Modeling Multi-Farm Spatial Interdependence using National Data Coverages:
A Regional Application to Manure Management

Marcel Aillery
Noel Gollehon
Marc Ribaudo
Vince Breneman
Jean Agapoff

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Abstract:
A regional modeling framework using national data series is developed to estimate the net cost of land applying manure under new federal guidelines for manure management. The model, applied to the Chesapeake Bay watershed, integrates GIS spatial data within an optimization model to generate manure hauling distances and costs.

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Environmental regulations may have widely varying impacts within subsectors of the farm economy. Assessments of cost and production adjustments often attempt to capture this variation through refinement of analysis based on representative farms and enterprises. Spatial interactions across farms may represent an additional important determinant of the nature and magnitude of a regulation's impact on producers. However, spatial relationships among farm operations are often ignored due to data and analytic limitations. In some cases, failure to consider spatial effects in representative farm analysis may bias assessments of the potential farm-sector impacts of environmental policies.

Consideration of the spatial interdependence of confined animal operations is particularly important in evaluating the effect of federal measures governing manure management. In 1999, the Environmental Protection Agency (EPA) and U.S. Department of Agriculture (USDA) issued joint guidelines for regulatory and voluntary measures to protect water quality and public health from animal-waste pollution. In 2003, EPA published new regulations affecting an estimated 15,500 concentrated animal feeding operations (CAFOs) (U.S. EPA, 2003). Meanwhile, USDA has a stated goal that all animal feeding operations (AFOs) develop and implement Comprehensive Nutrient Management Plans (CNMPs) to minimize potential water pollutant loadings from confined animal facilities and manure land application (USDA, 2000b). Nutrient standards that restrict applied manure nutrients to levels not exceeding crop needs are a central focus under both the USDA policies and EPA regulations. Implementation of nutrient standards will have implications for regions of the U.S. with substantial concentrations of confined animal

production, as per-acre restrictions on applied manure nutrients result in greater land requirements for manure spreading and increased competition for available acreage.

As part of the animal-waste research program at the Economic Research Service, a regional modeling framework was developed to evaluate the effect of new federal guidelines and regulations on land application of manure. The model is designed to incorporate the spatial interaction across animal operations and agricultural land resources that underlies the critical issue of competition for land to spread manure. An important feature of the framework involves the reliance on national data bases that are readily available, and that facilitate model update and potential model transferability across U.S. watersheds. The modeling framework is initially applied to the Chesapeake Bay Watershed (CBW), the focus of a major Federal/State initiative to reduce excessive nutrient loading to the Bay and tributary streams (Figure 1). The CBW encompasses several multi-county areas where manure-nutrient production from confined animal operations exceeds the capacity of cropland to utilize manure nutrients when applied at agronomic rates (Gollehon, et al., 2001).

This paper presents an overview of the regional modeling framework. The discussion addresses use of primary data bases to develop key data parameters for the manure-nutrient allocation problem. Selected equation sets highlight integration of Geographic Information Systems (GIS) data within the modeling framework to estimate manure hauling distances and costs. Empirical results from a Chesapeake Bay regional application are used to demonstrate the effect of competition for land on which to spread manure, and potential implications for costs to the animal sector. The paper closes with insights and lessons learned from the initial application of the modeling framework.

Regional Modeling Framework

The regional modeling framework is designed to minimize the total regional costs of manure management, transport, and application to agricultural lands in the CBW, given the existing structure and scale of the animal industry and current manure-storage technologies in use. The modeling system 1) tracks manure and related nutrient flows within the basin, from AFOs to site application and use, 2) computes the regional costs of land applying manure, given least-cost manure transfers within the basin; and 3) evaluates alternative land-application regulations and nutrient management policies. The regional model specification captures the critical element of competition for land on which to spread manure in areas with significant animal concentrations by endogenizing access to land and associated hauling costs. Components of the regional modeling system are presented in Figure 2.

Model data

The modeling system relies on two primary data sources: the 1997 Census of Agriculture and the National Land Cover Dataset from USGS. Farm-level Census data were used to generate county-level measures of animal operations and animal-units, total manure production, surplus recoverable manure (in excess of crop needs on the source farm), manure-nutrient content, and potential assimilative capacity of the land for applied manure nutrients. The National Land Cover Dataset was used to define the spatial pattern of land available for manure spreading and to simulate the spatial distribution of animal operations. Technology and cost coefficients for conditions in the CBW/Mid-Atlantic region were obtained from various sources, including the USDA's Natural Resources Conservation Service (NRCS) Cost and Capabilities Assessment (USDA, 2003), Agricultural Resource Management Survey (ARMS) data (USDA,

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2002; USDA, 2000a), published literature, and information provided by subject matter specialists within the government and universities.

The county serves as the primary modeling unit for the regional model. The county-level specification provides consistency with Census data and other county-level data, while permitting differentiation of institutions and regulatory conditions across county and State political boundaries within the watershed. Manure is produced in a 'source county' and land-applied (or otherwise utilized) in a 'destination county'. The full watershed model includes 160 non-municipality counties within the basin, representing potential 'source' and 'destination' counties. Additional 'sink' counties outside the watershed area serve as potential receiving areas for manure from the CBW, subject to net assimilative capacity after accounting for in-county manure applications. There are 104 sink counties included in the full watershed model, comprising all non-municipality counties within 60 kilometers (37 miles) of a CBW county (measured from the edge of the source county's cropland base). To account for manure flows at the basin level, model values for 'edge' counties that straddle the watershed boundary are apportioned based on the share of crop and pasture land within the watershed.

Agricultural Census. Using data collected for the 1997 Census of Agriculture (USDA, 1999), we estimate manure-nutrient surpluses on animal operations by applying farm-level measures of manure nutrient production relative to the farm's potential to utilize nutrients for crop production. For modeling purposes, results from the farm-level calculations are then summed across animal types and aggregated at the county level.[1] Manure-nutrient production, potential manure nutrient use by farms with animals, surplus recoverable manure nutrients, and potential assimilative capacity of farms without confined animals were computed following

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[1] Our analysis meets all respondent confidentiality requirements of the published Census of Agriculture values.

procedures in Gollehon, et al. (2001) and Kellogg, et al. (2000). Briefly, county-wide manure nutrient quantities were estimated from Census data on end-of-year animal inventories and annual sales, using coefficients of manure production by animal type. A composite manure-nutrient content is generated for each county based on the distribution of animal species. Potentials for manure nutrient use were estimated at the county level from reported yields and acres for 24 major field crops and permanent pasture, aggregated across farm types.

GIS Data. To estimate hauling distance requirements for manure spreading, we used a Geographic Information System (GIS) to create "area-to-distance" functions for county-level manure allocations in the study region. These functions are a central component of the optimization model—linking the area needed for manure spreading with the hauling distance required to dispose of surplus manure, and capturing the inherent competition for land that exists among animal producers.

GIS estimation of "area-to-distance" functions involved a series of procedures: 1) developing the spatial distribution of spreadable land for the CBW study area; 2) assigning location of animal feeding operations within CBW counties; 3) calculating "area-to-distance" relationships for in-county transfers; 4) calculating distant intercepts and "area-to-distance" relationships for out-of-county transfers; and 5) estimating linearized "area-to-distance" functions for inclusion in the model.

The modeling system uses the National Land Cover Dataset (NLCD) developed by the U.S. Geological Survey (Homer et al., 2000) to assess the spatial pattern of land available for manure application (hereafter termed "spreadable land"). This dataset is based on 1992 Landsat thematic mapper imagery at 30-meter resolution, classified into 21 landuse categories. By combining the crop and pasture land categories, we are able to assemble a spatial data set of

spreadable land in all counties of the study region, including counties within the CBW and adjacent counties within a 60-km reach of the watershed boundary.

Using the GIS, animal operations in the CBW were locationally assigned by county. While the number and average size of animal feeding operations can be obtained from the Census at a county level, the specific locations of operations within a county were not available. (The Census does not collect precise location information, and the data are not available at a regional scale from other sources.) For purposes of this analysis, animal operations were randomly assigned to a 30-meter grid location within cropland and pastureland portions of the county. We then computed the area-to-distance relationships by incrementally increasing, through a series of expanding 30-meter concentric bands, the search for farmland around each of the assigned animal operations. The change in aggregate spreadable area—excluding non-farmland and farmland previously 'claimed' by a competing operation in closer proximity—is measured for each additional distance increment. Thus, the area-to-distance relationship reflects the average distance that must be traveled, across all confined animal operations, to access a given level of spreadable acreage, accounting for competition among animal producers.

Area-to-distance functions for in-county manure transfers represent the average hauling distance from animal farms in a given county to spreadable land within the same county. With limited amounts of surplus manure, spreadable land is relatively accessible and hauling distances are generally short. As manure spreading requirements increase, animal operations must compete increasingly for the same acreage—reducing accessibility and increasing the hauling distance needed to access available acreage.[2] The relationship between the spreadable acreage

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[2] The actual area of available spreadable acreage used for manure application in a given county is determined by the optimization model, reflecting manure flows within and across counties that minimize disposal costs, subject to physical land limits and specified levels of "willingness-to-accept" manure.

requirement and average distance hauled is upward sloping and fairly linear along much of the observed range (Figure 3).

Out-of-county functions represent manure hauling distances from animal operations within a source county to spreadable acreage in other destination counties. Unique out-of-county functions were generated for all source and destination county combinations within an assumed 60-km linear transport radius. The transport radius for the 16 counties with the highest concentrations of surplus manure (10 percent of total) was expanded to 150-km (93 linear miles), reflecting the potentially greater hauling distances required from counties where animal production is concentrated.

A two-stage process was used to generate the area-to-distance functions for out-of-county transfers. First, distance was measured from each animal-operation/grid location in the source county to the closest edge of spreadable acreage in the destination county; this distance represents the intercept term of the functional relationship. To reduce the number of manure source-county grid alternatives, animal farms were aggregated (binned) by a 12-km grid across the watershed area. Although the binning procedure reduces the precision of the intercepts for out-of-county functions, the procedure was necessary to ensure tractability for model optimization. Second, the area-to-distance relationship was computed in a fashion similar to that for in-county transfers. Thus, the area-to-distance relationship represents average hauling distance to access a given spreadable area within the destination county, but measured from the direction of the source county.

For the regional model, area-to-distance relationships estimated from the GIS were linearized by truncating the upper and lower tails of the distribution (10 percent of acreage, respectively) and fitting a linear function to the mid-range observations (80 percent). The use of

linear representations reflects the significantly reduced computer memory requirements relative

to non-linear functions for the area-to-distance relationship, and the fact that observed

relationships were very nearly linear over the relevant mid-range. Regression coefficients for the

linear area-to-distance functions were incorporated as parameters in the regional model. These

include a unique set of slope coefficients for each in-county and out-of-county function, as well

as individual intercept terms by source-county grid for each out-of-county function.

Competition for spreadable land is, in part, a function of the spatial pattern of cropland

and pastureland. Where farmland is scattered, a higher slope of the area-to-distance relationship

reflects relatively long average hauls within the destination county to access a given spreadable

area. Where farmland distribution is more dense, a reduced slope reflects comparatively shorter

hauls to access a given acreage. The degree of competition also depends on the number, size,

and proximity of confined animal operations, both within and out-of-county. Greater

concentrations of animal operations can effectively reduce the average hauling distance where

competition is not a factor (i.e., an increase in the number of operations reduces the hauling

distance, on average, for a given quantity of manure). However, where land is limiting, greater

concentrations of animal production will increase competition for spreadable acreage, resulting

in longer hauling distances to access available land and greater potential for out-of-county

manure exports.[3]

Regional model structure

The regional optimization model minimizes the cost of manure land application in the

CBW, based on current manure production levels and land available for manure spreading. The

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[3] The random assignment of animal operations in the GIS—regarded as reasonable at the watershed scale—may yield somewhat conservative estimates of actual hauling distances. While the majority of animal operations tend to be located in proximity to crop and pasture land, operations may be separated from arable land since production is

modeling framework allocates total manure produced—net of manure diverted to industrial uses—across cropland and pastureland in the basin. Land-applied manure includes onfarm use and off-farm transfers, both in-county and out-of-county.

The optimization model minimizes the regional net cost of applying manure, subject to total manure produced, land availability for manure applications, and other utilization options. The model allocates manure flows across the watershed and neighboring sink counties to minimize the objective function expression:

(1) $\quad \sum_{ct} \sum_{ct2} [HAC_{ct,ct2} + INC_{ct2} + NM1_{ct} + NM2_{ct2} + ELA_{ct} - FS_{ct2}]$.

Costs include manure hauling and application costs (HAC), land incorporation costs (INC), and nutrient management plan charges for source (NM1) and destination (NM2) counties. A penalty cost for manure levels exceeding land application (ELA) capacity ensures that all surplus manure is land applied subject to available land, and that manure storage is not permitted where spreadable land is available within the transport radius of the manure source (this penalty cost is removed from reported costs). Aggregate costs are adjusted to reflect cost savings from reduced purchase and of application chemical fertilizers (FS).

In-county and out-of-county transfers of manure are the primary activities in the model. Potential county-to-county transfers are developed based on an assumed maximum radial distance of 60 kilometers (37 miles) or 150 kilometers (93 miles) for the largest manure-surplus counties (10 percent of total), measured from the outer edge of the source county's cropland base. There are 4,060 county-level transfer possibilities in the full watershed model, including in-county and out-of-county transfer combinations. Manure transfers are further disaggregated

not as sensitive to soil conditions. Moreover, observed clustering of animal operations in some cases will increase competition for adjacent land resources.

by subcounty grid location, manure system type, and distance interval, resulting in over 300,000 potential transfer alternatives.

The primary decision variables in the model are the quantity of manure transferred, acres used for manure spreading, and manure hauling distance. Model equations include 1) balance equations that track stocks and flows of manure and manure nutrients, 2) constraints on land availability, distribution of confined animal farms (manure sources), and manure nutrient use, and 3) cost accounting equations. In general, wet manure quantities are used to compute model hauling and application costs, while manure nutrient content and uptake rates determine the volume and direction of manure flows.

Primary manure transfer equations are:

(2) $M\_TRAN_{ct,ct2} = ((M\_AP_{ct,ct2,N*} * SH\_N_{ct2}) + (M\_AP_{ct,ct2,P*} * (1\text{-}SH\_N_{ct2}))) * AC\_SPR_{ct,ct2}$

(3) $\sum\limits_{ct} AC\_SPR_{ct,ct2} \leq A_{ct2} * WTAM_{ct2}$

(4) $M\_TRAN_{ct,ct2} = \sum\limits_{gr} \sum\limits_{sy} \sum\limits_{ds} M\_TRN_{ct,gr,ct2,sy,ds}$

(5) $\sum\limits_{ds} M\_TRN_{ct,gr,ct2,sy,ds} \leq M\_PRD_{ct,ct2} * SH\_M_{ct,gr,ct2,sy}$

where $N*$ represents a nitrogen (N) standard and $P*$ represents a phosphorus (P) standard, gr is county grid location, sy is manure system (lagoon, slurry, dry), and ds is hauling distance interval in miles. Onfarm hauling distance is based on estimated average county distance. Off-farm hauling distance is derived endogenously, falling within one of three intervals (0.5-2, 2-10, or greater than 10 miles) used to calculate hauling costs.

In Equation (2), dry manure tons (M_TRAN) is defined as the product of per-acre manure application rate (M_AP) for each county transfer—weighted by the acreage share under

an N standard (SH_N) and acreage share under a P standard (1- SH_N)—and receiving acres

(AC_SPR) in the destination county. (In order to frame the potential range of costs, separate

model runs were specified for all acreage under an N standard and all acreage under a P

standard.) Manure application rate for each individual in-county and out-of-county transfer is

based on: 1) average nutrient content of manure from the source county (*ct*); 2) average nutrient

removal rates for N and P in the destination county (*ct2*), weighted across cropland and

pastureland for each of three farm types (non-animal farms, non-confined animal farms, and

confined animal farms); 3) nitrogen volatization factors, with and without incorporation; and 4)

whether an N or P nutrient standard is in effect. Data specification by county and farm type

allows the model to capture potential variation in assimilative capacity due to differences in

cropping pattern, land in pasture, and crop yield.

Equation (3) restricts applied manure from all potential source counties to total

spreadable acreage (A) in the destination county. Actual acreage available will depend largely

on the willingness of landowners to accept manure on their farmland, reflecting concerns for

manure-nutrient variability, handling cost, odor, and other factors. Assumptions on landowner

willingness to accept manure (WTAM) are reflected in automated adjustments in both the

quantity of spreadable acreage and the slope of "area-to-distance" functions, or hauling distance

required to access a given spreadable area. Values for levels of willingness to accept manure on

non-animal farms and nonconfined animal farms range from 10 percent to 100 percent of

spreadable land area; all acreage on confined animal farms is assumed available for manure

spreading. Equation (4) sets aggregate county-level manure transfers (M_TRAN) equal to the

sum of manure transfers by source-county grid location (*gr*), system type (*sy*) and distance

interval (*ds*). Equation (5) bounds manure transfers by the share (SH_M) of total county-level

manure production (M_PRD) across system type and grid, based on allocation procedures followed in the GIS.

Equations (6) through (8) are used to balance manure production, use, surplus, and quantity of manure exceeding land application capacity at the county level.

(6) $M\_SRP_{ct} = M\_PROD_{ct} - M\_ONFRM_{ct}$

(7) $M\_USE_{ct2} = M\_ONFRM_{ct2} + \sum_{ct} M\_TRAN_{ct,ct2}$

(8) $M\_ELA_{ct} = M\_SRP_{ct} - \sum_{sy} M\_IND_{ct,sy} - \sum_{ct2} M\_TRAN_{ct,ct2}$

Equation (6) sets surplus manure (M_SRP) equal to manure production (M_PROD) less that used onfarm (M_ONFRM) in the source county. Equation (7) fixes manure use (M_USE) within a destination county to onfarm manure use plus that quantity obtained from off-farm sources (M_TRAN). Equation (8) sets the manure that exceeds land application capacity (M_ELA) due to insufficient assimilative capacity within the transport radius equal to the manure surplus in the source county, less the sum of industrial uses (M_IND) and the sum of manure transfers out-of-county. Manure used for industrial purposes is defined exogenously by county and waste-system type (eg. dry poultry litter) and converted to dry-ton equivalents for representation in the model.

Stocks and flows of manure nutrients (*np*)—nitrogen *n* or phosphorus *p*—are tied to manure quantities using the following equations:

(9) $M\_SRP_{ct} = NP\_EXC_{ct,np} / NP\_M_{ct,np}$

(10) $NP\_ONF_{ct2,np} = M\_ONFRM_{ct2} * NP\_M_{ct,np}$ where $_{ct} = {}_{ct2}$

(11) $NP\_TRN_{ct,ct2,np} = M\_TRAN_{ct,ct2} * NP\_M_{ct,np}$

Total excess manure nutrients (NP_EXC) are obtained from farm-level Census data on manure

production and onfarm assimilative capacity aggregated to the county level. Equation (9)

calculates surplus manure (M_SRP) based on excess N or excess P (NP), depending on the

nutrient standard in effect ($N*$ or $P*$) and county-average nutrient content per dry ton of manure

(NP_M). In Equation (10), onfarm manure nutrients (NP_ONF) reflect the quantity

(M_ONFRM) and composition of manure produced and used on confined animal feeding

operations. In Equation (11), manure nutrients transferred (NP_TRN) is measured as the

quantity of manure land-applied off the farm (transferred) times the county-average nutrient

content per ton of manure.

(12) $\quad DS_{ct,gr,ct2} \;=\; [(\alpha_{ct,gr,ct2} * \delta^1_{ct,ct2}) + (\beta_{ct,ct2} * (AC\_ONF_{ct} + \sum_{ct} AC\_SPR_{ct,ct2}))] * \delta^2_{ct2}$

(13) $\quad DS_{ct,gr,ct2} * M\_TRN_{ct,gr,ct2} \;=\; \sum_{sy} \sum_{ds} (DST_{ct,gr,ct2,sy,ds} * M\_TRN_{ct,gr,ct2,sy,ds})$

(14) $\quad D\_MN_{ds} \;\leq\; DST_{ct,gr,ct2,sy,ds} \;\leq\; D\_MX_{ds}$

Hauling distances are computed through Equations (12) – (14). In Equation (12),

average hauling distance (DS) from source county (*ct)* and grid location (*gr)* is calculated as a

function of onfarm and off-farm spreadable acres in the destination county (*ct2)*, based on

α and β distance coefficients from the GIS-derived linear regression estimates. The intercept

term, represents the linear hauling distance from the source farm for out-of-county transfers, is

adjusted by (δ^1) for selected county-to-county transfers due to natural barriers (e.g., large bodies

of water). In addition, the parameter (δ^2) is used to convert linear distance to road miles

(USDC, 1978). In Equation (13), average hauling distance is measured as a weighted average of

hauling distances (DST) across manure-system type (*sy)* and distance interval (*ds)*, reflecting

potential differences in cost structures. Minimum (D_MN) and maximum (D_MX) hauling

distance is specified by distance interval in Equation (14).

$$(15) \quad HAC_{ct,ct2} = \sum_{gr} \sum_{sy} \sum_{ds} [C1_{sy,ds} + (C2_{sy,ds} * DST_{ct,gr,ct2,sy,ds})]$$

$$* (M\_TRN_{ct,gr,ct2,sy,ds} / (1 - (MS_{sy} + BED_{sy})]$$

In Equation (15), manure hauling and application costs (HAC) are computed for onfarm

and off-farm transfers based on the loading, unloading, and application costs per ton hauled

(C1), a hauling cost per ton-mile (C2), average distance hauled (DST), and the quantity of

manure hauled in dry tons (M_TRN), adjusted for moisture content (MS) and bedding (BED).

Hauling and application costs vary across animal-waste systems due to differences in manure

moisture content and equipment used, by species and manure-system type. The model simulates

a stepwise cost function for manure hauling/application cost, with cost coefficients defined by

manure system type and hauling distance interval. Additional costs for incorporation of manure

in the soil are computed based on per-acre incorporation cost, total onfarm and off-farm acres

using manure, and the share of total acres on which manure is incorporated. For a more

complete discussion of the model equation system, see Ribaudo, et al., 2003.

Assessing the importance of spatial considerations

Results of the Chesapeake Bay Watershed analysis highlight the importance of spatial

considerations involving the concentration of animal operations relative to crop and pasture land,

and the resulting competition among animal operators for land on which to spread manure.

In our analysis, regionwide costs of manure land application varied widely depending on

the acreage available under each nutrient standard and landowner willingness to accept manure

(WTAM). Total annual cost of land-applying all manure in the CBW ranged from $123 to $134

million under an N standard, and $143 to $155 million under a P standard, depending on the WTAM level. Total annual cost is defined as the aggregate cost of manure hauling, field application, and incorporation, plus selected costs associated with the nutrient management plan (manure testing, soil testing, plan development)[4]. Net cost—representing total annual costs of land applying manure less fertilizer cost savings from reduced fertilizer purchases and reduced fertilizer application cost[5]—ranged from $55 to $73 million under the N standard and $75 to $91 million under the P standard (Ribaudo et al., 2003).

Transporting manure for land application—both onfarm and off-farm—represented the largest component of total annual cost in the watershed. Transport costs accounted for 64 to 66 percent of total costs ($78 to $89 million) under an N standard, and 63 to 68 percent ($90 to $102 million) under a P standard. Off-farm manure transfers to suitable crop and pasture land accounted for 25 percent of the transport and application costs at a WTAM level of 100 percent. The costs devoted to off-farm transfers increased from $28 to $43 million (25 to 35 percent) as the WTAM declined, with a shift from mainly 'within county' costs to primarily 'out-of-county' costs. However, a regional presentation masks local cost conditions by averaging values over the watershed, and most of the region's total out-of-county cost accrued in a relatively few counties which transported significant manure quantities out-of-county.

Findings at the aggregate regional level suggest that spatial factors underlying competition for spreadable land are an important consideration in assessing costs to the animal

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4 Total cost does not consider manure storage costs, costs associated with hauling and processing of manure that is not land applied, or costs of capital improvements that may be desirable, or necessary, to improve onfarm manure storage and handling systems to meet policy goals.
5 Savings in chemical fertilizer were based on nutrient costs of nitrogen and phosphorus in the region's most common commercial form and are sensitive to assumptions on fertilizer prices, forms, and application efficiencies. Only the manure nutrients that could be utilized by crops were assigned value. In meeting an N standard, adequate phosphorus would also be applied and the value of a reduced field operation was credited as "savings." However, nitrogen requirements are not met under a P standard. It was assumed that additional commercial nitrogen would

sector. Under an N standard, approximately 50 percent of the manure produced in the basin will

need to be land applied (or otherwise disposed of) off the farm, with this share increasing to 62

percent under the more stringent P standard. Clearly, the costs faced by producers are heavily

influenced by conditions off the farm, arguing for a regional spatial perspective. The capacity to

assimilate manure off-farm will depend on various spatial considerations—including the extent

of cropland and pastureland available for spreading, the regional crop mix that influences

assimilative capacity of the soils, the distribution of soils by nutrient standard requirement, the

willingness of landowners to accept manure, and the competition for available land among

competing animal producers.

Our finding that the willingness to accept manure has a significant impact on costs

suggests that competition among animal producers for land on which to spread manure is an

important factor in assessing potential costs. The primary cost adjustment as the WTAM

decreased was the increasing cost of transporting manure to land. In many areas of the basin,

long hauling distances (and an expanded volume of out-of-county hauls) may be required to

access sufficient spreadable area, reflecting the concentration of manure production relative to

agricultural land, the nutrient uptake of crops and nutrient standard required, and levels of

manure acceptance.

A comparison of six selected counties illustrates the importance of spatial factors on

manure hauling requirements (Table 1). Three counties represent areas of the watershed where

production of confined animals (primarily poultry) is heavily concentrated—Sussex, DE,

Rockingham, VA, and Lancaster, PA. Three additional counties were selected to represent areas

with lesser concentrations of manure production relative to spreadable area—Frederick, MD,

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continue to be applied, so the chemical fertilizer savings when meeting a P standard included no savings in field

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Buckingham, VA, and Clinton, PA. While the average onfarm spreadable acreage per animal-unit is roughly comparable across the six counties (ranging from 0.5 to 3.1 acres per AU), off-farm conditions differed substantially across sub-watershed areas, with important implications for manure hauling. In the case of Sussex, Rockingham and Lancaster counties, competition for available spreadable land resulted in average off-farm hauling distances for surplus manure of 83 miles, 89 miles, and 71 miles, respectively. Average hauling distance for all manure produced on the farm was substantially lower (68, 79, and 48 miles), reflecting the effect of short hauling distances for manure applied onfarm. In the case of Frederick, Buckingham, and Clinton counties, average off-farm hauling distances of 6 miles, 15 miles, and 4 miles were substantially lower, reflecting reduced competition for spreadable land off the farm in these producing areas. The substantial differences in reported hauling distances underscore the importance of off-farm competition in assessing costs of manure land application. The findings suggest that a representative farm-level analysis which does not explicitly account for effects of competition for land from competing manure sources may understate actual costs faced by animal producers.

What Have We Learned?

In developing the modeling framework presented in this paper, we gained several insights on the application of spatial relationships within an optimization framework to address agricultural policy issues. Our analysis suggests that it is possible to construct a regional model with a 'farm-based perspective', drawing from a national data series. The combination of farm-level Census data with detailed GIS-Landsat data and local technology data provides for considerable subregional differentiation in producer response to federal policies. The resulting

operations.

modeling framework provides a unique perspective relative to a representative farm or national

sector model, and may be preferable for certain empirical questions for which spatial

considerations involving farm operations and land patterns are important. The modeling

framework could also be applied to other regions, subject to the processing of national data

series in a manner useable within the optimization framework.

The findings from our application suggest that the availability of spreadable land matters.
Competition for spreadable land results in increased manure transport distances and costs, with

the most significant cost impacts observed in sub-watershed areas where the ratio of animals

produced to land availability is greatest. Indeed, it would be difficult to arrive at an accurate

representation of manure hauling costs in many animal producing areas of the country without

considering the spatial relationship of operators to the available landbase off the farm. Some of

the key insights drawn from the Chesapeake Bay regional study include:

- At low levels of landowner willingness to accept manure, there would be insufficient

  land to land apply all surplus manure in the CBW given transport limits assumed in the

  analysis. This is particularly true under the more stringent P standard.

- The willingness of landowners to accept manure is a critical element in determining the

  feasibility and costs of a land application strategy, and thus affects policy impacts.

- Handling of manure is expensive, and nutrient standards under new federal guidelines for

  manure land application will increase costs for many operators. As comprehensive data

  on current manure use are not available, the *increase* in sector costs cannot be accurately

  assessed.

- Most of the sector costs for manure handling occur 'on the farm' where manure is produced. Off-farm costs are, to a large extent, a function of the competition among animal operations for land on which to spread surplus manure.

- Out-of-county transfer costs are significant, and are concentrated in a few counties where confined animal production is centered. Opportunities may exist for developing alternative industrial uses for surplus manure in these areas.

As in any modeling activity, measures to ensure tractability of the modeling process necessarily introduce some bias in reported results. In integrating spatial GIS data and Census data within an optimization framework, it is somewhat difficult to assess the degree of bias—or net bias, considering these factors jointly. Some of the key GIS data-integration issues addressed during model development involved allocation procedures for animal operations within a county absent comprehensive locational data at a watershed scale and given concerns for producer confidentiality, the binning of manure-grid sources and specification of maximum hauling radii to reduce modeling dimensionality, and the linearization of area-to-distance functions to relax computational requirements. More research is required to provide insight on the tradeoffs in model precision and model performance, and the value and costs of additional spatial information.

Overall, we feel that the analytic framework developed here provides a unique and useful perspective to inform the policy process. The results highlight the importance of spatial factors in assessing potential costs under new federal guidelines for manure management, and help to illuminate several key areas for policy consideration. While the application of GIS spatial data within an optimization framework represents a potentially powerful tool for policy analysis, the computational requirements of the resulting model can be significant. Future research using a

regional approach may need to consider aggregating manure transfer alternatives to a greater

degree than in this application, thus trading locational precision for computational ease.

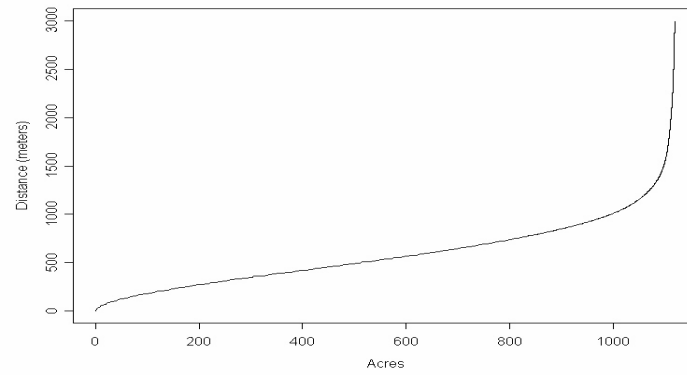**Figure 1. The Chesapeake Bay Watershed**
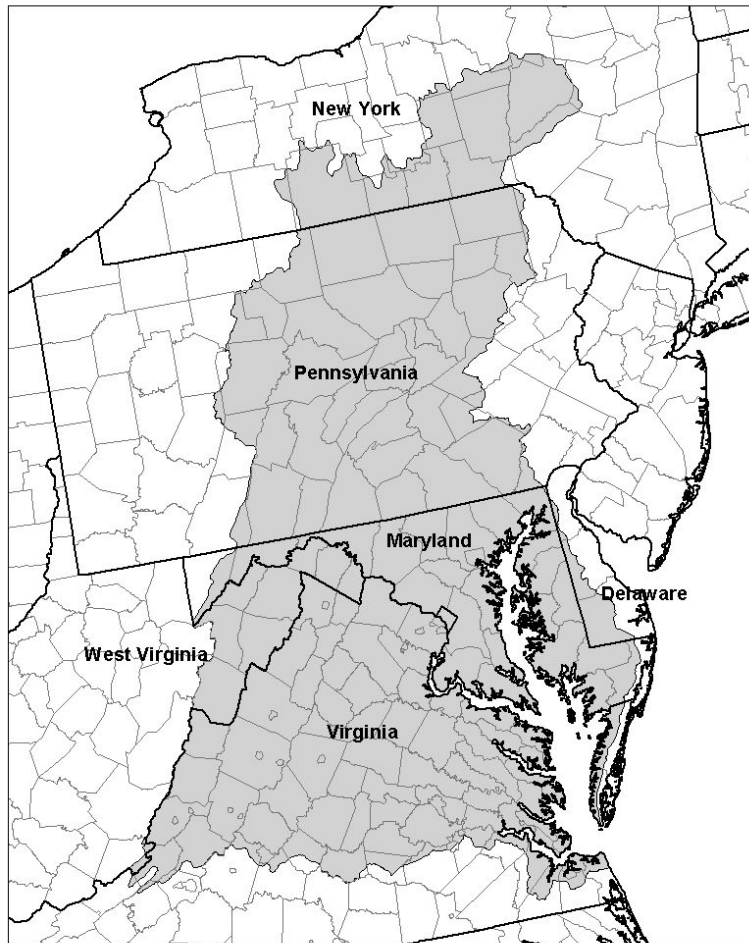
Figure 2. Regional Modeling System
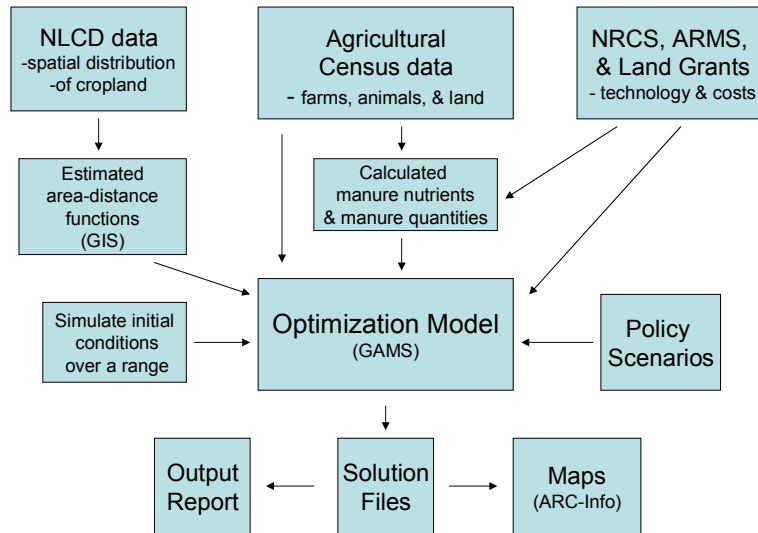
Figure 3. Representative area-to-distance function

**Table 1. Effect of Competition for Spreadable Land on Average Manure Hauling Distance
in the Chesapeake Bay Watershed   (Phosphorus Standard, 60% WTAM)**

Selected counties for sub-watershed areas with higher and lower concentrations of confined animal production	Confined AUs	Spreadable Acres		Spreadable Acres per AU		Average Hauling Distance	
		Farms with Confined Animals	All Farms	Farms with Confined Animals	All Farms	Off-farm only	On-farm & Off-farm
	(AUs)	(acres)	(acres)	(acres)	(acres)	(miles)	(miles)
Higher AU Concentrations							
Sussex, DE	78,881	131,803	273,389	1.7	3.5	83.43	67.51
Rockingham, VA	165,422	90,775	167,294	0.5	1.0	89.29	79.38
Lancaster, PA	244,270	278,388	353,774	1.1	1.4	70.64	47.95
Lower AU Concentrations							
Frederick, MD	37,734	89,119	175,871	2.4	4.7	6.32	2.92
Buckingham, VA	4,094	5,804	38,044	1.4	9.3	15.41	10.83
Clinton, PA	6,038	18,607	29,309	3.1	4.9	4.44	1.19

AU = animal units, defined as 1,000 pounds of live animal weight (Gollehon, et al., 2001)

WTAM = landowner willingness to accept manure (Ribaudo, et al., 2003)

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