Phosphorus Imbalances in the Chesapeake Bay Watershed: Can Forestland and Manure Processing Facilities Be the Answers?

Serkan Catma and Alan Collins

A mixed-integer linear programming model was formulated to minimize the cost of transport and processing of excess manure in the Chesapeake Bay watershed. The results showed that primarily poultry manure was moved out of surplus counties for land application or processing. In the base model, annual cost was more than $350 million, with the bulk of the cost arising from construction of energy facilities for poultry manure. Forestland application of poultry manure had the lowest average cost, and more forestland than agricultural land was used for manure application. The lowest cost scenario was $127 million annually when constraints were removed to expand manure application on agricultural land and allow unlimited construction of composting facilities. Such a low-cost solution could not realistically be implemented without further development of markets for compost.

Key Words: mathematical programming, water quality, animal manure, composting

Historically, regional concentrations of industrial animal agriculture have led to concerns about nutrient imbalances occurring within watersheds across the United States (Gollehon et al. 2001). These imbalances represent an excess of fertilizer and manure nutrients compared to crop nutrient needs. Kellogg et al. (2000) estimated that 73 counties across the United States had excess nitrogen (N) from manure, while 160 counties had excess phosphorus (P) from manure.

The Chesapeake Bay watershed (CBW) is a prime example of this concern. Previous work has documented that the CBW suffers from both N and P imbalances (Ribaudo et al. 2003, Mid-Atlantic Regional Water Program 2005). In the CBW, there are 11 times more livestock animals than humans, and about 40 percent of N and 54 percent of P applied to land within the watershed come from manure (Chesapeake Bay Foundation 2004). This same report estimates that animal manures contribute 18 percent of N and 25 percent of P reaching the Bay. Kellogg (2000) ranked the CBW among the three highest priority watersheds in the United States needing protection from manure nutrients.

The CBW has the highest land area to water volume ratio of any riverine estuary in the world (Taylor and Pionke 2000). This means that excess nutrients along with sediments can lead to excessive growth of phytoplankton in the Bay. In its most recent assessment, the Chesapeake Bay Program (2009) found that water quality in the Bay was at only 21 percent of its desired goal, while ecosystem health was at 38 percent of goal. Increased areas of low oxygen levels (called hypoxia zones) in the Bay and its tidal tributaries continue to be major problems, with dissolved oxygen standards being less than 50 percent of goal for most of the Bay during summer months. Populations of both native oysters and blue crabs in the Bay were estimated as being well below their restoration goals (Chesapeake Bay Program 2009). According to Baker (2009), immense areas of the Chesapeake Bay and its tidal tributaries are essentially dead due to a lack of dissolved oxygen

---

Serkan Catma is Assistant Professor in the Department of Financial Systems at West Liberty University in West Liberty, West Virginia. Alan Collins is Professor in the Department of Agricultural and Resource Economics at West Virginia University in Morgantown, West Virginia.

The Mid-Atlantic Water Program (http://www.mawaterquality.org/) provided funding and data to support this research. The authors would like to thank the reviewers for their insights and assistance in improving this article.

Agricultural and Resource Economics Review 40/1 (April 2011) 116–132

to sustain healthy life. It has been estimated that in order to remove the Bay and its tributaries from the "impaired waters" list, N flows would have to be reduced by 39 percent and P flows by 33 percent from their 2000 levels (Chesapeake Bay Foundation 2004).

Overall, non-point pollution sources are seen as being primarily responsible for rivers and streams in the United States not being able to meet their designated uses due to poor water quality (U.S. Environmental Protection Agency 2002). While point sources have been addressed in the past, indications are that non-point sources, mainly animal waste, contribute the majority of nutrient loads (82 percent of N and 62 percent of P) into the Chesapeake Bay (Cestti, Srivastava, and Jung 2003). Thus, reducing animal manure's contribution to nutrient flows into the Bay becomes essential to improving water quality.

Various state-level programs have been implemented to deal with manure in a manner that protects water quality. These include: manure transport subsidy programs in Maryland, Delaware, Virginia, and West Virginia; P-based nutrient management plans required in Delaware, Maryland, and Virginia; and state subsidies provided for poultry litter processing in Delaware. Even though there are many alternatives to utilize excess manure, the majority of existing studies (such as Ribaudo et al. 2003) focus only on the land application of manure as an alternative to commercial fertilizer. There has not been a comprehensive assessment conducted that combines both land resource availability (agricultural and forestland) with the potential to construct manure processing facilities.

This article is unique because it evaluates cost-minimizing manure management in the CBW that protects water quality and includes alternatives of both agricultural and forestland application along with composting, pelletization, and electricity generation. Determining the optimal number and location of processing facilities has been lacking in past studies and would be critical to shape the direction of future manure management efforts in the CBW. Mathematical modeling of manure transport and use for land application and processing options will be conducted in order to estimate least-cost approaches to manure management.

The research objectives of this article are as follows: (i) Provide an updated estimate of where excess manure exists throughout the CBW by including fertilizer use estimates; (ii) determine least-cost combinations of manure management to transport for land application or processing in order to eliminate manure P imbalances within the CBW; and (iii) create a base case and four realistic scenarios to evaluate least-cost strategies for manure management; the components of the base model and four scenarios are summarized in Appendix 1.

This article is organized as follows: a literature review, presentation of the theoretical framework and model, description of methods, results, and conclusions. We find that in order to appropriately manage manures to protect water quality throughout the CBW, annual costs range between $127 and $350 million. Our findings indicate that it is primarily poultry litter that must be transferred out-of-county or processed, and that including forestland and manure processing facilities, particularly composting, to the model was a vital component to minimizing costs.

Literature Review

Documentation of excess manure by county has been investigated by a number of researchers (Lander, Moffitt, and Alt 1998, Kellogg and Lander 1999, Kellogg et al. 2000, Gollehon et al. 2001). The Mid-Atlantic Water Program[1] determined counties with excess manure N and P within the Mid-Atlantic states. Landowner preferences, potential application problems, and costs associated with land application of manure were not considered in any of the studies mentioned above.

Most research on manure management has focused on land application of manure as an alternative to commercial fertilizer. However, high transportation and application costs can threaten the economic feasibility of this option, especially when the available land for manure application is limited (Bosch and Napit 1991, Ribaudo et al. 2003). Mathematical programming techniques have been widely used to determine the least-cost methods to utilize manure. Most of these studies have focused on minimizing transportation costs without considering processing options of manure (Bosch and Napit, 1991, 1992, Paudel et al. 2002, Ribaudo et al. 2003, Young et al. 2005, Keplinger and Hauck 2006). While these studies utilized

---

[1] http://www.mawaterquality.agecon.vt.edu.

standards or guidelines for environmentally protective manure management, Ancev et al. (2006) examined economically optimal strategies for manure management within a biophysical framework of pollution abatement within watersheds.

Transportation distances and cost implications of manure movement in the CBW have been examined by Ribaudo et al (2003), Aillery et al. (2005), and Aillery et al. (2009). These studies examined cost estimates for both N and P standards, plus air and water quality policies. Depending upon the willingness to accept manure, all manure in the CBW could be land-applied on agricultural land. For P-standard application rates, Ribaudo et al. (2003) estimated the total cost for manure transport and land application on agricultural land in the Chesapeake Bay watershed to be between \$140 and \$160 million annually. Net costs (minus reduced fertilizer) were under \$100 million annually.

Composting options have been examined separately by Fritsch and Collins (1993) and Vervoort and Keeler (1999). Other modeling efforts incorporated water pollution risks of manure application into the objective function within a goal programming model (Jones and D'Souza 2001) or a multi-criteria model (Giasson, Bryant, and Bills 2002). Other studies have employed models to maximize returns to crop production viewing manure as an alternative to commercial fertilizer (Govindasamy and Cochran 1995, 1998, Carreira, Young, and Goodwin 2005). None of these models considered alternatives such as manure application on forestland or manure processing options within their model.

Theoretical Framework and Model

The theoretical framework selected for this paper is one of constrained cost minimization. This framework examines manure management from a cost-effectiveness perspective, such that a specified policy goal (e.g., eliminating P nutrient imbalances within agriculture in the CBW) is set and the cost of achieving this goal is minimized. Cost-effectiveness is an appropriate analysis when the benefits from prevented economic damages are difficult to measure (Tietenberg and Lewis 2009), as is the case with non-point pollution reductions due to nutrient management.

Our specific goal in this paper is to minimize the annual costs across society from the transport and/or processing of manure in order to eliminate county-level P excesses within agricultural land as a means of providing water quality protection from nutrient and manure management. This approach is typical of other existing research on the economics of manure management (Paudel et al. 2002, Ribaudo et al. 2003, Young et al. 2005, Aillery et al. 2009). A basic transportation problem approach is utilized where the cost of manure transported or processed is minimized by moving from surplus nodes (counties with excess manure P) to deficit nodes (counties with not enough P for agricultural land or counties with processing facilities). We focus on a watershed-wide analysis, using accepted guidelines for the balancing of nutrient inflows and uptakes on agricultural land on a county basis.

Our base model presented below is divided into seven equations. First, the objective function minimizes the costs of appropriately utilizing all excess manure P within the CBW. The objective function is represented as

(1a)

$$Min\ TC\left(\left[\sum_i\sum_j Qts_{ij} \times Cts_{ij}\right] + \left[\sum_i\sum_j Qtd_{ij} \times Ctd_{ij}\right] + \left[\sum_i\sum_j Qtp_{ij} \times Ctp_{ij}\right]\right)$$

(1b)

$$+\left(\left[\sum_i\sum_k Yts_{ik} \times Ctsf_{ik}\right] + \left[\sum_i\sum_k Ytd_k \times Ctdf_{ik}\right] + \left[\sum_i\sum_k Ytp_{ik} \times Ctpf_{ik}\right]\right)$$

(1c)

$$+\left(\left[\sum_t\sum_n\sum_\alpha Fc_t \times B_{tn\alpha}\right] + \left[\sum_i\sum_t\sum_n\sum_\alpha Wp_{itn\alpha} \times Ccp_{it\alpha}\right]\right)$$

(1d)

$$+\left(\left[\sum_d\sum_x\sum_\alpha Fd_d \times B_{dx\alpha}\right] + \left[\sum_i\sum_d\sum_x\sum_\alpha Wd_{idx\alpha} \times Ccd_{id\alpha}\right]\right)$$

$$(1e) \qquad +\left(\left[\underset{r\ y\ \alpha}{\sum\sum\sum} Fp_r \times Bp_{ry\alpha}\right] + \left[\underset{i\ r\ y\ \alpha}{\sum\sum\sum\sum} Wtp_{iry\alpha} \times Ptp_{ir\alpha}\right]\right)$$

$$(1f) \qquad +\left(\left[\underset{e\ z\ \alpha}{\sum\sum\sum} Fep_e \times Bep_{ez\alpha}\right] + \left[\underset{i\ e\ z\ \alpha}{\sum\sum\sum\sum} Wep_{iez\alpha} \times Pep_{ie\alpha}\right]\right)$$

$$(1g) \qquad -\left[\sum_i Prf_i \times (Fex_i)\right],$$

where

TC is the total cost of utilizing excess manure in the CBW,

i refers to county with surplus manure phosphorus,

j refers to county where crop and pastureland have deficit phosphorus,

k refers to county where forestland needs phosphorus,

a refers to county where processing facilities are constructed,

t refers to number of litter composting facility capacities,

n refers to number of litter composting facilities for every capacity type,

d refers to number of cattle manure composting facility capacities,

x refers to number of cattle manure composting facilities for every capacity type,

r refers to number of pelletization facility capacities,

y refers to number of pelletization facilities for every capacity type,

e refers to number of energy plant capacities, and

z refers to number of energy plants for every capacity type.

The objective function consists of seven components to equation (1). While equations (1a) and (1b) deal with the costs of applying manure on agricultural and forestlands, the next four equations [(1c) through (1f)] consider the costs of processing manure by composting, pelletization, and energy generation;[2] and finally, equation (1g) consists of a reward for reducing commercial fertilizer use. These processing options are included in the model because they expand the number of potential uses for manure beyond just agriculture or forestry. Both poultry litter and cattle manure are allowed for composting, while only poultry litter is considered technically feasible for pelletization and energy generation. Determining cost-minimizing location and number of these processing facilities can serve as a guideline for future planning of facility location. While there is an existing pelletization plant in Delaware, there are currently no manure-to-energy or high-capacity, off-farm composting facilities located within the CBW.

Equations (1a) and (1b) minimize transportation costs of manure (swine, cattle, and poultry) from surplus counties to deficit cropland and forestland counties based on phosphorus needs. Six variables—Qts_{ij}, Qtd_{ij}, Qtp_{ij}, Yts_{ik}, Ytd_{ik}, and Ytp_{ik}—represent decisions for tons of swine, cattle, and poultry manure transported from the ith surplus P county to a jth cropland P deficit or kth forestland P deficit county respectively. The transportation costs—Cts_{ij}, Ctd_{ij}, Ctp_{ij}, $Ctsf_{ik}$, $Ctdf_{ik}$, and $Ctpf_{ik}$—include manure hauling costs and other costs such as loading, unloading, and application costs. Deficit P cropland counties include those within the CBW plus sink counties that are located adjacent to the CBW and so could potentially import manure from the watershed. Since excess manure calculations conducted for each county did not include P balances on forestland, transporting manure to a forestland within a surplus county is allowed for this option.

Equations (1c), (1d), (1e), and (1f) minimize the costs of constructing and operating poultry and dairy composting facilities using poultry or cattle manure, pelletization facilities using poultry manure, and energy plants using poultry manure, respectively. Annualized capital costs of a processing facility are represented for composting poultry manure ($Fc_{\alpha t}$), composting dairy manure ($Fd_{\alpha d}$), litter pelletization (Fp_r), and energy production from poultry manure (Fep_e). These facilities are distinguished by capacity size for each type of facility (tth and dth for composting, rth

---

[2] Poultry litter and cattle manure are considered for composting while only poultry litter is considered for pelletization and energy generation.

for pelletization, and eth for energy) and county location (αth). Variables $B_{tn\alpha}$, $Bd_{dx\alpha}$, $Bp_{ry\alpha}$, and $Bep_{ez\alpha}$ are binary and equal to 1 when facilities are built and zero when no facilities are constructed. Variables $Wp_{itn\alpha}$ and $Wd_{idx\alpha}$ represent decisions for the tons of poultry manure and cattle manure that are transported from the ith surplus county to nth and xth composting facility each with tth and dth capacity type at the αth facility county. $Ccp_{it\alpha}$ and $Ccd_{id\alpha}$ include the hauling cost per ton of poultry manure from the ith surplus county to each composting facility with tth and dth capacity type at the αth facility county and the production cost per ton of input poultry and cattle manure.

The variable $Wtp_{iry\alpha}$ represents decisions about the tons of poultry manure that are transported as inputs for pelletization from the ith surplus county to the yth facility with rth capacity type located at the αth facility county. Net cost includes transportation and operating costs ($Ptp_{ir\alpha}$) per ton of litter. The variable $Wep_{iez\alpha}$ represents decisions on the tons of poultry manure that are transported from the ith surplus county to the αth facility county for electricity generation where the zth plant with eth capacity type is constructed.

Lastly, equation (1g) represents total commercial fertilizer savings when replaced with manure. The variable Fex_i is a decision for each surplus county concerning the tons of commercial fertilizer P removed. Removing commercial fertilizer P and replacing it with manure P is assumed to create a constant cost saving of Prf_i per ton.

As described in the "Methods" section, computations of agricultural surplus or deficit P for each county are based on nutrient inflows from manure and commercial fertilizer and outflows from crop uptake. Excess P ($EXCP$) is computed for each county, and the model allows this excess to be divided into P from manure by animal type. To ensure that all excess P from manure in each surplus county is utilized, four primary surplus constraints are constituted in equations (2a)–(2d):

$$\text{(2a)}\quad \sum_j Qts_{ij} \times Ps_i + \sum_k Yts_{ik} \times Ps_i - ESP_i = 0$$

$$\text{(2b)}\quad \sum_j Qtd_{ij} \times Pd_i + \sum_k Ytd_{ik} \times Pd_i + \sum_d \sum_x \sum_\alpha Wd_{idx\alpha} \times Pd_i - EDP_i = 0$$

$$\text{(2c)}\quad \sum_j Qtp_{ij} \times Ppi + \sum_k Ytp_{ik} \times Pp_i + \sum_t \sum_n \sum_\alpha Wp_{itn\alpha} \times Pp_i + \sum_r \sum_y \sum_\alpha Wtp_{iry\alpha} \times Pp_i + \sum_e \sum_z \sum_\alpha Wep_{iez\alpha} \times Pp_i - EPP_i = 0$$

$$\text{(2d)}\quad ESP_i + EDP_i + EPP_i + Fex_i = EXCP(i)\,.$$

Equations (2a), (2b), and (2c) limit utilization of swine, cattle, and poultry manure P to total excess manure P in each surplus county. Tons of each manure type transported for land application and processing options are multiplied by county-average phosphorus content per dry ton of swine manure (Ps_i), cattle manure (Pd_i), and poultry manure (Pp_i) at the ith surplus county. The variables ESP_i, EDP_i, and EPP_i transmit $EXCP_i$ to tons of swine, cattle, and poultry manure P in each surplus county, respectively. Subtracting these variables from total tons of manure P transported for various options and setting the right-hand side equal to zero ensures that all excess manure P is properly utilized in surplus counties. Based on equation (2d), tons of total excess manure P generated at each surplus county is equal to total manure P replaced commercial fertilizers or transported for either land application or processing options. By ensuring that all surplus manure P is utilized appropriately, equation (2d) provides environmental protection for water quality [see Mid-Atlantic Regional Water Program (2005) for an explanation of the connections between nutrient balances and water quality].

A feasible solution requires that ESP_i, EDP_i, and EPP_i cannot exceed tons of manure P generated from each manure type in that surplus county. The three components of equation (3) ensure that this limitation exists in the model:

$$\text{(3a)}\quad ESP_i \le Swmp_i$$

$$\text{(3b)}\quad EDP_i \le Catmp_i$$

$$\text{(3c)}\quad EPP_i \le Plitp_i\,,$$

where $Swmp_i$, $Catmp_i$, and $Plitp_i$ are the total quantities of P generated from swine, cattle, and poultry manure in each surplus county i, respectively. A less than or equal sign is included in each equation (3) constraint to avoid over-transportation of manure by limiting manure transportation to the total amount of manure generated in each surplus county. In addition, the amount of commercial fertilizer replaced by animal manure is constrained by actual commercial fertilizer P usage in each surplus county (G_i) based on data from Terry and Kirby (2002). The commercial fertilizer constraint is presented as

$$Fex_i \leq G_i. \tag{4}$$

Deficit constraints of equation (5) limit the total manure that can be applied on crop and forestlands in P-deficit counties based upon computed tons of deficit P (TDP_j and $TDPF_k$):

$$\begin{aligned}\sum_i Qts_{ij} \times Ps_i + \sum_i Qtd_{ij} \times Pd_i \\ + \sum_i Qtp_{ij} \times Pp_i \leq TDP_j\end{aligned} \tag{5a}$$

$$\begin{aligned}\sum_i Yts_{ik} \times Ps_i + \sum_i Ytd_{ik} \times Pd_i \\ + \sum_i Ytp_{ik} \times Pp_i \leq TDPF_k.\end{aligned} \tag{5b}$$

The above constraints allow the model to transport less than total manure nutrient deficit if the model finds it cost-efficient to do so. The potential for developing nutrient imbalances within deficit counties is avoided by inclusion of equation (5) constraints in the model.

If willingness to accept (WTA) manure in deficit counties is accounted for, then this parameter will influence total manure received by limiting total acreage available for manure application. Because most of these spatial factors are not available as datasets, county-specific WTA manure is assumed to be determined by one spatial factor in this study. For each county, WTA manure is specified as the ratio of cropland and forestland acres that are not within a quarter-mile radius of developed land divided by the total acres of cropland and forestland. Equation (6) constraints are in addition to those in equation (5). These secondary deficit county constraints are based on the assumptions that the capacity of an area to absorb manure is affected by the proportion of the cropland suited to receive manure and that landowners' preferences will affect the amount of manure transported to deficit counties for land application:

$$\sum_i \frac{Qts_{ij}}{Ms_j} + \sum_i \frac{Qtd_{ij}}{Md_j} + \sum_i \frac{Qtp_{ij}}{Ms_j} \leq TA_j \times WTA_j \tag{6a}$$

$$\sum_i \frac{Yts_{ik}}{Ms_k} + \sum_i \frac{Ytd_{ik}}{Md_k} + \sum_i \frac{Ytp_{ik}}{Ms_k} \leq TA_k \times WTA_k\,. \tag{6b}$$

Manure application in each cropland- and forestland-deficit county is restricted by introducing total spreadable acreage (TA) adjusted for assumptions on willingness to accept manure values (WTA). In the base model, WTA for manure in cropland and forestland counties is assumed to be one.

The final options considered for excess manure are processing facilities. Given the cost-minimization objective function, the higher cost options of processing manure would be selected only when the option of commercial fertilizer replacement is exhausted and the transport for land application opportunities becomes too expensive. Equation (7) facility constraints require that incoming poultry and dairy manure be less than constructed facility capacities for composting (7a and 7b), pelletization (7c), and energy production (7d):

$$\sum_i Wp_{itn\alpha} \leq CAPC_t \times B_{tn\alpha} \tag{7a}$$

$$\sum_i Wd_{idx\alpha} \leq CAPD_d \times Bd_{dx\alpha} \tag{7b}$$

$$\sum_i Wtp_{iry\alpha} \leq CAPP_r \times Bp_{ry\alpha} \tag{7c}$$

$$\sum_i Wep_{iez\alpha} \leq CAPE_e \times Bep_{ez\alpha}\,. \tag{7d}$$

Poultry and cattle manure composting facilities are limited to two different capacities in receiving tons ($CAPC_t$, $CAPD_d$). Pelletization plants have only one capacity ($CAPP_r$), and energy facilities have two capacity options ($CAPE_e$). Number of facilities with the same capacity in a given facility county is represented by n, x, y, and z for poultry manure composting, cattle manure composting, pelletization, and electricity-generation facilities, respectively. On a per county basis, composting and energy facilities are limited in the base model to two based on two size capacities assumed, while pelletization facilities are limited to one.

Methods

The study area is the Chesapeake Bay watershed in the Mid-Atlantic region of the United States. The CBW consists of 150 major rivers and streams and eleven major tributaries. This watershed includes portions (in parentheses) of the following states: Delaware (40 percent), Maryland (97 percent), New York (13 percent), Pennsylvania (49 percent), Virginia (54 percent), and West Virginia (15 percent). All of the District of Columbia is located in the watershed. There are 172 counties located within the watershed, along with 50 counties adjacent to the CBW border (called sink counties), also included in the analyses (Figure 1).

Manure considered in this research comes from the six major types of animal production in the region: beef cattle, dairy cattle, swine, and the three main poultry types (layers, broilers, and turkeys). P is the nutrient analyzed because, relative to crop needs, manure (particularly poultry) contributes more P than N when land-applied. The potential for over-application of P is high due to no agronomic penalty from applying too much P. These factors along with massive importations of feed into the CBW have led to an unacceptably high buildup of P in many area soils within the CBW (Coale 2000, Taylor and Pionke 2000).

Computations of excess and deficit manure P by county are required to accurately formulate the mathematical programming model. Excess and deficit manure P in tons is calculated by the sum of cropland and pastureland assimilative capacity minus commercial fertilizer P and manure P from swine, cattle, and poultry available for application. Only loblolly pine trees on private land are considered for forestland manure application because this species' response to fertilization has been well documented (Lynch and Tjaden 2004). Because current commercial fertilizer application on forestland is not known, P balance on forestland counties is estimated by multiplying annual pine P recommendation rates by loblolly pine acres in each county. Appendix 2 shows the list of references utilized to estimate P surplus and deficits within agriculture.

Figure 2 shows the distribution of excess P within the CBW. A total of 154 counties have surplus P in the watershed. The major surplus counties (over 2,000 tons of excess P) include Sussex County in Delaware; Adams, Franklin, and Lancaster Counties in Pennsylvania; and Rockingham County in Virginia. Overall, the surplus is computed to be 65,000 tons of P in the CBW. Without commercial fertilizer applications, this surplus is reduced to just over 7,000 tons.

To estimate the above base model, a mixed-integer linear programming model is formulated using General Algebraic Modeling System (GAMS). Previous studies (Bosch and Napit 1992, Fritsch and Collins 1993, Paudel et al. 2002, Ribaudo et al. 2003, Aillery et al. 2009) have used linear and non-linear transportation models to address solutions for excess manure problems. None of these studies utilized a mixed-integer transportation model where non-agricultural land options of manure utilization are included. Such a model is used to solve for cost-effective transport and to determine facility locations for processing manure at the least cost within the CBW. The model is designed to substitute commercial fertilizer with manure for land application and process manure in the watershed.

Cost figures utilized in the model are adjusted to a 2006 base year and estimated using appropriate assumptions and utilizing various data sources (Appendix 3). Based on USDA (2006a) commercial fertilizer price data, it is assumed that replacement of a ton of P from commercial fertilizer with manure saved $1,674. Land application costs of manure are based on the assumption that the manure to be applied is free but that buyers are responsible for cleaning out the facility, loading the manure, and transporting it. Methods to estimate these costs are adopted from Pelletier and Kenyon (2000).

Costs associated with composting cattle and poultry manure are based on updated estimates from Safley and Safley (1991). For each manure type, low- and high-capacity facilities are assumed to have annual capacities of 6,500 and

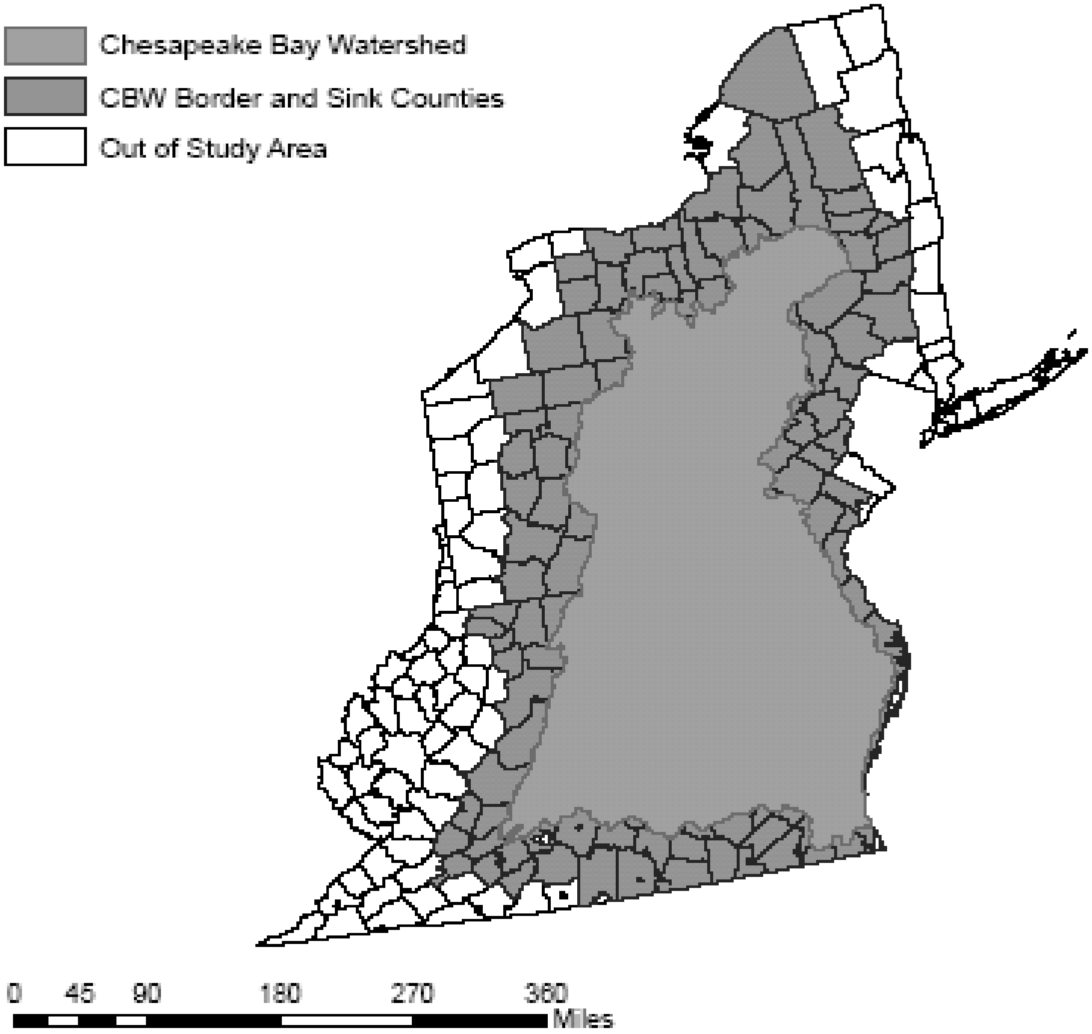

Figure 1. Chesapeake Bay Watershed Border and Sink Counties

26,000 tons of manure, respectively. Estimated composting costs consist of two parts: annual fixed costs and variable costs. Costs associated with pelletization and energy generation are based on estimates provided by Lichtenberg, Parker, and Lynch (2002). The annual input capacity of a pelletization plant is assumed to be 70,000 tons of poultry manure. Two energy plant capacity types are considered in this study, with an input capacity of 140,800 and 500,000 tons of manure a year.

Once the base model is estimated, four scenarios are then evaluated based on the following:

(1) allowing more than two composting facilities per county,
(2) altering landowner's WTA manure based on proximity to developed land,
(3) allowing commercial fertilizer replacement in deficit counties from surplus counties, and
(4) combining (1) and (3) analyses.

For WTA manure, Natural Resource Inventory 2001 land use data are used to determine cropland and forestland within a quarter-mile radius of

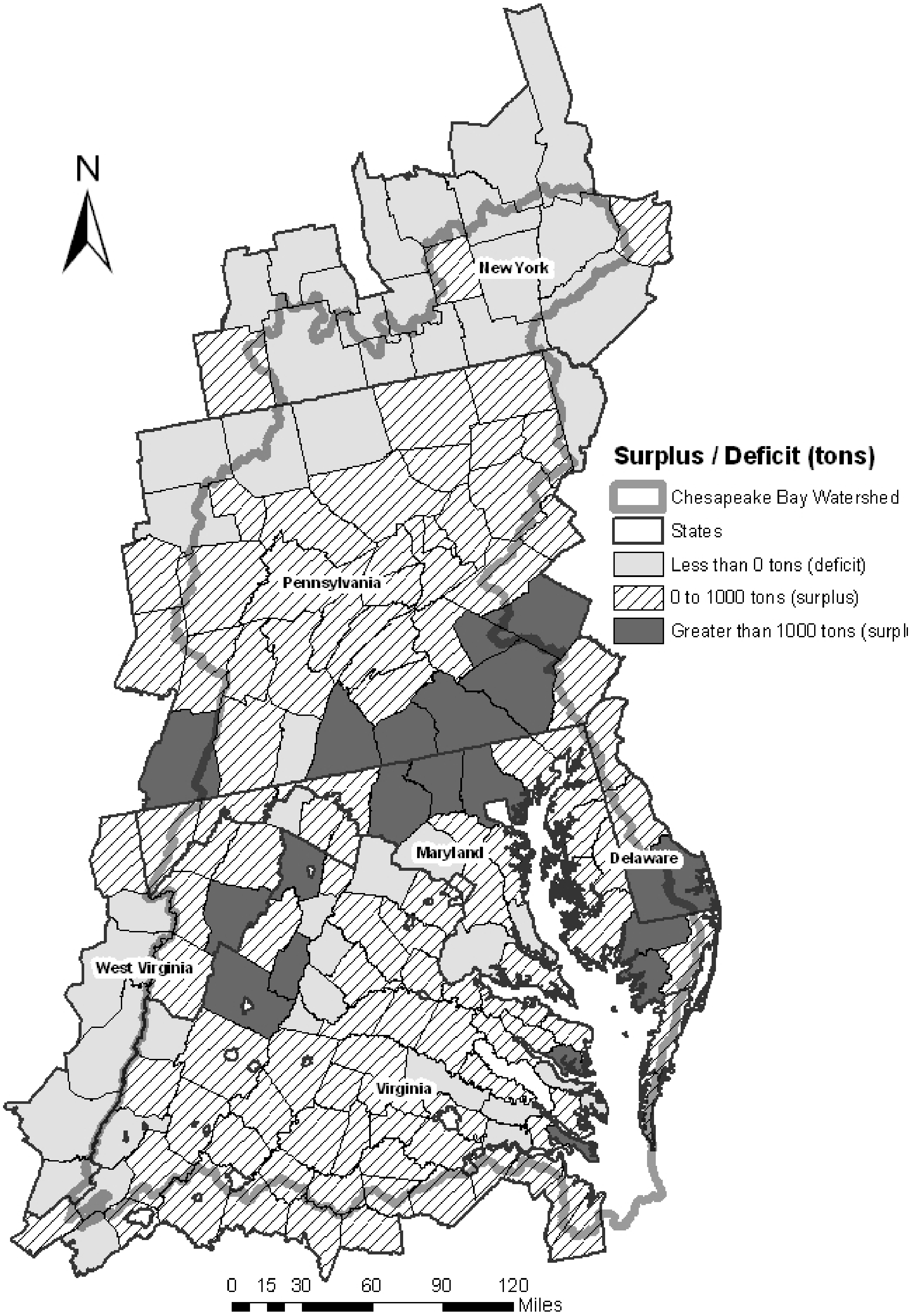

Figure 2. P Surplus and Deficit Counties in the Chesapeake Bay Watershed

developed land using ArcGIS software. On a county basis, WTA manure is based on a ratio of cropland and forestland that were not within a quarter-mile radius of developed land over total acres of cropland and forestland. Based on these results, the average WTA is 0.966 for cropland and 0.973 for forestland, with the lowest ratio being 0.49.

Results

To solve for excess manure P in the CBW, the base model results replaced just under 40,000 tons of P applied by commercial fertilizer with manure generated in surplus counties. This amounts to a 77 percent reduction in commercial P fertilizer utilized within the surplus P counties. The commercial fertilizer constraint is binding in 37 percent of the surplus counties.

Once fertilizer replacement is complete, the base model solved excess manure P by transporting for land application or processing 27,967 tons of manure P, of which 85 percent consisted of P from poultry manure. This translated into 10.4 million tons of manure being either transported for land application or processed (Table 1). About 60 percent of this manure consisted of poultry litter, with energy processing being by far the largest utilization of manure. The remaining 40 percent is land-applied, with forestland applications of manure exceeding those on agricultural land. Of the 4.36 million tons land-applied, 70 percent is cattle manure (mainly dairy). Almost all the 900,000 tons of swine manure is applied on forestland.

Under the model base assumptions, 11 energy, 15 pelletization, and 30 composting facilities are constructed to process poultry manure. In addition, nine cattle manure composting facilities are constructed. In every surplus P county allowed by the model, three facilities are constructed: a pelletization plant plus both a low- and high-capacity composting facility. Energy facilities are built in all five states: Delaware (Sussex County), Maryland (Somerset and Wicomico Counties), Pennsylvania (Berks, Franklin, Lancaster, and Lebanon Counties), Virginia (Page County and two in Rockingham County), and West Virginia (Hardy County).

The net cost of the base model is slightly more than $350 million annually, which includes almost $67 million in fertilizer savings (Table 1). The bulk of the net costs (94 percent) arise from facilities to process poultry manure, of which energy facilities make up 88 percent of poultry costs. On a per ton basis, poultry manure application on forest and agricultural lands are the least costly, followed by cattle manure application on agricultural or forestland (Table 1). Average processing cost per ton is more than twice as costly as land application for cattle and poultry manures. Energy processing is by far the most expensive utilization of manure—more than twice as costly as the next highest average cost per ton for pelletization. As discussed below when examining the four scenarios, energy facilities and pelletization plants are constructed because composting facilities are limited to two per county, and replacement of commercial fertilizer in deficit counties is not allowed.

The base model cost estimate of $350 million is substantially higher than those estimates provided by the USDA Economic Research Service's modeling efforts (Ribaudo et al. 2003, Aillery, Gollehon, and Breneman 2005). These previous models did not consider the amount of commercial fertilizer currently being utilized in their models. Thus, more agricultural land was considered available for use in these models than in our model. This difference is the primary reason why all manure could be land-applied on agricultural land in their models, but forestland and processing are required in our model. When no commercial fertilizer is included in surplus and deficit county calculations, the transport and processing costs were found to be $176 million, approximately the total costs estimated for P standard application rates by Ribaudo et al. (2003) (see Catma 2008).

Cost results of the four scenarios are reported in Table 2. Total costs vary between $126.9 and $351.1 million. Based on Scenario 1 and 3 results, the main constraints to lowering objective function costs are limiting the number of composting facilities and allowing commercial fertilizer replacement in deficit counties. The Scenario 3 result shows that changing WTA from 100 percent to less than 100 percent depending upon development only slightly increases the objective function cost (less than $1 million). In addition, slightly more manure is land-applied on agricultural land and slightly less manure is applied on forestland in Scenario 3.

When the composting facility constraint is removed in Scenario 2, the objective function cost

Table 1. Base Model Quantity and Cost Results

Use Category	Manure Utilized (million tons)	Annual Cost ($ millions)	Average Cost ($ per ton)
Agricultural land application	1.99	28.7	
cattle	1.84	26.3	14.28
poultry	0.066	0.8	11.23
swine	0.086	1.6	19.06
Forest land application	2.36	41.0	
cattle	1.23	18.2	14.82
poultry	0.31	2.9	9.28
swine	0.82	19.9	24.32
Processing	6.08	347.62	
composting (cattle)	0.23	6.87	29.35
composting (poultry)	0.49	15.51	31.83
energy (poultry)	4.31	290.37	67.38
pelletization (poultry)	1.05	34.87	33.21
Fertilizer cost savings		-66.92	
Totals	10.44	350.46	

Table 2. Cost Results of Scenarios 1 through 4[a]

Use Category	Scenario 1 Annual Cost ($ millions)	Scenario 2 Annual Cost ($ millions)	Scenario 3 Annual Cost ($ millions)	Scenario 4 Annual Cost ($ millions)
Agricultural land application	26.78	28.2	52.18	54.02
cattle	22.22	26.0	30.1	32.15
poultry	0.76	0.66	9.28	9.01
swine	3.80	2.52	12.8	12.86
Forest land application	30.61	40.35	18.24	18.17
cattle	10.63	18.28	8.39	8.61
poultry	4.36	2.85	6.79	6.61
swine	15.62	19.22	3.06	2.96
Processing	178.13	348.53	255.10	128.93
composting (cattle)	21.93	7.55	3.59	0.00
composting (poultry)	156.2	15.28	15.06	128.93
energy (poultry)	0.00	290.57	201.9	0.00
pelletization (poultry)	0.00	35.13	34.55	0.00
Fertilizer cost savings	-66.92	-66.92	-74.25	-74.25
Totals	168.60	351.17	350.46	126.88

[a] Scenario 1 allows more than two composting facilities per county. Scenario 2 alters landowner's WTA manure. Scenario 3 allows commercial fertilizer replacement in deficit counties from surplus counties. Scenario 4 combines Scenario 1 and 3 analyses.

falls dramatically, to $168 million. No energy and pelletization facilities are constructed, and most of the 5.36 million tons which were utilized in those facilities in the base model are transferred to composting. This model recommends that a total of 227 poultry manure composting facilities be constructed in the CBW. These results show that composting facilities are the most cost effective processing type. These facilities are concentrated in the counties where the base model constructed energy facilities. Leading counties are 46 composting facilities in Rockingham County, Virginia, and 41 in Sussex County, Delaware. With this transfer, average fixed plus variable costs of processing falls from $57 to $27 per ton of manure, along with a reduction of overall average cost per ton from $39.99 to $22.56. In order to avoid building any energy facilities, at least 10 composting facilities per county must be allowed in the model. To avoid building pelletization facilities, the maximum number of composting facilities needs to be set at 26.

The lowest objective function cost is found when Scenarios 1 and 3 are combined in Scenario 4 (Table 2). Here, more than two times the manure is applied on agricultural land in deficit counties compared to the base model with application of all three manure types increasing by similar amounts. The dual price results of relaxing the equation (4) constraint show that replacement of commercial fertilizer generates the largest cost savings in the state of Maryland, as seven out of the top ten dual prices for equation (4) are from counties in this state. Compared to the base model, manure use is reduced by 35 percent and 21 percent for forestland application and processing, respectively. Seventy percent of all forestland application of manure occurs in Virginia. Only poultry manure is composted under this scenario, and the average cost of manure transport and/or processing is $19.27.

Finally, in Scenario 4, manure generated in three counties (Lancaster, Pennsylvania; Rockingham, Virginia; and Sussex, Delaware) accounts for almost half the costs of land application and processing in the model ($91 million out of the $200 million). The bulk of the costs in each county are associated with composting facilities—67 percent in Lancaster, 95 percent in Rockingham, and 100 percent in Sussex. All excess manure in Delaware was composted so that none was transported out of surplus counties to be land-applied. Thus, our model identified composting as a less costly alternative to pelletization, which is currently being practiced at a facility in Sussex County, Delaware.

Conclusions

Nutrient imbalances in the Chesapeake Bay watershed stem primarily from the use of imported livestock feed from outside the watershed, thereby adding more P from manures than can be utilized by crops and pasture. Our model of minimum cost utilization of P includes three additional options that have not generally been considered in the development of optimal manure utilization models: inclusion of current commercial fertilizer use, forestland application, and processing facilities. Each of these options plays a crucial role in the optimal solutions.

Commercial fertilizer replacement is an obvious choice for inclusion in each model as it has a negative coefficient in the cost-minimization objective function. Fertilizer replacement should be a key element of policies designed to protect the Chesapeake Bay. However, fertilizer replacement alone does not solve excess P problems in the watershed. By including forestland to our model, the base model utilizes more forest than agricultural land for land application. Even lower cost scenarios utilize substantial acreages of forestland for land application. Lastly, extensive use of poultry manure composting facilities is essential to dramatically reduce the cost of creating a nutrient balance for P in the watershed. Thus, Chesapeake Bay policies should encourage all three manure uses with regional foci of composting in Delaware, commercial fertilizer replacement in Maryland, and forestland application in Virginia.

To lower manure utilization costs substantially, our model recommends building 227 composting facilities in the CBW. This number of composting facilities would more than double the amount of compost currently being produced annually in Maryland, Pennsylvania, and Virginia.[3] Since compost utilization generally depends primarily upon local markets, without government intervention it is doubtful that compost markets in the region

---

[3] An estimate of current compost production was derived using a count of facilities multiplied by the average production per facility from "Composting Facilities in EPA Region 3," available at http://www.epa.gov/reg3wcmd/solidwastecomposting.htm#association.

could absorb the additional compost production of approximately 4.5 million tons annually.

The annual costs of P utilization in our models range from $127 million to over $350 million. If this utilization could effectively eliminate manure impacts on water quality in the Chesapeake Bay, then an approximate nutrient reduction of 20 percent would occur. From an economic perspective, there are two questions raised by these results: (i) are manure transport and processing the most cost efficient strategies to achieve P load reductions in the Chesapeake Bay? and (ii) do the benefits of P reductions from manure transport and/or processing exceed the costs? For both questions, somewhat limited evidence suggests that the answer is probably no.

For the first question, Johansson and Randall (2003) find that efficient targeting of P abatement with agricultural practices could achieve a 22 percent nationwide reduction in P loads, at an average cost of $21 per kilogram of P. If applied to the CBW, efficient targeting would cost around $40 million annually, although information and administration costs of P abatement targeting in the CBW are not included in this estimate. In addition, Ancev et al. (2006) examined five scenarios and found that practices of alum use, agricultural land use changes, and variable litter application rates produced much lower total abatement costs of meeting efficient P emission targets when compared to those scenarios where litter transport was included in the abatement strategy.

The answer to the second question is based on limited information available on the ecological and monetary benefits from such a 20 percent nutrient reduction. One study by Bockstael, McConnell, and Strand (1989) estimated aggregate annual use benefits on the Chesapeake Bay from a 20 percent improvement in water quality to be in the range of $32 to $97 million (updated to 2006 dollars). While this range is lower than our computed annual costs, these benefits include only beach recreation, boating, and sport fishing, while not considering values derived by non-users from water quality improvements.

This article analyzes nutrient surpluses and deficits from a P-based management perspective. Under N-based management, lower surpluses would be generated because crop N requirements are higher than crop P requirements. This reduces the number of surplus counties. N-based management would also decrease the land requirement for manure used as a fertilizer. Thus, as found by Ribaudo et al. (2003) and Aillery et al. (2005), total cost of excess manure utilization in the region would be lower under N-based management.

Limitations of this research include assumptions regarding agricultural data utilized in the model (WTA manure, constant cropping patterns within the CBW, and manure P generated by livestock), along with how the model was structured, including cost-size relationships employed for processing facilities. Because additional data are not available, WTA manure is based on distance of crop and forestland from developed land rather than a more preferable measure of landowner behavior and/or attitudes.

Cropping patterns as of 2002 are assumed for surplus and deficit P computations, along with P usage by agricultural land application. Changes in cropping patterns would impact all of these computations, but does increased manure application on agricultural land change cropping patterns? This has been shown at an individual farm level [one example is Yap et al. (2004)]. However, we are unaware of any studies documenting regional cropping changes that can be attributed to manure replacing commercial fertilizer.

Finally, manure P calculations are based on typical animal diets, which have changed over time as phytase has become a standard component of pre-mixed formulations for non-ruminants (Stahlman, McCann, and Gedikoglu 2008). Thus, our WTA assumptions probably overestimate agricultural land available for manure application, while diet changes over time would increase manure applications by reducing excess P in manure.

As for the structure of our model, dynamic programming is not adopted in this study because (i) fixed costs associated with building processing facilities are annualized instead, and (ii) soil P data, which are essential for dynamic considerations of land-applied manure, are not available for each county in the watershed. Lastly, no economies of scale are considered for processing facilities. Existing pelletization and energy facilities in the United States have not been operating long enough to show any economies of scale.

Future research to address these limitations includes obtaining better WTA information for the Chesapeake Bay watershed by conducting a survey of landowners who might accept manure not generated from their operation—something similar to, say, a survey done by Norwood, Luter, and Massey (2005) in Oklahoma. Additionally, a dynamic component could be added to our model with constraints to limit P application on agricultural land based on soil P accumulation over time. Fixed costs for each processing plant could also be distributed over time instead of being annualized. Production cost of each processing type would also differ across time by incorporating economies of scale. Finally, markets for composts and biosolids could be incorporated into a model to reflect changing market outcomes from larger production of compost.

References

Aillery, M., N. Gollehon, and V. Breneman. 2005. “Technical Documentation of the Regional Manure Management Model for the Chesapeake Bay Watershed.” Technical Bulletin No. 1913, Economic Research Service, U.S. Department of Agriculture, Washington, D.C.

Aillery, M., N. Gollehon, V. Breneman, and S. Bucholtz. 2009. “Modeling Firm Spatial Interdependence Using National Data Coverages: A Regional Application to Manure Management.” *Natural Resource Modeling* 22(1): 42–66.

Aillery, M., N. Gollehon, R. Johansson, J. Kaplan, N. Key, and M. Ribaudo. 2005. “Managing Manure to Improve Air and Water Quality.” Economic Research Report No. 9, Economic Research Service, U.S. Department of Agriculture, Washington, D.C.

American Society of Agriculture Engineers (ASAE). 2004. “Manure Production and Characteristics” (D384.1). In *ASAE Standards*, ASAE, St. Joseph, MI.

Ancev, T., A.L. Stoecker, D.E. Storm, and M.J. White. 2006. “The Economics of Efficient Phosphorus Abatement in a Watershed.” *Journal of Agricultural and Resource Economics* 31(3): 529–548.

Baker, W. 2009. “Chesapeake Bay Restoration: Status Report and Recommendations.” Statement made by Will Baker, President and CEO of the Chesapeake Bay Foundation, to the U.S. Senate Committee on Environment and Public Works Subcommittee on Water and Wildlife, April 20.

Bockstael, N.E., K.E. McConnell, and I.E. Strand. 1989. “Measuring the Benefits of Improvements in Water Quality: The Chesapeake Bay.” *Marine Resource Economics* 6(1): 1–18.

Bosch, D.J., and K.B. Napit. 1991. “The Economic Potential for More Effective Poultry Litter Use in Virginia.” Unpublished paper, Department of Agriculture and Applied Economics, Virginia Tech University, Blacksburg, VA.

____. 1992. “Economics of Transporting Poultry Litter to Achieve More Effective Use as Fertilizer.” *Journal of Soil and Water Conservation* 47(4): 342–346.

Carreira, R.I., K.B. Young, and H.L. Goodwin. 2005. “Too Litter, Too Late: Economic Logistics of Transporting Nutrient Rich Poultry Litter Out of Nutrient-Saturated Regions.” Selected paper for presentation at the American Agricultural Economics Association’s annual meetings, July 24–27, Providence, RI. Available at http://ageconsearch.umn.edu/handle/19383 (accessed January 15, 2007).

Catma, S. 2008. “Utilization of Excess Manure within the Chesapeake Bay Watershed: A Cost Minimization Approach.” Unpublished Ph.D. dissertation, West Virginia University, Morgantown, WV.

Cestti, R., J. Srivastava, and S. Jung. 2003. “Agriculture Non-Point Source Pollution Control: Good Management Practices—The Chesapeake Bay Experience.” The World Bank, Washington, D.C.

Chesapeake Bay Foundation. 2004. “Manure’s Impact on Rivers, Streams and the Chesapeake Bay.” Available at http://www.cbf.org/Document.Doc?id=137 (accessed December 12, 2007).

Chesapeake Bay Program. 2009. “Bay Barometer: A Health and Restoration Assessment of the Chesapeake Bay and Watershed in 2008.” Report No. CBP/TRS 293-09 and Report No. EPA-903-R-09-001, Chesapeake Bay Program, Annapolis, MD. Available at http://www.chesapeakebay.net/content/publications/cbp_34915.pdf (accessed November 29, 2009).

Coale, F.J. 2000. “Phosphorus Dynamics in Soils of the Chesapeake Bay Watershed: A Primer.” In A.N. Sharpley, ed., *Agriculture and Phosphorus Management: The Chesapeake Bay*. Boca Raton, FL: Lewis Publishers.

Dickens, E.D., P.B. Bush, and L.A. Morris. 2003. “Poultry Litter Application Recommendations in Pine Plantations.” E-publication by the University of Georgia, Athens, GA. Available at http://www.bugwood.org/fertilization/PLARPP.html (accessed September 12, 2007).

Fritsch, D.A., and A.R. Collins. 1993. “The Economic Feasibility of Poultry Litter Composting Facilities in Eastern West Virginia.” *Agricultural and Resource Economics Review* 22(2): 199–209.

Giasson, E., R.B. Bryant, and N.L. Bills. 2002. “Environmental and Economic Optimization of Dairy Manure Management: A Mathematical Programming Approach.” *Agronomy Journal* 94(4): 757–766.

Gollehon, N., M. Caswell, M. Ribaudo, R.L. Kellogg, C.H. Lander, and D. Letson. 2001. “Confined Animal Production and Manure Nutrients.” Agriculture Information Bulletin No. 771, Economic Research Service, U.S. Department of Agriculture, Washington, D.C.

Govindasamy, R., and M.J. Cochran. 1995. “The Feasibility of Poultry Litter Transportation from Environmentally Sensitive Areas to Delta Row Crop Production.” *Agricultural and Resource Economics Review* 24(1): 101–110.

____. 1998. “Implications of Policy Regulations on Land Applications of Poultry Litter.” *Agricultural and Resource Economics Review* 27(1): 85–94.

Johansson, R.C., and J. Randall. 2003. "Watershed Abatement Costs for Agricultural Phosphorus." *Water Resources Research* 39(4): 1088.

Jones, K., and G. D'Souza. 2001. "Trading Poultry Litter at the Watershed Level: A Goal Focusing Application." *Agricultural and Resource Economics Review* 30(1): 56–65.

Kellogg, R.L. 2000. "Potential Priority Watersheds for Protection of Water Quality from Contamination by Manure Nutrients." Paper presented at the Animal Residuals Management Conference, Kansas City, MO. Available at http://www.cbf.org/Document.Doc?id=137 (accessed August 12, 2006).

Kellogg, R.L., and C.H. Lander. 1999. "Trends in the Potential for Nutrient Loading from Confined Livestock Operations." Presented at the State of North America's Private Land Conference, Chicago, IL (January 19–21). Available at http://www.nrcs.usda.gov/technical/land/pubs/ (accessed May 15, 2006).

Kellogg, R.L., C.H. Lander, D.C. Moffitt, and N. Gollehon. 2000. "Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States." Report No. nps00-0579, U.S. Department of Agriculture, Washington, D.C. Available at http://www.nrcs.usda.gov/technical/NRI/pubs/manntr.pdf (accessed May 1, 2006).

Keplinger, K.O., and L.M. Hauck. 2006. "The Economics of Manure Utilization: Model and Application." *Journal of Agricultural and Resource Economics* 31(2): 414–440.

Lander, C.H., D. Moffitt, and K. Alt. 1998. "Nutrients Available from Livestock Manure Relative to Crop Growth Requirements." Resource Assessment and Strategic Planning Working Paper No. 98-1, Natural Resources Conservation Service, U.S. Department of Agriculture, Washington, D.C.

Lanyon, L.E., and R.M. Schlauder, Jr. 1988. "Nutrient Management Assessment Worksheets" (2nd ed.), Agronomy Series No. 102, Pennsylvania State University, State College, PA.

Lichtenberg, E., D. Parker, and L. Lynch. 2002. "Economic Value of Poultry Litter Supplies in Alternative Uses." Policy Analysis Report No. 02-02, Center for Agricultural and Natural Resource Policy, University of Maryland, College Park, MD.

Lynch, L., and R. Tjaden. 2004. "Would Forest Landowners Use Poultry Manure as Fertilizer?" *Journal of Forestry* 102(5): 40–45.

Mid-Atlantic Regional Water Program. 2005. "Nutrient Budgets for the Mid-Atlantic States." Available at http://www.mawaterquality.agecon.vt.edu/ (accessed May 3, 2006).

Midwest Plan Service. 2004. *Manure Characteristics* (Section 1) (2nd ed.). Iowa State University, Ames, IA.

Norwood, F.B., R.L. Luter, and R.E. Massey. 2005. "Asymmetric Willingness-to-Pay Distributions for Livestock Manure." *Journal of Agricultural and Resource Economics* 30(3): 431–448.

Paudel, K., M. Adhikari, A. Limayem and N. Martin. 2002. "Phosphorus-Based Management of Broiler Litter as Agricultural Fertilizer." *Journal of Environmental Systems* 29(4): 311–339.

Pelletier, B., and D. Kenyon. 2000. "Poultry Litter for Corn Exchange Program for Virginia." Virginia Cooperative Extension Bulletin No. 448-246/REAP R048, Rural Economic Analysis Program, Virginia Tech, Blacksburg, VA.

Pfost, D.L., and D.F. Charles. 2004. "Dairy Waste Management Systems in Missouri." Cooperative Extension Service Report No. EQ301, University of Missouri, Columbia, MO.

Ribaudo, M., N. Gollehon, M. Aillery, J. Kaplan, R. Johansson, J. Agapoff, L. Christensen, V. Breneman, and M. Peters. 2003. "Manure Management for Water Quality: Costs to Animal Feeding Operations of Applying Manure Nutrients to Land." Agricultural Economic Report No. 824, Economic Research Service, U.S. Department of Agriculture, Washington, D.C.

Safley, C.D., and L.M. Safley, Jr. 1991. "Economic Analysis of Alternative Poultry Litter Compost Systems." Department of Agricultural and Resource Economics Information Report No. 85, North Carolina State University, Raleigh, NC.

Stahlman, M., L.M.J. McCann, and H. Gedikoglu. 2008. "Adoption of Phytase by Livestock Farmers." Poster presentation at the American Agricultural Economics Association meetings, Orlando, FL (July 27–29). Available at http://purl.umn.edu/43235 (accessed April 5, 2008).

Steinhilber, P., P. Shipley, and J. Salak. 2002. "Phosphorus Removal by Crops in the Mid-Atlantic States." Maryland Cooperative Extension Report No. NM-3, University of Maryland, College Park, MD.

Taylor, A.W., and H.B. Pionke. 2000. "Inputs of Phosphorus to the Chesapeake Bay Watershed." In A.N. Sharpley, ed., *Agriculture and Phosphorus Management: The Chesapeake Bay*. Boca Raton, FL: Lewis Publishers.

Terry, D.L., and B.J. Kirby. 2002. "Commercial Fertilizers 1988, 1992, 1997 and 2002." American Association of Plant Food Control Officials, Inc., Lexington, KY.

Tietenberg, T., and L. Lewis. 2009. *Environmental and Natural Resource Economics* (8th ed.). Boston: Pearson Addison Wesley.

U.S. Department of Agriculture. 2002a. "Census of Agriculture." National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C.

____. 2002b. "Crop Nutrient Tool." National Resources Conservation Service, U.S. Department of Agriculture, Washington, D.C.

____. 2003. "Natural Resources Inventory Landuse Dataset." National Resources Conservation Service, U.S. Department of Agriculture, Washington, D.C.

____. 2006a. "Commercial Fertilizer Prices." National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C.

____. 2006b. "Forest Inventory Data." Forest Service, U.S. Department of Agriculture, Washington, D.C. Available at http://www.fia.fs.fed.us/ (accessed May 15, 2007).

____. 2006c. "Agricultural Prices." National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available at http://www.nass.usda.gov/Charts_and_Maps/Agricultural_Prices/ (accessed March 22, 2007).

U.S. Environmental Protection Agency. 2002. "Water Quality Conditions in the United States: A Profile from the 2000 National Water Quality Inventory." In *2000 National Water Quality Inventory*, U.S. Environmental Protection Agency, Washington D.C.

U.S. Energy Information Administration. 2006. "Motor Gasoline Retail Prices." U.S. Energy Information Administration, Washington D.C. Available at http://www.eia.gov (accessed April 2, 2007).

Van Dyne, D.L., and C.B. Gilbertson. 1978. "Estimating U.S. Livestock and Poultry Manure Nutrient Production." Economics, Statistics and Cooperatives Service, U.S. Department of Agriculture, Washington, D.C.

Vervoort, R.W., and A.G. Keeler. 1999. "The Economics of Land Application of Fresh and Composted Broiler Litter with an Environmental Constraint." *Journal of Environmental Management* 55(4): 265–272.

Yap, C., K. Forster, P. Preckel, O. Doering, and B. Richert. 2004. "Mitigating the Compliance Cost of a Phosphorus-Based Swine Manure Management Policy." *Journal of Agricultural and Applied Economics* 36(1): 23–34.

Young, K., R.I. Carreira, H.L. Goodwin, and E. Wailes. 2005. "Economics of Transporting Poultry Litter from Northwest Arkansas to Eastern Arkansas Croplands." Selected paper at the Southern Agricultural Economics Association annual meetings, Little Rock, AR. Available at http://agecon search.umn.edu/bitstream/35635/1/sp05yo01.pdf (accessed March 29, 2007).

Appendix 1. Components of the Base Model and Scenario Changes[a]

Base Model	Landowner's willingness to accept manure (WTA) is assumed to be 100 percent in each deficit county. On a per county basis, composting and energy facilities are limited to two, while pelletization facilities are limited to one. Commercial fertilizer replacement in deficit counties from surplus counties is not allowed.
Scenario 1	Landowner's WTA manure is assumed to be 100 percent in each deficit county. *More than two composting facilities are allowed in each county.* Commercial fertilizer replacement in deficit counties from surplus counties is not allowed.
Scenario 2	*The percentage of landowner's WTA manure is altered based on proximity of agricultural land to developed land in each deficit county.* On a per county basis, composting and energy facilities are limited to two, while pelletization facilities are limited to one. Commercial fertilizer replacement in deficit counties from surplus counties is not allowed.
Scenario 3	Landowner's WTA manure is assumed to be 100 percent in each deficit county. On a per county basis, composting and energy facilities are limited to two, while pelletization facilities are limited to one. *Commercial fertilizer replacement in deficit counties from surplus counties is allowed.*
Scenario 4	*Combination of Scenario 1 and Scenario 3.*

[a] Scenario changes are in italics.

Appendix 2. References Used to Estimate Phosphorus Budget

Total animal production	U.S. Department of Agriculture (2002a)
Manure coefficients[a]	Kellogg et al. (2000) American Society of Agriculture Engineers (2004) Lander, Moffitt, and Alt (1998) Midwest Plan Service (2004) Van Dyne and Gilbertson (1978)
Total crop and pasture production	U.S. Department of Agriculture (2002a)
Crop coefficients[a]	U.S. Department of Agriculture (2002b) Lander, Moffitt, and Alt (1998) Lanyon and Schlauder (1988) Steinhilber, Shipley, and Salak (2002)
Forestland acreage	U.S. Department of Agriculture (2003) U.S. Department of Agriculture (2006b)
Forestland phosphorus uptake	Dickens, Bush, and Morris (2003)
Commercial fertilizer usage and prices	Terry and Kirby (2002) U.S. Department of Agriculture (2006c)

[a] Based on Mid-Atlantic Water Program estimations.

Appendix 3. Cost References

Land application costs	Methods of estimation were adopted from Pelletier and Kenyon (2000) Pfost and Charles (2004) U.S. Department of Agriculture (2006c) U.S. Energy Information Administration (2006)
Composting costs	Composting cost estimates were updated from Safley and Safley (1991) John Deere 5603 100 hp utility tractor—www.johndeere.com 2001 Caterpillar 928G front-end loader—http://catused.cat.com John Deere 4995 and 4985 windrowers—www.johndeere.com HSMS430 manure spreader—http://www.beavervalleysupply.com/sectionc/hsms-1.htm Atlas Nissan 3000lbs forklift—http://www.northerntool.com TQ1500 2 hp water pump—http://www.plumbingsupply.com/boosterpumps.html Industrial 6 ft. long thermometer—http://www1.agric.gov.ab.ca 45″ x 48″ plastic pallets—http://pallets.handlinginnovations.com/exportPallets.php
Pelletization and energy-generation costs	Pelletization and energy cost estimates were based on Lichtenberg, Parker, and Lynch (2002)