Trading Poultry Litter at the Watershed Level: A Goal Focusing Application

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We explore the transfer of poultry litter among watersheds incorporating both economic characteristics (litter demand and supply) and environmental characteristics (vulnerability to phosphorus runoff, a major pollutant). A combination of techniques was employed: the Lemunyon-Gilbert P-Index model to determine watershed environmental vulnerability, GIS for land use coverages, and a goal focusing model (incorporating Saaty's eigen-value approach for penalty weight estimation) to identify optimal litter shipments among watersheds. Both primary and secondary data were used. The results should be useful to producers and policy makers in the study area and in other areas where poultry production is linked to water quality, and contribute to a more sustainable poultry sector.

Increasing production is often accompanied by increasing pollution, and agriculture is no different than any other industry in this regard. The potential for increased pollution is especially severe from concentrated production, which describes much of the U.S. poultry industry. Since the passage of the Clean Water Act in 1972, great progress has been made in the control of point sources of pollution. Further control of remaining point source problems is becoming increasingly less cost-effective. However, significant water quality problems remain unresolved. Hence, more attention is being placed on controlling runoff as the cause of impairment of the 55% of surveyed river length and 58% of surveyed lake area in the U.S. still having water quality problems (Shapley et al. 1994).

This study is aimed at exploring ways to transfer poultry litter among watersheds in an area, taking into account economic characteristics (litter demand and supply), and environmental characteristics (vulnerability of the watersheds to phosphorus runoff, a major pollutant). The study area is Hardy county in the eastern panhandle of West Virginia, an important and rapidly growing poultry producing area and, by virtue of its proximity to the Potomac River and adjacent high population areas, a geographically sensitive one as well.[1] The Potomac Headwaters area has witnessed a doubling in size of the poultry industry between 1993 and 1996; currently, 870 poultry houses are in operation in this area, producing 90 million birds annually (Basden 1997). The goal is to contribute to the sustainable growth of the poultry sector in the study area. The choice of the watershed level of analysis, perhaps unique for a study of this nature, is not arbitrary. Watersheds are considered the appropriate hydrologic unit for evaluating environmental processes such as runoff and nonpoint source pollution (Dixon 1989). For instance, they can reflect both upstream and downstream effects, rather than only one or the other, important in any nutrient management analysis such as this. In addition, many water quality process models operate at the watershed level and, finally, watersheds are the focal point for implementation of many re-

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We wish to acknowledge the data and information support provided by Larry Bennett and K. Brooke Engstrom, together with the assistance of D.K. Bhumbla, Alan Collins, and Tim Phipps during various stages of this study, and the helpful review comments of Dale Colyer, Qingshui Zhou, and the anonymous reviewers on earlier versions.

Published with the approval of the Director of the West Virginia Agricultural and Forestry Experiment Station as Scientific Article #2696. This research was supported with funds appropriated under the Hatch/McIntire-Stennis, etc. Act.

[1] Following a court-ordered limit on water pollution reaching WV waterways, the EPA has recently mandated that agricultural runoff from Hardy county be cut by 38%.

Agricultural and Resource Economics Review 30/1 (April 2001) 56–65

search and resource management programs (Prato and Wu 1996).

This study emphasizes the phosphorus run-off aspect of the poultry litter problem. There is an inherent policy challenge in changing the basis of nutrient management recommendations from nitrogen to phosphorus. However, agencies such as the NRCS are already making this transition, recognizing the need to prevent further contamination from excess P loadings particularly in regions with a long history of animal agriculture. Given the relatively high content of P in poultry litter, together with the concentration of poultry production (and, in some parts of the country, poultry litter disposal as well), a policy focus on phosphorus is important for poultry litter management, a case made convincingly by Govindasamy, Cochran and Buchberger (1994 and 1995); Govindasamy and Cochran (1998); and Shapley et al. (1994).

Previous economic analyses include studies by Fritsch and Collins (1993), who investigate the feasibility of poultry litter composting, and Govindasamy and Cochran (1995), who examine the feasibility of litter transport between regions. Although both studies were motivated primarily by environmental considerations, they both use models that rely mainly on economic criteria, to the exclusion of environmental criteria. Govindasamy and Cochran found that it was indeed economically feasible to ship litter from one corner of Arkansas to another; although their study did not explicitly consider environmental measures such as a P-index, as this work attempts, the motivation behind such long-distance hauls of poultry litter is the environmental risk associated with continued land-spreading of poultry litter in poultry production areas. Harsch (1995) further discusses litter production and distribution in Arkansas. Many poultry-producing regions have litter transportation schemes already in place. Lancaster County, PA and the Eastern Panhandle of WV are just two examples. In spite of efforts such as these, a recent study (Marks and Knuffke 1998) which examined environmental pollution from "animal factories" in 30 U.S. states concludes that while some progress has been made, overall, state programs have failed to curb "factory farm" pollution.

Theoretical Background

A trend in contemporary economic analysis is to integrate ecological and environmental processes with economic analysis (Lee and Lovejoy 1991). Our analysis is consistent with this trend to the extent that it seeks to incorporate both the environmental and economic dimensions of the poultry litter problem at the watershed level in the study area. The economic dimension was represented by supply, demand and price of litter; the environmental dimension was captured by vulnerability to phosphorus run-off from soil to water, a major problem in poultry producing areas.

Goal focusing (GF) is the framework used. A variant of goal programming (GP) (other variants including lexicographic goal programming and weighted goal programming), each has specific attributes (discussed in Romero and Rehman 1989 and Thompson and Thore 1992) that make them useful in a particular setting. GF permits the introduction of "soft constraints" which can include those that the market does not explicitly consider (e.g., phosphorus run-off in this case); soft constraints can be violated in the model, but at a cost.

Thompson and Thore (1992) define the objective of the GF program as the satisfaction of the prior (non-goaled) program adjusted by the sum of all penalties. The costs ("penalties") that are levied may represent cash charges prescribed by a control authority or an ordinal system of priorities advocated by policy makers. The more urgent the goal, the greater the penalty for violation of the corresponding constraint. The larger the penalty associated with deviation from a goal, the more likely the satisfaction of the goal. The GF program still seeks the prior objective as long as the goals permit. The possibility of trade-offs is then introduced if all goals cannot be completely fulfilled.

The penalty weights were generated using Saaty's eigen-value approach (Saaty 1977). This approach involves the derivation of weights by making pairwise judgements about the relative importance of criteria. Consider n objects are being compared according to their relative weights. Let the objects be $A_1, A_2, A_3, \ldots, A_n$ and their weights be $w_1, w_2, w_3, \ldots, w_n$. Let w be a column vector representing the n weights. The pairwise comparison matrix **A** was then formed as:

$$\begin{array}{c|ccccc} & A_1 & A_2 & \cdot & \cdot \ \cdot & A_n \\ \hline A_1 & w_1/w_1 & w_1/w_2 & \cdot & \cdot \ \cdot & w_1/w_n \\ A_2 & w_2/w_1 & w_2/w_2 & \cdot & \cdot \ \cdot & w_2/w_n \\ \cdot & \cdot & \cdot & \cdot & \cdot \ \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \ \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \ \cdot & \cdot \\ A_n & w_n/w_1 & w_n/w_2 & \cdot & \cdot \ \cdot & w_n/w_n \end{array}$$

Let the entries of **A** be denoted a_{ij} such that all $a_{ij} > 0$. The matrix is a reciprocal matrix since $a_{ij} = 1/a_{ji}$. If **A** is multiplied by the transpose of w, $w^T = (w_1, w_2, w_3, \ldots, w_n)$, the vector nw is obtained. From this, we get $\mathbf{A}w = nw$. If the matrix **A** is known given some scale, w can be recovered by solving $\mathbf{A}w = nw$ for w. That is, one must solve $(\mathbf{A} - n\mathbf{I})w = 0$ where **I** is the identity matrix of dimension $n \times n$. Invoking the Perron-Frebonenius theory, the existence of a largest real positive eigenvalue of **A** is ensured since **A**'s entries are all nonzero. Such a system has a solution if, and only if, n is an eigenvalue of **A** (i.e., n is a root of the characteristic equation of **A**). When considering the matrix **A**, one observes that every row of **A** is a constant multiple of the first row (i.e., row $k = w_k$ * row 1). Because of this, **A** has unit rank. Therefore, except for the eigenvalue equal to n, all other eigenvalues, $\lambda_l = 0$ $(l = 1, 2, \ldots, n)$. Hence the solution to the above system is any of the columns of **A**. The solution differs by a multiplicative constant. To ensure that it is unique, the column of **A** chosen as the solution must be normalized.

To form the matrix **A** (given some scale), one must generally determine $C^n_2 = n!/(n-2)!2! = n(n-1)/2$ entries a_{ij}. To determine **A**, one only needs to know n entries (any row of **A**) and use the cardinal consistency property $a_{ik} = a_{ij}a_{jk}$. The latter has the advantage of potentially reducing the number of comparisons to be made. Details on goal focusing as well as goal programming are contained in Romero and Rehman (1989) and Zeleny (1982).

P-Index Model

The P-Index model was developed by Lemunyon and Gilbert (1993) to provide field staff, watershed planners, and land users with a tool to assess the various land forms and management practices for potential risk of P movement to water bodies. The P-index model enables the ranking of sites according to the risk of P movement (Shapley 1995). Lemunyon and Gilbert assign a weighting factor to each of several pre-selected site characteristics (including soil, hydrology, and land management site characteristics) based on the extent to which each characteristic could cause P loss from that site. The higher the weight factor, the greater the resulting potential P loss. To calculate a site's vulnerability to phosphorus runoff, the actual measure of each site characteristic was multiplied by its respective weighting factor. The sum of all such products was then found. A site whose total of weighted rating values (TWRV) is less than 8 is said to have "low vulnerability" to P loss. If $8 < \text{TWRV} < 14$, then the site has "medium vulnerability." If $15 < \text{TWRV} < 32$, the site has "high vulnerability" and finally if $\text{TWRV} > 32$ then the site has "very high vulnerability" to P loss. The Bhumbla et al. (1996) version of the P-index model was selected for use here since it is best suited to the study area.

Numerous factors contribute to phosphorus loss from a field. Among them are the source, method, rate and timing of P application; susceptibility of a given soil to erosion; and management practices. The P Index quantitatively determines the relative risk of P movement from a given field by considering the above factors that govern P losses.

The major modification to the Gilbert-Lemunyon P-Index model that characterizes the Bhumbla et al. version is adjustment of the weight used for the components. The main difference is that in the P-index model irrigation is assigned a nonzero value. Because little or no irrigation is used in the study area, irrigation is assigned a weight of zero in the Bhumbla et al. version. Bhumbla et al. adjusted the weights to fit the general topography, predominant crop types, etc. of WV. The components of the Bhumbla et al. version of the P-index model are: (1) P-index rating value from soil (based on lbs. P/acre); (2) P-index rating value from manure application (based on lbs. P_2O_5/acre from manure applied); (3) P-index value rating value from fertilizer application (based on lbs. P_2O_5/acre from fertilizer applied); (4) P-index value from manure/fertilizer application method (based on timing and/or depth); (5) P-index rating value from soil erosion (based on tons/acre/year soil loss from field); and (6) P-index rating value from surface runoff (based on cm surface runoff). These are the components that go into calculating the TWRV.

Ranking Watersheds

Results from actual soil samples taken between 1995 and 1997 in the study area were used to rank watersheds by vulnerability to P loss. The vulnerability rankings involved placing the individuals fields (using the NRCS-assigned tract numbers of fields owned by farmers in the study area) in their respective watershed. After calculating vulnerability levels for each field, the average (weighted by acres) vulnerability value from representative fields across each watershed was calculated. Details on these calculations are presented in Jones et al. (1998).

Poultry Litter Demand

Estimating the demand for poultry litter econometrically for each watershed is costly in data and time. Since individual farm-input mixes are unknown, a proxy for the demand for poultry litter was used. For this study, the demand for poultry litter in a watershed was calculated based on both the N and the P crop requirements separately for the various crops (lbs N or P/acre): corn, pasture and hay. To determine the number of acres in the various crop categories, data from WVDA and GIS (ArcView 3.0) were employed. Landuse and watershed coverages of the study area were used for this purpose. These coverages, together with the crop N and P requirement information and the poultry nutrient analysis data, were subsequently used to estimate litter demand.

Two types of information were used in the analysis: implicit and explicit. Prior information on land uses is implicitly used in calculating the TWRV. For example, two components of the P-index model, P-index rating value from soil erosion and P Index rating value from surface runoff, specifically used historical crop rotations, historical data on tillage (i.e., conventional or no till, etc.) and other pertinent historical data. With regard to land spreading, we follow the account of Basden et al. (1994), which shows that a majority of farmers in the study area used poultry manure as soil amendment. Here too we have some historical data on land use.

Poultry Litter Supply

This computation is relatively straightforward. We calculated litter supply based on the number of poultry houses and the number of growouts per year (obtained from secondary sources, PHIWQ, 1996). The tons of litter produced per watershed is therefore a sum of the product of the number of specific bird houses in the watershed and the estimated tons of litter generated annually per house.

In summary, the analysis involved the following main components: (1) Watersheds within the Potomac River basin that have a potential P runoff problem were identified by interviewing NRCS officials and Extension personnel in the study area, following which the watersheds were ranked based on vulnerability to P runoff using the Lemunyon-Gilbert P-index model; (2) The supply of and demand for poultry litter in each watershed were determined given current production and management practices, using secondary data as described above; and (3) The optimal litter shipments among watersheds given multiple objectives (economic and environmental) and supply and demand constraints were subsequently determined using a GF model and employing Saaty's eigenvalue approach.

Empirical Model

LP was used to minimize the aggregate transportation cost of litter among watersheds given the supply of, and demand for, poultry litter by watershed. In reality the price of poultry litter varies (depending on factors such as the type of litter, its quality, and handling and storage); however, due to a lack of data, we assume that the price of poultry manure is constant and independent of quantity purchased (i.e., $P_m = k$ [constant] where P_m is the price of manure). We make the assumption that the system is a closed one. That is, the model does not allow for poultry litter leaving or entering the watersheds used in this study (if data are available, this assumption can easily be relaxed). The primal transportation problem then is:

$$(1)\quad \textit{minimize}\quad \Sigma_i\Sigma_j c_{ij}{}^{*}\, \textit{Watershed}_{ij}$$

$$(2)\quad \textit{subject to}\quad \Sigma_j \textit{Watershed}_{ij} = a_i,\ \text{for } i = 1,2,3,\ldots,m$$

$$(3)\quad \Sigma_i \textit{Watershed}_{ij} \geq b_j,\ \text{for } j = 1,2,3,\ldots,n \text{ and}$$

$$(4)\quad \textit{Watershed}_{ij} \geq 0,\ \text{for } i = 1,2,3,\ldots,m,\ j = 1,2,3,\ldots,n$$

where watershed$_{ij}$ is the quantity of poultry litter (in tons) transported from watershed i to watershed j; c_{ij} is the ton mile cost of transporting litter; a_i is the total supply of litter (in tons) in Watershed i;[2] and b_j is the total demand for litter (in tons) in Watershed j. Equation (1) is set up to minimize the aggregate value of transportation costs among the watersheds. Equation (2) constrains the supply of litter in each watershed to the quantity actually produced in that watershed. Note that the a_is in equation 2 are different from the $a_{jk}s$ of the comparison matrix. The former refer to supply of poultry litter from the i^{th} region, while the latter are the j^{th}, k^{th} components of the comparison matrix used for illustration. Equation (3) constrains the quantity of litter shipped into each watershed to at least equal the demand for litter within that watershed, and equation (4) constrains the quantity of watershed shipments in the study area to be strictly positive.

A necessary condition that a feasible solution exists is that the total demand be at most as large as the total supply of poultry litter (if not, a penalty is attached to the shipment, consistent with the GF framework):

$$(5)\quad \Sigma_j b_j \leq \Sigma_i\Sigma_j\ \textit{Watershed}_{ij} = \Sigma_i a_i.$$

Watershed Transportation Costs

The distance measure between pairs of watersheds is meaningless without anchor points or points of reference. One measure of proximity is the distance between any two watershed centroids. ArcView 3.1 was also used in this determination. Rather than using a highway routing program to determine distance for transportation cost purposes, we chose to use watershed centroids as a measure of distance between watersheds. One reason is that there are several modes of transportation available: barge, train and truck. The existence of alternative modes of transportation means that there are many possible routes to consider. When coupled with the fact that farms using poultry manure for land spreading are not found in one specific region in each watershed, there are numerous route possibilities for transporting poultry manure between two watersheds. By assuming that the distance between two watersheds is simply the distance between the centroids, we ignore the important but very difficult and prohibitively expensive (both in time and money) issue of optimal choice of routes. The centroids were found using ArcView. They were based on calculations involving locational coordinates (either x,y or longitude, latitude) of the watershed boundaries and therefore ignore the possible physical routes available. Using centroids for distances inherently assumes that there is a central collection, storage and shipping location in each region and therefore alleviates the problems that arise when a farmer in a given watershed has multiple buying/selling possibilities in another watershed.

Thus, the cost of transportation between any two watersheds is a function of the distance between the two watersheds. While it is generally possible to use other modes of transportation, we assumed that trucking is the only mode used (a realistic assumption in this illustration since the study area lacks barge access and has insufficient storage capacity and volume to justify rail transportation). Transportation costs (obtained from PHIWQO 1996) do not include loading charges since the prevailing practice is that the poultry litter suppliers load the litter themselves. Since, unlike transportation costs, loading charges are constant, this does not affect shipment patterns.

Watershed Shipments

Given the initial primal transportation cost problem, the new GF problem, including the potential of P loss across the various watersheds, is given as:

$$(6)\quad \textit{minimize}\ \Sigma_i\Sigma_j c_{ij}{*}\textit{Watershed}_{ij} + Mg^{+} + Ng^{-}$$

$$(7)\quad \textit{subject to}\quad \Sigma_j \textit{Watershed}_{ij} = a_i,\ \text{for } i = 1,2,3,\ldots,m$$

$$(8)\quad \Sigma_i \textit{Watershed}_{ij} \geq b_j,\ \text{for } j = 1,2,3,\ldots,n$$

$$(9)\quad \textit{Watershed}_{ij} \geq 0,\ \text{for } i = 1,2,3,\ldots,m,\ j = 1,2,3,\ldots,n$$

$$(10)\quad \Sigma_i \textit{Watershed}_{ij} - g^{+} + g^{-} = g \quad \text{for } j = 1,2,3,\ldots,n\ \ g^{+},g^{-} \geq 0$$

where g^+,g^- and g are n-dimensional column vectors; g^+ and g^- consist of entries g_j^+ and g_j^- and represent positive and negative deviations, respectively, from goal g_j; M = [M_j] and N = [N_j] are n-dimensional penalty (or importance weight) row vectors; and the other variables are the same as defined previously. For this particular application, there were no penalties for negative deviations from the stated goals: given the trading of poultry manure across watersheds, an increase in the quantity of manure coming to a watershed increases the P runoff (assuming no change in factors contributing to runoff). Thus, while we impose a penalty for the increase in manure coming in, we do not want to penalize out shipments of manure. Hence N = [O_j]. To determine penalty row vector M, Saaty's approach is used. Saaty's scale (ranging from the numbers 1–9) represents what is termed "intensity of importance." It is used to compare different objects, activities, etc. If a rank of "1" means that the activities (objects) are equally important relevant to the researcher's objectives, then "3" means weak importance of one over the other, "5" represents essential or strong importance of one over the other, "7" is demonstrated importance, and "9" means "absolute importance." Intermediate values are based on values between two adjacent judgements. Hence, 1,2,3, . . . ,9 are possible candidates for the first row of the comparison matrix. Based on the comparison matrix, weights (M's) are generated by the method described earlier.

Now assume we've executed the procedures for ranking the watersheds and that we've succeeded in ranking the watersheds based on P vulnerability (in our case 1, 2, 3 and 4). Comparing each watershed to itself (i.e., along the diagonal of the comparison matrix), we will have a rank as described above. However, subjectivity comes into play when we try to say how, for example, the watershed ranked 1 compares to the watershed ranked 4 using Saaty's scale. Hence, using alternative intensity schemes (based on the data and NRCS expert opinion) row 1 of the comparison matrix is a way to compare our results given the inevitable subjectivity.

Estimation of Criteria Weights

The major determining factor is row one in comparison matrix **A**, defined previously. Row one was obtained using the P ranking described previously in conjunction with the ranking made by the Potomac Valley Soil Conservation District (PVSCD). We selected three different importance intensity specifications. The first row under the three intensity schemes is as follows: (1, 1, 8, 9), (1, 7, 8, 9) and (1, 9, 9, 9). The "1" reflects the fact that the Lost River watershed is ranked first. The numbers following this one reflect how Lost River is compared with the other three watersheds (North River, South Fork, South Branch, respectively), using Saaty's scale. For illustration, consider the second weighting scheme (1, 7, 8, 9) using Saaty's scale. Invoking the cardinal consistency property yields the following reciprocal matrix:

$$\begin{array}{c|cccc} & \textbf{LR} & \textbf{NR} & \textbf{SF} & \textbf{SB} \\ \hline \textbf{LR} & 1 & 7 & 8 & 9 \\ \textbf{NR} & 1/7 & 1 & 8/7 & 9/7 \\ \textbf{SF} & 1/8 & 7/8 & 1 & 9/8 \\ \textbf{SB} & 1/9 & 7/9 & 8/9 & 1 \end{array}$$

Any of the columns of this matrix gives an appropriate set of weights. However, to ensure uniqueness of the resulting weights generated from the importance intensity given, we normalize any one column to generate the unique weight vector of norm one. The resulting normalized weight vectors for the weighting specifications are:

$$\mathbf{M}_1 = (\mathbf{LR,NR,SF,SB}) = (0.9767, 0.1395, 0.1221, 0.1805),$$
$$\mathbf{M}_2 = (\mathbf{LR,NR,SF,SB}) = (0.7022, 0.7022, 0.0877, 0.0780), \text{ and}$$
$$\mathbf{M}_3 = (\mathbf{LR,NR,SF,SB}) = (0.9819, 0.1091, 0.1091, 0.1091).$$

The relationship among the three main components of the analysis can be visualized in figure 1. Each of the concentric rings shows one phase of the analysis, with the order moving from the innermost ring to the outermost ring.

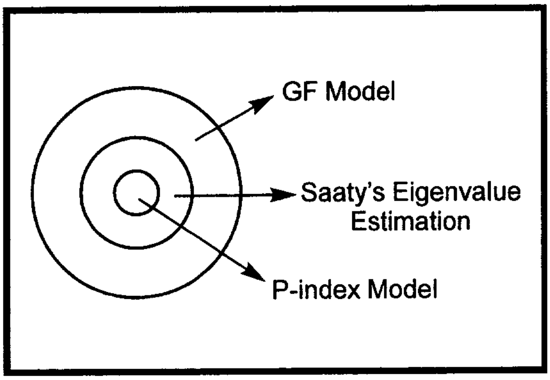

Figure 1. The Three Components of the Analysis

Results

The estimated vulnerability ratings for the four watersheds in the study area are shown in table 1. The higher the ranking, the greater the potential for P loss and, therefore, adverse water quality problems. Accordingly, Lost River is the most environmentally sensitive watershed and South Branch the least. Considering the total of weighted relative values (TWRV) generated, the rankings in table 1 show that Lost River is the most vulnerable to P runoff and South Branch is the least vulnerable. The ranking is based on vulnerability to P runoff (not N leaching and/or runoff). There was no comparison made on the basis of nitrogen vulnerability. The emphasis, as noted earlier, is on P runoff.

In addition to generating results for alternative penalty weight structures ($\mathbf{M}_1 - \mathbf{M}_3$, as described previously), as part of a sensitivity analysis, results are derived for alternative poultry litter supply-demand scenarios, one scenario each for litter demand based on crop N and crop P requirements, and the third involving an increase in annual litter supply. The annual poultry litter supply and demand quantities by watershed are presented in table 2.

Tables 3 to 5 show the optimal quantities of litter shipments, and associated total shipment cost, for each specified litter supply-demand scenario

Table 1. Estimated Watershed Vulnerability Ranking

Watershed	Vulnerability Ranking
Lost River	one
North River	two
South Fork	three
South Branch	four

Table 2. Estimated Annual Supply-Demand for Poultry Litter by Watershed[a]

Watershed	Annual Litter Supply (tons)	Annual Demand Based on Crop N Requirement (tons)	Annual Demand Based on Crop P Requirement (tons)
Lost River	24,870	9,863	10,875
North River	1,700	3,233	3,522
South Branch	19,445	17,512	19,704
South Fork	3,305	4,339	4,859
TOTAL	49,320	34,947	38,960

[a] Demand estimated by assuming a recommended (according to WV Extension Service) N application level of 150 lb/acre for corn silage and 50 lb/acre for pasture; and P levels of 35 lb/acre and 26 lb/acre for corn silage and pasture, respectively.

Table 3. Optimal Litter Shipments for Penalty Weight Structure One

Origin	Destination	Scenario 1	Scenario 2	Scenario 3
South Fork	South Fork	3,305	3,305	3,636
South Branch	South Branch	19,445	19,445	21,390
North River	North River	1,700	1,700	1,870
Lost River	South Fork	1,554	1,468	703
Lost River	North River	1,533	1,533	1,363
Lost River	Lost River	21,783	21,869	25,291
TOTAL COST		$3,667	$3,592	$2,670

Note: Scenarios 1, 2 and 3 represent annual litter demand based on crop P requirement; litter demand based on crop N requirement; and a 10% increase in litter supply for all watersheds (litter demand fixed), respectively.

Table 4. Optimal Litter Shipments for Penalty Weight Structure Two

Origin	Destination	Scenario 1	Scenario 2	Scenario 3
South Fork	South Fork	3,305	3,305	3,636
South Branch	South Branch	19,445	19,445	21,390
North River	North River	1,700	1,700	1,870
Lost River	South Fork	1,034	1,034	703
Lost River	North River	1,533	1,533	1,363
Lost River	Lost River	22,303	22,303	25,291
TOTAL COST		$3,214	$3,214	$2,670

Note: Scenarios 1, 2 and 3 represent annual litter demand based on crop P requirement; litter demand based on crop N requirement; and a 10% increase in litter supply for all watersheds (litter demand fixed), respectively.

Table 5. Optimal Litter Shipments for Penalty Weight Structure Three

Origin	Destination	Scenario 1	Scenario 2	Scenario 3
South Fork	South Fork	3,305	3,305	3,636
South Branch	South Branch	19,445	19,445	21,390
North River	North River	1,700	1,700	1,870
Lost River	South Fork	12,462	12,488	16,131
Lost River	North River	1,533	1,533	1,363
Lost River	Lost River	10,875	10,849	9,863
TOTAL COST		$13,157	$13,179	$16,092

Note: Scenarios 1, 2 and 3 represent annual litter demand based on crop P requirement; litter demand based on crop N requirement; and a 10% increase in litter supply for all watersheds (litter demand fixed), respectively.

and penalty weight structure. The first noteworthy result is that, regardless of the penalty weight structure, the optimal litter shipments do not differ much for scenarios 1 and 2 (litter scenarios based on crop P and crop N requirement, respectively). Next, under all scenarios and across all penalty weight structures specified, the transportation paths are similar although the quantities are quite different, showing the relative insensitivity of the results to changes in selected parameters. There are intrawatershed shipments in all cases; Lost River is the only watershed from which there also are interwatershed shipments, reflecting both the large supply of litter from this watershed as well as its status as the most environmentally vulnerable watershed. Basden et al. (1994) suggest that precisely such a transportation scheme is necessary (i.e., large volume of litter exports from Lost River) given the amount of litter produced relative to the amount of treatable land in this watershed.[2]

The optimal solutions obtained under the different scenarios for weighting schemes $\mathbf{M}_1$ and $\mathbf{M}_2$ do not differ much. However, when the weighting scheme ($\mathbf{M}_3$) that takes Lost River as absolutely important (as per its vulnerability ranking) is considered, then, as expected, the quantity of litter remaining in Lost River is reduced drastically, with most of it shipped to South Fork. Of course, there are higher total economic (shipping) costs associated with this, as shown in table 5; this has to be balanced against the potential improvement in environmental quality associated with the reduction in P run-off into this watershed.

The different scenarios examined are intended to provide an illustration (results for additional scenarios are presented in Jones et al. 1998). Thus, if the supply of, and demand for, poultry litter are known ahead of time (they can easily be estimated as demonstrated here), a pre-selected agency in the region (such as the NRCS or Extension Service) could employ the preceding framework to determine optimal litter shipment patterns such that producer and societal objectives were simultaneously accomplished. These patterns would change over time as P vulnerability, transportation costs, and supply-demand characteristics changed (for example, soil tests are recommended every two to three years, causing possible changes in watershed vulnerability rankings).[3] Furthermore, if actual shipment patterns among watersheds are known (this can be ascertained through surveys), they can be compared to optimal patterns (estimated by using the framework in this study for example) to determine where inefficiencies exist. Correcting these will require a cooperative effort among producers, local agencies and policy makers and would entail a larger geographical area (i.e., more watersheds) for implementation.

Conclusions

Poultry production is an important and growing activity in the study area. Accompanying the increase in production is an increase in waste, creating an associated waste disposal problem. Given the concentrated production of poultry and the fixed amount of treatable land available for land-spreading poultry manure (which is the predominant litter disposal method in the region), there is the potential for pollution resulting from P runoff from the study area into bodies of water such as the Potomac River. Thus, this study was designed to examine the feasibility of poultry litter disposal taking into account both economic and environmental characteristics. Perhaps unique in this regard, the study was done at the watershed level of analysis. On a theoretical level, the analysis demonstrates the richness and adaptability of the goal focusing technique. More importantly, from a practical perspective, the contribution of this study is to explore potential solutions (even if they are somewhat obvious) to the vexing poultry litter problem, a growing concern in the mid-Atlantic and other poultry-producing areas. Specifically, this study proposes a way to *operationalize* the solution to this vexing problem and seeks to quantify some of the costs and benefits thereof.

Currently, a litter brokerage established by the Extension Service includes the study area, the purpose of which is to match individuals who want litter with poultry producers wanting to dispose of litter. This brokerage service has certainly helped mitigate the disposal problem and has resulted in some value-added to poultry litter. However, the environmental impacts of the litter transfer are not considered. This study accounts for economic and environmental characteristics simultaneously as a

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[2] In requiring that agricultural runoff from Hardy county be reduced by 38% (footnote 1), the EPA has targeted runoff reductions specifically to Lost River, which the EPA characterizes as being overloaded with animal waste, contributing to a high level of fecal coliform bacteria.

[3] Other ways exist to reduce phosphorus runoff, and can be, or are being, used side by side with the mechanism proposed here. For instance, studies have shown that chickens receiving feed augmented by the enzyme phytase, retain up to 60% of phosphate from feed, thereby reducing phosphorus contents of litter and, ultimately, runoff (*Progressive Farmer* March 1998). In addition, in recent years, the poultry industry has also (largely voluntarily) implemented nutrient management plans (e.g., EQIP/NRCS), dead bird composting, and on-farm storage facilities, all of which have the potential to reduce adverse impacts from waste.

means of minimizing both adverse environmental impacts on water quality and aggregate transportation cost of litter. Intended primarily as an illustration, if data are available, it can be expanded to a larger study area in this state or others where poultry production is tied to water quality.

The implementation of the prescribed optimal disposal options identified in this study is impossible without cooperation of all the agents involved. Poultry producers, farmers using the poultry litter as a soil amendment, the Extension Service, and government agencies would have to work in concert to implement the estimated optimal solution. Incentives for compliance (or penalties for noncompliance) would have to be determined by the enforcement agency.[4] How can such a subsidy/tax rule be set up? Instead of setting the weights based on a system of ordinal rankings, the decision maker can exogenously determine penalties (monetary charges) for both positive and negative deviations from the goals. To effect this, one must instead consider the dual problem. For each primal constraint there is an associated dual variable. Information about the variables that are of interest in determining the level of subsidy or tax is contained in the corresponding dual solution to the primal goal constraint (i.e., equation (10) in the primal model). If the optimal solution results in the goal being exceeded such that the deviation g_j^{+*} is positive for a given watershed then the dual solution for that watershed equals the negative of the unit penalty for excessive demand (dual solution $j = -M_j$). Alternatively, if g_j^{-*} is positive, then the dual solution equals the unit penalty for deficit demand (dual solution $j = N_j$). If, however, the optimal solution coincides with the goal, the dual solution j will be such that $N_j \leq$ dual solutions $j \leq N_j$. It should be noted that optional spreading distribution will include spreading costs as well (assumed constant in the model). Differences in the latter, in turn, could impact costs per acre depending upon the need for P or N.[5]

The study is limited primarily by data availability. Thus, although it incorporates economic and environmental variables, biological variables (such as the impact of poultry litter on crop yields which would need information on crop yield response to litter) are omitted.[5] If data are available, some of the other extensions suggested earlier can be investigated. For larger study areas with a greater number of watersheds than used here (which, ultimately, is needed to implement an actual poultry litter trading system), uniform data collection protocols will also be needed. Subsequently, a system of tradable pollution permits could be devised. To do this, future researchers would have to estimate the P abatement cost at a micro (e.g., watershed) level, for which more complex and/or dynamic water quality models (such as AGNPS) are needed to more accurately capture environmental quality impacts. If the marginal abatement costs are significantly different across watersheds, then this would enhance the feasibility of a marketable permit system based on the vulnerability to P runoff. Ultimately, such a system could maximize the effectiveness of market-based economic incentives, minimize the need for government intervention, and optimize development in the poultry industry.

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[4] Voluntarily-imposed solutions such as this can preempt potential law suits, a growing threat. For example, in July 1998, the state of Maryland filed a lawsuit against a poultry firm operating in the state, alleging that it contaminated the groundwater around its plant, the second such lawsuit filed by that state against a poultry company operating in the state in the same month.

[5] We thank an anonymous reviewer for pointing this out.

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