizers and manure application and sales to maximize the sum of the present value of profit of all farms in the region

(7) $$\int_0^\infty \sum_j \pi_j(t) e^{-rt} dt$$

subject to the soil dynamics given by equations (1), (2), and (3), the manure balance condition (4) on each farm, and initial nutrient stocks on each farm $Z_j(0)$, $N_j(0)$, and $P_j(0)$.

The present value Hamiltonian for this optimization problem is

(8)

$$\begin{aligned} H(t) = \sum_j \{\pi_j + \lambda_j[(1-\beta)\alpha_n m_j A_j - \delta Z_j] + \psi_{nj}[\beta\alpha_n m_j A_j + n_j A_j + \delta Z_j - \gamma_n N_j - e_n(N_j, \theta_j)]\} \\ + \sum_j \left\{\psi_{pj}[\alpha_p m_j A_j + p_j A_j - \gamma_n P_j - e_p(P_j, \theta_j)] + \mu_j[M_j + \sum_{k \neq j}(b_{jk} - s_{jk}) - m_j A_j - y_j]\right\}. \end{aligned}$$

The necessary conditions for a maximum are, for each farm j:

(9a)
$$\begin{aligned} &-w_n + \psi_{nj} \le 0, \\ &n_j(-w_n + \psi_{nj}) = 0 \end{aligned}$$

(9b)
$$\begin{aligned} &-w_p + \psi_{pj} \le 0, \\ &p_j(-w_p + \psi_{pj}) = 0 \end{aligned}$$

(9c)
$$\begin{aligned} &-w_m + \lambda_j(1-\beta)\alpha_n + \psi_{nj}\beta\alpha_n + \psi_p\alpha_p - \mu_j \le 0, \\ &m_j[-w_m + \lambda_j(1-\beta)\alpha_n + \psi_{nj}\beta\alpha_n + \psi_p\alpha_p - \mu_j] = 0 \end{aligned}$$

(9d)
$$\begin{aligned} &-(v_m + c_{jk}) + \mu_j \le 0, \\ &b_{jk}[-(v + c_{jk}) + \mu_j] = 0 \end{aligned}$$

(9e)
$$\begin{aligned} &v_m - \mu_j \le 0, \\ &s_{jk}[(v_m - \mu_j] = 0 \end{aligned}$$

(9f)
$$\begin{aligned} &v_e - \mu_j \le 0, \\ &y_j(v_e - \mu_j) = 0 \end{aligned}$$

(9g)
$$(r+\delta)\lambda_j - \delta\psi_{nj} = \dot{\lambda}_j$$

(9h)
$$\left(r + \gamma_n + \frac{\partial e_n}{\partial N_j}\right)\psi_{nj} - \gamma_n A_j \frac{\partial f}{\partial N_j} = \dot{\psi}_{nj}$$

(9i)
$$\left(r + \gamma_p + \frac{\partial e_p}{\partial P_j}\right)\psi_{pj} - \gamma_p A_j \frac{\partial f}{\partial P_j} = \dot{\psi}_{pj}$$

plus equations (1)-(4) and the initial nutrient stock conditions on each farm.

Steady State Nutrient Management

The steady state shadow prices of bioavailable soil nitrogen, N_j, soil phosphorus, P_j, and organic matter nitrogen, Z_j, are, respectively,

(10a)
$$\psi_{nj}* = \frac{\dfrac{\partial f(\gamma_n(\theta_j)N_j*, \gamma_p(\theta_j)P_j*)}{\partial N_j} \cdot \gamma_n A_j}{r + \gamma_n + \dfrac{\partial e_n(N_j*, \theta_j)}{\partial N_j}}$$

(10b) $$\psi_{pj}* = \frac{\dfrac{\partial f(\gamma_n(\theta_j)P_j*, \gamma_p(\theta_j)P_j*)}{\partial P_j} \cdot \gamma_p A_j}{r + \gamma_p + \dfrac{\partial e_p(P_j*, \theta_j)}{\partial P_j}}$$

(10c) $$\lambda_j* = \frac{\delta}{r+\delta} \cdot \psi_{n\,j}*.$$

The shadow price of bioavailable soil nitrogen (soil phosphorus) equals the present value of the marginal product of bioavailable nitrogen (phosphorus) on the farm. Here the discount factor includes depreciation adjustments for losses to the environment, $\partial e_n/\partial N_j$ ($\partial e_p/\partial P_j$) and to crop uptake, γ_n (γ_p) as well as the interest rate, r. The shadow price of organic matter nitrogen, Z_j, equals the present value of its annual contributions to the bioavailable soil nitrogen stock $\delta\psi_{nj}*$, with a discount factor adjusted for the decay rate, $r+\delta$.

Manure will be applied in a steady state as long as its unit cost does not exceed its nutrient value. The unit cost of manure equals sum of the application cost, w_m, and the opportunity cost of manure, μ_j. The nutrient value of manure equals $\alpha_n\psi_{nj}*\left[\dfrac{r\beta+\delta}{r+\delta}\right]+\alpha_p\psi_{pj}*$, the value of nitrogen and phosphorus available immediately plus the present value of nitrogen made available over time. Conditions (9e) and (9f) indicate that the shadow price of the farm's stock of manure, μ_j, equals the maximum of v_e, the price of manure in the alternative non-agricultural use, and v_m, the farm's return on manure sold in the least cost trade possible in the market. If the nutrient value of manure exceeds $\max\{v_e,v_m\}$, the farm will use manure as fertilizer in a steady state. If the nutrient value of manure is sufficiently high, the farm will find it profitable to purchase manure from others.

If the farm uses manure in a steady state, its total use of manure, derived from the state equation (1), will be

$$(11) \qquad m_j * A_j = \frac{\delta Z_j *}{(1-\beta)\alpha_n},$$

i.e., manure will be applied in order to offset depletion of the organic matter nitrogen stock, Z_j*, so that the organic matter nitrogen stock remains constant. Equation (11) suggests that the steady state use of manure will tend to be high on farms whose desired organic matter nitrogen stock is large, when the decay rate of the organic matter nitrogen stock is high, when the nitrogen content of manure is low, when a large fraction of manure is not immediately bioavailable (β is high), and when the farm has a large amount of cropland relative to its own stock of manure M_j. Equations (10a) and (10c) suggest that the desired stock of non-available nitrogen will be high when the farm's soil is highly productive (so that the shadow price of bioavailable nitrogen, and thus that of non-available nitrogen, is high), when the crop's nitrogen uptake rate, γ_n, is high, when the farm has a large amount of cropland, and when losses to the environment are low.

If manure applied at the optimal application rate defined by equation (11) is insufficient to keep steady state bioavailable nitrogen and/or phosphorus stocks at their optimal steady state levels, farms will find it profitable to use both manure and synthetic fertilizers. In such cases, conditions (9a) and (9b) imply that the shadow prices of the available soil nitrogen and soil phosphorus stocks, ψ_{nj}* and ψ_{pj}*, equal the respective prices of nitrogen and phosphorus fertilizer, w_n and w_p. Nitrogen and phosphorus fertilizer will be applied at rates sufficient to maintain the optimal steady state stocks of available nitrogen and phosphorus.

It is also possible that farms will not use manure in a steady state at all. If the nutrient value of manure is less than its value in the best alternative use, $\max\{v_e,v_m\}$, the farm will sell all of the manure it generates. As we have seen, the nutrient value of manure depends on the shadow prices of the stocks of bioavailable nitrogen and phosphorus, which are low when the farm's soil is not very productive (so that the marginal productivity of soil nutrient stocks is low), when the crop's nutrient uptake rates, γ_n and γ_p, are low, when the farm has little cropland, and when losses to the environment are high.

Nutrient Management in the Transition to a Steady State

This problem is linear in all of the control variables so that it is optimal to reach steady state nutrient stocks via the most rapid approach path. Generally speaking, if initial nutrient stocks are below steady state levels, synthetic fertilizer and manure should be added in order to attain those steady state levels as soon as possible (within one period if feasible). If initial nutrient stocks exceed steady state levels, it will be optimal to forego the use of manure and/or synthetic fertilizers until crop uptake achieves steady state nutrient stocks.

The initial shadow prices of the stocks of organic matter and bioavailable nitrogen and of phosphorus equal the marginal change in the present value of profit over the entire (infinite) time horizon due to a change in initial stocks. They will be higher than the corresponding steady state shadow prices when initial stocks are lower than the steady state stocks. Manure will be especially valuable during the transition phase when the initial organic matter nitrogen stock on a farm is lower than the farm's steady state level. In such cases, manure will be applied to bring the organic matter nitrogen stock up to the steady state level as rapidly as possible—provided that the farm's soil phosphorus stock does not (or is not made to) exceed its optimal steady state level. If the farm's soil phosphorus stock is high, it will likely to be optimal to build up organic matter nitrogen more slowly. Such is the case in regions where repeated applications of poultry litter have resulted in extremely high soil phosphorus levels while crop uptake, leaching, and runoff have sufficed to keep soil nitrogen stocks relatively low. Under those conditions, it may be optimal to apply nitrogen fertilizer in the short run to maintain crop productivity while foregoing the use of manure and phosphorus fertilizer until soil phosphorus levels have declined sufficiently, waiting to build up the organic matter nitrogen stock until the soil phosphorus stock is sufficiently low.

Socially Optimal Nutrient Management

In a social optimum, nutrient management takes into account environmental damage as well as farm profit. The necessary conditions remain the same as before with the exception of the costate equations (9h) and (9i), which now take into account marginal environmental damage from environmental losses as well as future productivity reductions from losses to the environment. The steady state shadow prices of bioavailable nitrogen and phosphorus in a social optimum are

$$\psi_{nj}* = \frac{\dfrac{\partial f}{\partial N_j} \cdot \gamma_n A_j - \phi_{nj} D' \cdot \dfrac{\partial e_n}{\partial N_j}}{r + \gamma_n + \dfrac{\partial e_n}{\partial N_j}} \tag{12a}$$

$$\psi_{pj}* = \frac{\dfrac{\partial f}{\partial P_j} \cdot \gamma_p A_j - \phi_{pj} D' \cdot \dfrac{\partial e_p}{\partial P_J}}{r + \gamma_p + \dfrac{\partial e_p}{\partial P_j}}, \tag{12b}$$

the present value of the value of marginal output less marginal environmental damage, with the discount factor adjusted as before for crop uptake and losses to the environment.

The analysis of nutrient management in a steady state and during a transition remains largely as before. Socially optimal stocks of bioavailable nitrogen and phosphorus will be lower than their privately optimal counterparts. The use of manure and chemical fertilizers will be correspondingly lower as well.

Empirical Application

The Delmarva Peninsula is one of the top poultry producing regions in the U.S. Annual broiler production is about 600 million broilers, producing over 700,000 tons of poultry litter. The region has flat, fairly sandy soils, the majority of which are used to produce a variety of rotations of corn, soybeans and winter wheat.

Manure has been traditionally used by growers as a crop nutrient source on their own crops or traded away to neighboring crop farmers (often for the services of cleaning out the poultry production house). Longer distance trades may also be necessary as the amount of farmland near any poultry producer is limited due to the region's long, narrow shape. Several local alternative uses for poultry litter also exist. In the center of the poultry producing area is the Perdue AgriRecycle plant which pelletizes nearly 80,000 tons of poultry litter annually for shipmet out of the region. Other alternative uses include composting and forest fertilization. Electric power production and steam cogeneration are also feasible, although the region currently has no energy conversion facilities.

In 1998, Maryland passed one of the strictest nutrient nonpoint source water pollution control laws in the nation. The Water Quality Improvement Act of 1998 requires virtually all agricultural operations in the state to write and implement a nutrient management plan. Since this law was passed, Delaware has passed a law requiring nutrient management by most large crop producers and nearly all poultry producers, and Virginia requires nutrient management plans for all poultry producers. In addition, recent changes to water quality permitting from the EPA require nutrient management plans on an increasing number of animal operations. While Maryland's law is more inclusive, most laws follow Maryland's lead in how nutrient management planning will be carried out. The Maryland nutrient management regulations require growers to assess yield expectations and adjust bioavailable and organic matter nutrient stocks accordingly. For soils with low phosphorus stocks, most nutrient management regulations require that nitrogen stocks be managed in a manner that limits environmental losses. The nutrient contribution of manure directly and from organic matter stock decay are typically not large enough relative to meet crop uptake demand, hence the use of chemical fertilizer is typically necessary. For soils with medium to high phosphorus stocks, regulations require the use of the Phosphorus Site Index (PSI) to assess the potential for phosphorus losses to the environment. The PSI assesses the field's potential to create nonpoint source phosphorus pollution by ranking local risk factors such as soil type, slope, distance to waterways, existing soil phosphorus stocks, and planned phosphorus applications. Thus, the PSI operates very much like the soil quality index in the theoretical model, influencing both the production function and the environmental loss function. The use of manure on soils with medium to high soil phosphorus is subject to limitation based on its contribution to the soil phosphorus stock, which cannot exceed the maximum acceptable level for the site as determined by the PSI>

Data limitations restrict the empirical analysis to the case of a fixed proportions technology in which nitrogen and phosphorus uptake per unit of crop production are constant. As a result, steady state stocks of organic matter nitrogen, bioavailable nitrogen, and phosphorus are determined by the farmer's yield goal. Regulatory restrictions on phosphorus application (and thus acceptable yield goals) are determined by the PSI. The optimal combination of manure and chemical fertilizers then depends on their relative prices and on the value of manure as fertilizer relative to its sale value both to other farmers and for alternative non-agricultural uses.

Soil phosphorus status is the principal source of heterogeneity in the region. Soils and climate are quite similar throughout the region, so that the share of manure that is bioavailable immediately, β, the organic matter decay rate, δ, and crop uptake rates for any given crop, γ_n and γ_p, do not vary much. About half of the nitrogen in poultry litter is mineralized ($\beta = 0.5$) and thus available for uptake during the year in which the litter is applied. An additional 20 percent is mineralized and thus available during the year after application while 5 percent more is mineralized two years after application, suggesting that $\delta \approx -1.5$, $t \leq 2$. The remaining 25% is lost through volatilization, leaching, and runoff. All of the phosphorus and potassium is assumed to be available immediately. The nutrient content of manure also varies little, largely because five integrators control placement of all birds in the region. Data from the Maryland Cooperative Extension manure testing program indicate that poultry litter averaged 3.522% nitrogen (α_n), 2.971% phosphorus (α_p), and 2.343% potassium during the period 1995-2001, the most recent period for which data are available.

Poultry Litter Use on the Delmarva Peninsula

Farm-level data were not available, so the empirical analysis was conducted at the county level. Physical quantities of poultry litter produced annually were estimated at the county level by multiplying the average amount of litter generated per bird, 1.2 tons per 1,000 birds (Carr), times the number of broilers produced annually in each county. The number of broilers produced annually was estimated using data from two sources: (1) the 1997 Census of Agriculture and (2) the Agricultural Statistics Annual Summaries for Maryland Delaware, and Virginia. The annual agricultural statistics reports published by each state provide figures on the number of broilers sold annually; data from the most recent year available (2000) were used. The Census of Agriculture provides county-level estimates of broiler production. The Census figures were used to estimate each county's share of total broiler production, which were then used to allocate the year 2000 production figures across counties. To simplify the analysis, broiler production in

New Castle County, Delaware was included in the figure for Kent County, Delaware. This procedure generated an estimate of 589,205,105 broilers produced on the Delmarva Peninsula during 2000. The total amount of poultry litter generated annually on the Peninsula was thus estimated to be 706,399 tons (Table 1).

Value of Poultry Litter Applied to Cropland as Fertilizer

The value of poultry litter in land application as fertilizer was calculated using equations (9a,b,c,g) assuming steady state soil nutrient stocks. The value of poultry litter nutrient content ranges from $19 to $34 per ton, depending on rotation and nutrient management plan (see Table 2; for details see Lichtenberg, Parker, and Lynch). This range is consistent with other recent estimates (see for example Pierson and Wyvill). Less of the phosphorus and potassium contained in the litter applied are taken up by crops under nitrogen-based nutrient management plans than under phosphorus-based nutrient management plans, so that the average nutrient value per ton of litter is lower under the former than the latter. The per-ton value is highest under a corn-wheat-soybean rotation because it utilizes the largest share of the total nutrient content of the litter applied. A continuous corn rotation utilizes more nitrogen but less phosphorus and potassium than a corn-soybean rotation.

Transportation distances were estimated using information on the distribution of soil phosphorus status within each county. The amount of poultry litter that can be applied as fertilizer depends on the phosphorus status of the soil in the field, as indicated by a combination of the field's soil test phosphorus Fertility Index Value (FIV) and its Phosphorus Site Index (PSI). Soils were divided into four categories based on manure application restrictions due to phosphorus levels and runoff potential. Soils with a FIV in excess of 150 and a PSI greater than 100 are classified as having very high phosphorus runoff potential; poultry litter cannot legally be applied to these fields. Soils with a FIV in excess of 150 and a PSI between 75 and 100 are classified as having a high phosphorus runoff potential; poultry litter can be applied to these fields in accordance with a phosphorus-based nutrient management plan, which limits the amount of phosphorus applied to the crop removal rate. Soils with an FIV in excess of 150 and a PSI between 50 and 75 are classified as having medium phosphorus runoff potential; poultry litter can be applied to these fields in accordance with a nitrogen-based nutrient management plan but cannot be planted to corn continuously. Soils with a FIV less than 150 or PSI less than 50 are classified as having a low phosphorus runoff potential; poultry litter can be applied to these soils in accordance with a nitrogen-based nutrient management plan.

As noted above, the principal crops grown on the Delmarva Peninsula are corn and soybeans, grown in rotation. Since nitrogen is not applied to soybeans, we assumed that it would be economical to apply poultry litter only to fields in which corn was grown. Application rates were determined by soil phosphorus status and the phosphorus index level, adjusted to take into account likely crop rotations, as discussed below. Planted corn acreage was assumed to equal the year 2000 level; the most recent figures reported in each state's agricultural statistics (see Table 1). Corn acreage in Cecil County, Maryland was not included in the analysis. Corn acreage in New Castle County, Delaware was not included in the total for Kent County, Delaware, even though broiler production in New Castle County was included in the total for Kent County.[1]

The following legally permissible application rates were used in the analysis. As noted above, in accordance with current regulations, it was assumed that no poultry litter could be applied to fields with very high phosphorus runoff potential. Poultry litter can be applied to land

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[1] This procedure overestimates hauling requirements by ignoring land on which winter wheat is grown in rotation with soybeans and corn and corn acreage in New Castle County,.

with high phosphorus runoff potential at a rate equal to the crop removal rate, so that no additional phosphorus accumulates in the soil. It was assumed that the phosphorus removal rate for corn corresponded to a poultry litter application rate of 1 ton per acre. It was assumed that land with medium phosphorus runoff potential would be farmed using a two-year corn-wheat-soybean rotation with poultry litter applied at nitrogen-based nutrient management plan application rate of 3 tons per acre on corn, 1 ton per acre on wheat, and none on soybeans, giving an average annual application rate of 2 tons per acre. Poultry litter can be applied to land with low phosphorus runoff potential at a rate equal to the crop nitrogen removal rate, which was assumed to correspond to a poultry litter application rate of 3 tons per acre.

FIV and PSI values calculated from data from soil tests conducted by the University of Maryland were used to estimate the shares of corn acreage with very high, high, medium, and low runoff potential. These estimates were made on a regional basis: All counties on the Lower Eastern Shore were assumed to have the same distribution of soil phosphorus runoff potential, as were all counties on the Upper Eastern Shore (Table 4). Data from individual counties were used to extrapolate the Maryland data to Delaware and Virginia.[2]

As Table 4 indicates, there is more than enough crop acreage to absorb poultry litter applied as fertilizer at legally permissible rates in all but five counties on the Delmarva Peninsula. As a result of having very large numbers of broilers relative to corn acreage, those five counties—Caroline, Somerset, Wicomico and Worcester Counties in Maryland and Sussex County, Delaware—generate an estimated total surplus of 229,921 tons of poultry litter that cannot legally be applied as fertilizer. However, other counties on the Peninsula have sufficient

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[2] Sussex and Kent Counties in Delaware were assumed to have the same distribution of phosphorus runoff potential as Caroline and Wicomico Counties combined. Accomack County, Virginia, was assumed to have the same distribution of phosphorus runoff potential as Somerset and Worcester Counties combined.

corn acreage to absorb an additional 218,496 tons of poultry litter, about 11,000 tons less than the excess generated in the other 5 counties.

This figures indicate that transportation costs are negligible for over two-thirds of the Peninsula's annual poultry litter supply, which can generally be applied on land within a mile of poultry production facilities. They are not large for much of the remainder, since poultry producing areas of many counties with surpluses of poultry litter are adjacent to poultry producing areas of counties with surplus cropland that can absorb additional poultry litter. The cost of longer distance hauling would be about $1.85 per ton within a 5-mile radius, $2.85 per ton within a 10-mile radius, and $4.55 per ton within a 15-mile radius. Hauling litter even longer distances would be necessary only rarely.

Alternative Uses of Poultry Litter

Poultry litter is currently used for several alternative uses. Table 5 reports estimated willingness to pay (net of hauling costs) for poultry litter for these uses, including pelletization, composting, forest fertilization, steam/electricity cogeneration, and electricity production. All are less than the value of poultry litter as fertilizer, except in cases where litter must be hauled more than 15 miles. The value of poultry litter in pelletization appears to be lower than the value of fertilizing either cropland or forestland, but it is still positive. The price received by growers close to the pelletization plant may exceed the price paid for poultry litter by buyers sufficiently far away. The value of poultry litter in compost appears to be relatively low, suggesting that the use of poultry litter for this purpose is unlikely to expand much beyond the 10,000-15,000 tons (1-2 percent of the total poultry litter supply) used at present. The value of poultry litter in forest fertilization is quite high relative to other uses but could account for no more than 2-3 percent of the poultry litter generated on the Delmarva Peninsula in any year. The value of poultry litter in cogeneration of steam and electric power is positive but small. It could be larger if renewable energy tax credits were applicable but would still be less than the value of poultry litter in pelletization. The value of poultry litter in electric power generation appears to be negative and thus would be economically viable only if the generator were able to charge growers for disposing of poultry litter. Since poultry litter has a reasonable economic value in uses that can easily absorb the total amount produced by the Delmarva broiler industry, there is little chance that generators would be able to charge growers for this purpose. Thus, electric power generation is unlikely to be an economically viable use of poultry litter.

Conclusions

We present a theoretical and empirical analysis the impacts of nutrient management regulations in a heterogeneous region. The theoretical analysis indicates that in the absence of phosphorus based regulation the use of manure will be determined by desired organic matter nitrogen stocks. Nutrients provided by decaying organic matter will be supplemented by chemical fertilizers. In areas with high soil phosphorus stocks, however, it may be necessary to avoid the use of manure until crop uptake has depleted soil phosphorus stocks to desired steady state levels. The empirical analysis focuses on phosphorus-based management of poultry litter on the Delmarva Peninsula. The analysis indicates that in the presence of smoothly functioning manure markets there is sufficient cropland to absorb all the poultry litter generated, Moreover, hauling will be required only for short distances; the resulting negligible to low transportation cost makes poultry litter an economically attractive alternative to chemical fertilizers.

The key assumption of the empirical analysis was that manure markets function smoothly. While there are currently a few individuals working on matching buyers and sellers (largely ancillary to their main business of hauling manure), extensive, transparent manure marketing institutions are not presently in place. The development of such institutions is crucial for efficient nutrient management.

Another obstacle to efficient nutrient management in the region is the imbalance in the ratio of manure nutrient content (α_n/α_p) to the ratio of crop uptake (γ_n/γ_p). Current research suggests that by 2010, feed manipulation and additives may allow producers to alter manure nutrient contents such that $\alpha_n/\alpha_p = \gamma_n/\gamma_p$. Bringing those ratios into line with each other would allow growers to apply significantly more manure on their fields while remaining in compliance with phosphorus-based nutrient management regulations.

Table 1. Broiler Production and Poultry Litter by County, Delmarva Peninsula

	Land Area (Acres)	**Corn Planted (Acres)**	**Farms with Broiler Sales**	**Number of Broilers Sold**	**Litter (Tons)**
Maryland					
Caroline	204,889	22,600	138	38,539,026	46,247
Cecil	222,805	20,300	-	-	-
Kent	178,837	42,100	12	3,953,882	4,745
Queen Anne's	238,210	47,100	33	11,389,932	13,668
Talbot	172,248	34,900	35	13,282,962	15,940
Dorchester	356,824	20,100	71	21,826,885	26,192
Somerset	209,416	10,500	150	46,496,103	55,795
Wicomico	241,389	21,300	283	84,278,399	101,134
Worcester	302,871	34,600	233	62,466,511	74,960
Delaware					
Kent	378,048	38,600	136*	43,899,605*	52,680*
Sussex	600,128	98,400	669	240,100,395	288,120
Virginia					
Accomack	290,944	21,500	61	22,971,405	26,919
Delmarva	3,396,610	443,700	1,821	589,205,105	706,399

* Includes New Castle County.

Table 2. Value of Poultry Litter as a Fertilizer Substitute (Net of Application and Testing Cost)

	Nutrient Value	*Application Cost*		*Testing Cost*	*Cleanout*	*Net Value*	
		Low	*High*			*Low*	*High*
Continuous Corn							
Phosphorus-Based Nutrient Management Plan	$32.26	$ 7.31	$14.63	$ 0.20	$ 4.00	$13.44	$20.75
Nitrogen-Based Nutrient Management Plan	$19.24	$ 3.63	$ 7.26	$ 0.20	$ 4.00	$ 7.78	$11.41
Corn-Soybean Rotation							
Phosphorus-Based Nutrient Management Plan	$31.20	$ 7.31	$14.63	$ 0.20	$ 4.00	$12.37	$19.69
Nitrogen-Based Nutrient Management Plan	$24.02	$ 3.63	$ 7.26	$ 0.20	$ 4.00	$12.56	$16.19
Corn-Wheat-Soybean Rotation							
Phosphorus-Based Nutrient Management Plan	$34.40	$ 7.31	$14.63	$ 0.20	$ 4.00	$15.58	$22.89
Nitrogen-Based Nutrient Management Plan	$28.60	$10.28	$20.56	$ 0.20	$ 4.00	$3.84	$14.12

Table 3. Estimated Distribution of Soil Phosphorus Runoff Potential

	Share of Land Classified with Runoff Potential as:			
	Very High	High	Medium	Low
Maryland				
Upper Eastern Shore				
Caroline	0.0331	0.0993	0.1126	0.755
Kent	0.0331	0.0993	0.1126	0.755
Queen Anne's	0.0331	0.0993	0.1126	0.755
Talbot	0.0331	0.0993	0.1126	0.755
Lower Eastern Shore				
Dorchester	0	0.1185	0.1852	0.6963
Somerset	0	0.1185	0.1852	0.6963
Wicomico	0	0.1185	0.1852	0.6963
Worcester	0	0.1185	0.1852	0.6963
Delaware				
Kent	0	0.172	0.266	0.563
Sussex	0	0.172	0.266	0.563
Virginia				
Accomack	0	0.061	0.106	0.833

Source: University of Maryland FIV and PSI data, evaluated by university scientists.

Table 4. Poultry Litter Production and Crop Land Capacity

County	Total Poultry Litter Generated (tons)	Surplus Capacity (tons)	Excess Poultry Litter (tons)
Maryland			
Upper Eastern Shore			
Caroline	46,247		5,533
Kent	4,745	66,352	
Queen Anne's	13,668	71,182	
Talbot	15,940	46,932	
Lower Eastern Shore			
Dorchester	26,192	12,182	
Somerset	55,795		35,749
Wicomico	101,134		60,469
Worcester	74,960		8,902
Delaware			
Kent	52,680	18,039	
Sussex	288,120		107,843
Virginia			
Accomack	26,919	15,233	
Total Delmarva	706,399	218,496	229,921

Table 5. Alternative Uses for Poultry Litter

Alternative Use	Value (per ton)	Current Usage (tons)	Potential Usage (tons)
Pelletization	$8.50	80,000	150,000
Composting	$1 - $4.40	10,000	15,000
Forest Fertilization	$6 - $13	None	23,750
Cogeneration	$0 - $5.70	None	400,000
Electricity Production	Negative	None	500,000

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