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MODELING FIRM SPATIAL INTERDEPENDENCE USING NATIONAL DATA COVERAGES: A REGIONAL APPLICATION TO MANURE MANAGEMENT

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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 possible policy provisions to limit water- and air-quality emissions. The modeling framework, applied to the Chesapeake Bay watershed, integrates GIS-based spatial data within an optimization model to capture spatial effects at a subwatershed scale.

KEY WORDS: Regional optimization, geographic information systems, spatial data, manure management, confined animals, nutrient policies, Chesapeake Bay.

1. Introduction. The spatial interdependence of producing firms and production resources is often an important consideration in evaluating the effect of federal environmental policy measures. In the case of agriculture, environmental regulations may have widely varying impacts by locales and subsectors of the farm economy due to spatial differences in resource endowments, farm structure, and enterprise type. Economic assessments of policy adjustments often attempt to capture this variation through analysis of representative farms and enterprises. However, spatial interactions *across* farm operations—often ignored due to data and analytic limitations—can also be an important

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determinant of the nature and magnitude of regulatory impacts. In some cases, failure to consider spatial effects in representative farm analysis may bias assessments of potential farm-sector impacts of environmental policies.

Spatial considerations have had an important influence on firm sitting and production decisions in many economic sectors. High technology firms are often spatially clustered due to concern for agglomeration economies, infrastructure requirements, and localized markets for information, labor, and capital (Maggioni [2002]). Retail planning is significantly affected by market and transportation considerations that are spatial in nature (Arentze et al. [1997]). Spatial relationships involving environmental factors can also influence firm decisions. Rural amenities are often important considerations in residential land use planning (Irwin and Bockstael [2004]), and wetland restoration requires consideration of hydrologic, ecological, and land use processes in a spatial context (Van den Bergh et al. [2004]).

Spatial considerations are particularly important in agricultural production decisions (Mulligan [1997]). Spatial factors affecting agricultural production are too numerous to detail. Several important factors involve soil and climate resource effects on commodity choice and technology use; the spatial interdependence of farm-production and processing activities; the cost of transport and access to agricultural markets; and spatial proximity to topographic features and human activities that largely determine the environmental impact of agricultural production. The challenge for the policy analyst is to devise analytic tools with available supporting data that capture the impact of key spatial variables in analysis of agricultural policy concerns. In this article, we describe a methodology developed to incorporate spatial considerations in analysis of policy measures to limit the pollution potential of animal waste.

2. Manure management policies and concerns. The management of animal manure from livestock production facilities has emerged as an important public policy concern, with implications for future regulatory controls and resulting increases in producer costs. 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; USEPA [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 for controlling nutrient movement to water supplies. Implementation of nutrient standards for applied manure may impose significant costs in regions with substantial concentrations of confined animal production. As policies will require that much of the manure move off the source farm, costs to the animal sector will depend on the availability of land resources and the competition among animal producers to access land for manure spreading.

In addition to the water-quality concerns, confined animal operations are the largest source of ammonia emissions in the United States (Abt Associates [2000]). Emissions occur at all phases of the manure production cycle, from animal discharge to manure storage and land application. In some cases, accepted manure management practices for water-quality protection have contributed to air-quality concerns. Lagoons, for instance, are commonly used to store and treat manure waste from swine operations. These storage systems volatilize nitrogen, thereby reducing the concentration of nitrogen in lagoon effluent. Reduced nitrogen in manure requires less land area for manure spreading at crop-based rates, reducing the cost of land-applying manure to achieve water-quality requirements. However, the volatilized nitrogen compounds escape into the air, creating odors and contributing to fine particulates (haze) and greenhouse gas emissions (National Research Council [2003]).

Although the spatial nature of animal concentrations relative to land available for manure application has long been recognized, earlier policy assessments have generally not considered spatial factors due to data and model processing limitations. More recently, however, a number of studies have sought to incorporate spatial data in assessments of animal-waste policy on environmental quality and sector costs. Cook and Silberberg [1998] considered the spatial distribution of cropland by field slope, soil characteristics, and cover type in assessing manure land application in Missouri. Fleming and Long [2002] examined the cost impacts of a regulatory policy that would restrict fieldslope permitted for applied manure in Kentucky. Deerhake et al. [2005] evaluated the effect of ammonia-N emissions from AFOs on air-quality measures in eastern North Carolina.

The Economic Research Service, USDA, has conducted a multiyear research program to evaluate the effect of federal guidelines and regulations on the costs of manure management. (Major findings of this research program may be found in Gollehon et al. [2001], Ribaudo et al. [2003], and Aillery et al. [2005b].) In support of this research program, ERS researchers developed a unique methodology that incorporates key spatial policy variables within an optimization modeling framework. The ERS framework applies a series of functional expressions, derived in a geographic information system (GIS), to capture the spatial relationship between animal farms and land for manure spreading. The distribution of farmland and animals across the landscape includes important spatial variation in both the nutrient content of manure and nutrient assimilative capacity of available land. The functional relationships were estimated from publicly available, secondary data sources, which dramatically lowers the cost of incorporating spatial factors in large-scale modeling applications.

The ERS modeling framework was developed to estimate the costs of various manure management alternatives for water-quality and air-quality improvement in the Chesapeake Bay watershed (CBW). The CBW is the focus of a major federal/state restoration initiative to protect water quality in the Bay and tributary waterways by reducing nutrient loadings from agriculture and other sources. The CBW encompasses several multicounty areas where manure nutrient production from confined animal operations exceeds the local capacity of agricultural land to utilize manure nutrients when applied at crop-based rates (Gollehon et al. [2001]). In areas of high animal concentrations, farmers will face significant competition for land to spread manure under new regulations that restrict the rate of applied manure nutrients.

This paper discusses the ERS regional modeling framework, with emphasis on the use of national data series to capture spatial relationships in farmland and manure production that drive the cost of environmental policies. The framework addresses an important policy concern for the animal sector—How far must manure be transported, given that other producers are also seeking land for manure application? Empirical results from an application to the CBW highlight the importance of spatial factors in assessing competition for land and manure hauling costs under differing policy settings.

3. Regional modeling framework. Figure 1 presents a schematic of components and linkages in the overall modeling framework, including data, analysis, and output. The modeling framework features a regional, nonlinear, cost-minimization model of manure-nutrient production and distribution.[1] The model is designed to assess the regional costs of annual manure transport and land application, given the existing structure of the animal industry, manure-storage technologies, and manure disposal options prevailing in the late 1990s. The model allocates manure nutrients produced within the CBW to agricultural land for crop use in a manner that minimizes hauling and land application costs incurred by the regional animal sector.[2] Primary policy variables involve nutrient standards for applied manure, technology enhancements for manure storage and application, assumptions on landowner willingness to accept manure, and alternative manure disposal options. The model code was developed in the General Algebraic Modeling System (GAMS), using the MINOS solver for large nonlinear applications.

The model was defined at a watershed spatial scale that includes portions of six states (Virginia, Maryland, Delaware, Pennsylvania, New York, and West Virginia) to account for the regional distribution of crop and pasture land as well as animal operations competing for available land resources. A watershed scale is appropriate to assess implications of federal manure management policies, given the regional resource interactions and federal role in water-quality protection. Within the region, counties serve as the primary modeling unit. The county-level specification provides consistency with agricultural census data and other data available at a county level. At the same time, the county scale permits differentiation in animal production, nutrient uptake, and waste technologies across county and state boundaries within the watershed.

Although the regional optimization model represents the core of the system, data development activities were essential in estimating

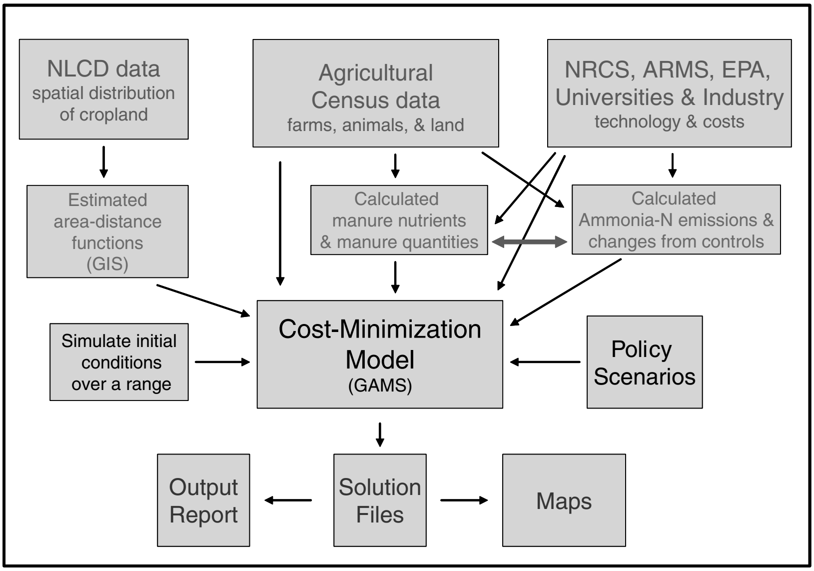

FIGURE 1. CBW modeling system overview.

spatial relationships that drive the model. The model relies primarily on national data series from the U.S. Department of Agriculture and U.S. Geological Survey (details below) for key model parameters. These data ensure consistency across the watershed, while facilitating the potential for model updates and transferability to other U.S. watersheds. Model data specified at the county level permit important subregional differentiation in cost determinants such as animal production by species, nutrient uptake, waste technologies, and regulatory conditions across county and state boundaries. Additional supporting data used in generating technology, cost, and emission coefficients representative of the CBW or Mid-Atlantic region were obtained from various sources, including the Natural Resources Conservation Service's (NRCS) Cost and Capabilities Assessment (USDA [2003]), the National Emission Inventory (USEPA [2004]), the Agricultural Resource Management Survey (ARMS) data (USDA [2002]; USDA [2000a]), published literature, and information provided by subject matter specialists within the government and universities.

4. Modeling spatial relationships. In evaluating potential costs of off-farm manure hauling, a modeling framework was needed to capture the range of manure transfer options. The framework had to be sufficiently flexible to consider alternative policy specifications, with manure of differing types and nutrient composition. Although a detailed grid of manure source farms and receiving lands could conceivably incorporate all possible manure transfers at a watershed scale, the sheer dimensionality of the activity matrix would render the model intractable. Instead, we used the information inherent in spatial relationships in land and animals to derive functional expressions for manure transfers, integrating county-based data on manure production with GIS land coverages to simulate hauling requirements.

The model includes 160 nonmunicipality counties with farmland in the CBW. Each of these counties contains confined animal farms that represent a source of manure (source) and/or farms with land potentially available for manure application (destination). Manure is produced in a source county and land applied (or otherwise disposed of) in a destination county. In addition, the model includes 55 "sink" counties comprising nonmunicipality counties within 60 kilometers (37 miles) of cropland in the CBW. These are destination counties with cropland wholly outside the basin area, serving as potential receiving areas for manure exported from the watershed. For 52 modeled counties that form the watershed edge, manure nutrient use is apportioned by share of cropland within the basin to more accurately account for effects at a watershed scale.

Farm-level data from the 1997 Census of Agriculture (USDA [1999]) were used to calculate county-level measures of animal operations and animal units, total manure production, and potential nutrient use of farms, with and without animals. These data provide the nutrient assimilative capacity of land for manure nutrients (based on crop type and yield) and the quantities of surplus recoverable manure on farms with animals (in excess of crop needs on the farm) that requires off-farm transport for land application or use in an industrial process. The calculations were done at the farm-level and summed to the county level for all farms in the 1997 Census of Agriculture[3] following procedures in Gollehon et al. [2001] and Kellogg et al. [2000].

Land area available for manure application is based on the 1994 National Land Cover Dataset (NLCD), developed by the U.S. Geological

Survey (Homer et al. [2000]). The NLCD is derived from 1992 Landsat thematic mapper imagery at 30-meter resolution, classified into 21 landuse categories. By combining the cropland and pasture land categories within a GIS, we were able to define the spatial pattern of land available for manure spreading in the study region (hereafter, "spreadable" land), including counties within a 60-kilometer reach of the watershed boundary. There are approximately 14 million acres of spreadable land across 64,000 square miles of the watershed.

Manure is allocated within each county using a three-step procedure. First, county data on the numbers of confined animal farms were processed with GIS to simulate the location of animal operations. As precise locations of confined operations are not available for the entire watershed, animal operations in a given county were randomly assigned within cropland and pastureland portions of the county, based on a 30-meter grid overlay. Second, assigned farms were then aggregated (binned) within a 24-square kilometer grid overlay across counties in the watershed. The binning procedure substantially reduces the number of manure sources and transfer alternatives in the model, with only a small tradeoff in locational specificity. The assignment procedure, with binning of animal farms in 24-square kilometer grids, resulted in 828 subcounty units (termed "grids") with confined animal farms in the full watershed model. Finally, county-level manure is apportioned uniformly across subcounty grids based on the number of confined animal farms by subcounty grid.

4.1 Area-to-distance functions. Drawing on the spatial distribution of manure sources relative to land potentially available for manure spreading, GIS was used to create "area-to-distance" functions for within-county and out-of-county manure allocations across the CBW study region. These functions form the core of the model, linking manure hauling distance with the area needed for manure spreading, and implicitly capturing the inherent competition for land that exists among animal producers.

Area-to-distance relationships for within-county manure transfers represent the average hauling distance from confined animal operations in a given county to spreadable land within the same county. The relationships were generated for each of 160 counties in the CBW using a Euclidean distance function procedure within ARC GIS. The

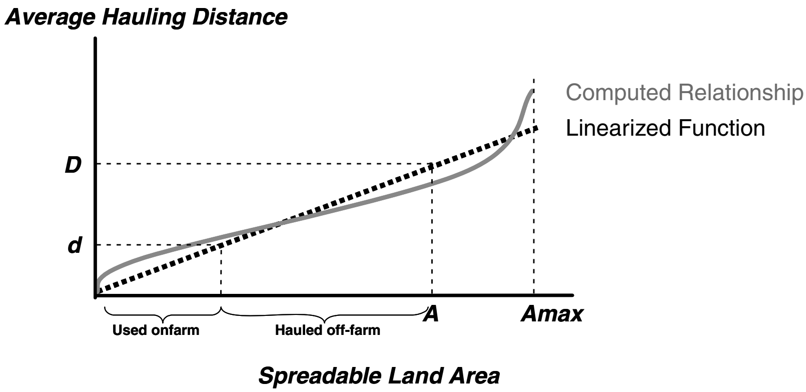

FIGURE 2. Within-county area-to-distance function.

relationships were estimated by incrementally increasing, through a series of expanding 30-meter concentric bands, the search for farmland around the location of each animal operation. The change in aggregate spreadable area—excluding nonfarmland 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 across all confined animal operations that manure must be hauled to access a given level of spreadable acreage in the county—accounting for competition among animal producers. In general, the relationship between the spreadable acreage requirement and average distance hauled is upward sloping and fairly linear along much of the observed range, as depicted in the stylized area-to-distance relationship in Figure 2. Figure 2 also illustrates that the closest land available for manure is on the farmer's own operation. Both on-farm use and off-farm manure transfers are tracked in the modeling system.

Out-of-county functions represent manure hauling distances from animal operations in a given county to spreadable land in other destination counties. Unique out-of-county functions were generated for all county combinations within a 60 kilometer transport radius, or 37 linear miles. The transport radius was expanded to 150 kilometer (93 linear miles) for the 10% of counties with the highest concentrations of surplus

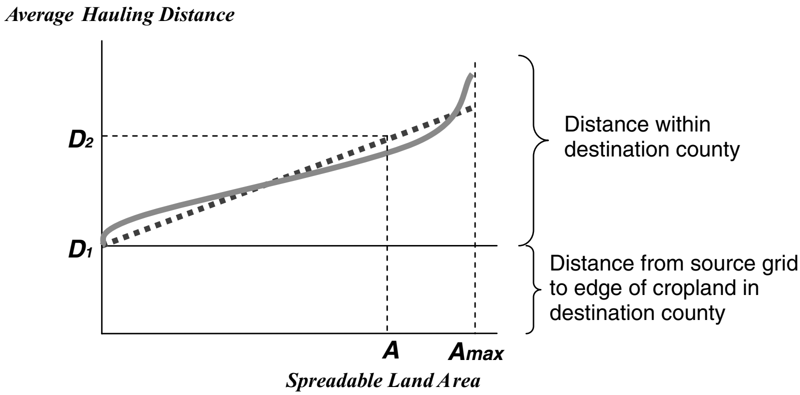

FIGURE 3. Out-of-county area-to-distance function.

manure, reflecting the potentially greater hauling distances where animal production is concentrated.

A two-stage process was used to generate the area-to-distance relationships for out-of-county transfers. First, an intercept term was measured as the distance from a source subcounty grid location to the closest edge of spreadable land area in the destination county. This was repeated for all source subcounty grids and potential destination counties within the transport radius. Second, the area-to-distance relationship within the destination county was computed in a fashion similar to that for within-county transfers. Thus, the area-to-distance relationship represents the distance hauled from source grid to edge of land area in the destination county, plus the average hauling distance to access a given spreadable area within the destination county, measured from the direction of the source grid (Figure 3).

For use in the regional model, area-to-distance relationships were linearized by truncating the upper and lower tails of the distribution (10% of acreage, respectively) and fitting a linear function to the mid-range observations (80%). 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 model. These include a unique set of slope coefficients for each within-county and out-of-county function, as well as individual intercept terms by source county grid for each out-of-county function. Figure 3 shows a linearized area-to-distance function for out-of-county manure transfers.

The area-to-distance functions internalize two important spatial concepts within the model. The first involves the spatial density of cropland and pastureland. Where farmland is scattered, a higher slope of the area-to-distance relationship reflects longer average hauls within the destination county to access a given spreadable area. Similarly, where farmland distribution is more concentrated, a reduced slope reflects shorter hauls to access a given acreage. The second involves the spatial concentration of manure. In general, spreadable land is relatively accessible where there is limited surplus manure. As manure spreading requirements increase due to an increasing amount of surplus manure, animal operations must compete increasingly for the same acreage. An increase in hauling distance needed to access available acreage is reflected in movement along the area-to-distance function. In areas with highest animal concentrations relative to land, most of the manure will need to be hauled off the farm, with increased likelihood of long-distance hauling and out-of-county exports. The degree of competition will depend on the demand for land to spread manure.

An important determinant of the degree of competition is the amount of farmland that is available for spreading manure. A share of the farmland base may not be available due to the reluctance of some landowners to accept manure, reflecting concerns for manure-nutrient variability, handling cost, odor, and other factors. Assumptions on landowner willingness to accept manure are captured in the model through adjustments in the landbase available for manure spreading, as well as automated adjustments in the slope of area-to-distance functions that effectively increase the average hauling distance required to access a given spreadable area.

5. Model structure. The following section presents selected equations, and associated variables and parameters, in the Chesapeake Bay regional modeling framework. Our discussion here focuses primarily on the use of spatial relationships in manure production and land area used in calculating manure hauling costs in the model. For a complete review of the full model equation system, see Aillery et al. [2005a].

$$(1)\quad \mathrm{OBJ} = \sum_{ct}\sum_{ct2}\mathrm{HAC}_{ct,ct2} + \sum_{ct}[\mathrm{NM1}_{ct} + \mathrm{ELA}_{ct}] + \sum_{ct2}[\mathrm{INC}_{ct2} + \mathrm{NM2}_{ct2} - \mathrm{FS}_{ct2}]$$

$$(2)\quad \mathrm{M\_TRAN}_{ct,ct2} = ((\mathrm{m\_ap}_{ct,ct2,N^*} * \mathrm{sh\_n}_{ct2}) + (\mathrm{m\_ap}_{ct,ct2,P^*} * 1 - \mathrm{sh\_n}_{ct2}))) * \mathrm{AC\_SPR}_{ct,ct2}$$

$$(3)\quad \mathrm{M\_TRAN}_{ct,ct2} = \sum_{gr}\sum_{sy}\sum_{ds}\mathrm{M\_QTY}_{ct,gr,ct2,sy,ds}$$

$$(4)\quad \mathrm{DS}_{ct,gr,ct2} = \left[\left(\alpha_{ct,gr,ct2} * \delta^1_{ct,ct2}\right) + \left(\beta_{ct,ct2} * \left(\mathrm{ac\_onf}_{ct} + \sum_{ct}\mathrm{AC\_SPR}_{ct,ct2}\right)\right)\right] * \delta^2_{ct2}$$

$$(5)\quad \mathrm{DS}_{ct,gr,ct2} * \sum_{sy}\sum_{ds}\mathrm{M\_QTY}_{ct,gr,ct2,sy,ds} = \sum_{sy}\sum_{ds}(\mathrm{DST}_{ct,gr,ct2,sy,ds} * \mathrm{M\_QTY}_{ct,gr,ct2,sy,ds})$$

$$(6)\quad \mathrm{HAC}_{ct,ct2} = \sum_{gr}\sum_{sy}\sum_{ds}[c1_{sy,ds} + (c2_{sy,ds} * \mathrm{DST}_{ct,gr,ct2,sy,ds})] * (\mathrm{M\_QTY}_{ct,gr,ct2,sy,ds}/(1 - (\mathrm{ms}_{sy} + \mathrm{bed}_{sy})]$$

where:

Objective function

OBJ = net regional costs of manure land application

Variables

HAC = manure hauling and application costs
INC = manure incorporation costs
NM1 = nutrient management plan charges—production source
NM2 = nutrient management plan charges—field application
ELA = penalty cost for surplus manure exceeding land application capacity in the basin
FS = purchase and application costs for chemical fertilizers
M_TRAN = total dry tons of manure hauled off the source farm, by county-level transfer
M_QTY = dry tons of manure hauled off the source farm, by system type and distance interval
AC_SPR = acres manured in the destination county
DS = average hauling distance from source county and grid
DST = hauling distances by manure system type and distance interval

Parameters

m_ap = per-acre manure application rate by county transfer
sh_n = share of cropland and pastureland acreage subject to a nitrogen standard, by county
ac_onf = acreage for on-farm manure use on confined animal farms
α = intercept coefficient for GIS-derived functional relationships—linear hauling distance from the source farm for out-of-county transfers
β = slope coefficient for GIS-derived functional relationships—within-county and out-of-county transfers
δ^1 = adjustment factor (linear hauling distance from the source farm for out-of-county transfers) to reflect significant natural barriers (e.g., large bodies of water)
δ^2 = circuity parameter that converts linear distance to road miles
c1 = loading, unloading, and application costs per ton hauled
c2 = hauling cost per ton-mile
ms = moisture content of manure
bed = bedding content of manure

Subscripts

ct = source counties where manure is produced
$ct2$ = destination counties where manure is land-applied
N = nitrogen standard
P = phosphorus standard
gr = county grid location
sy = manure system (lagoon, slurry, dry)
ds = hauling distance interval (miles)

The model allocates manure production in the CBW to minimize the net cost of manure land application in the CBW, based on land available for manure spreading (on- and off-farm), policy provisions for manure land application, and share of manure allocated to industrial processes. Net costs are defined as costs associated with manure land application, less savings due to reduced commercial fertilizer use.[4] The model allocates manure production in source counties (ct) to spreadable land in destination counties ($ct2$) to minimize the value of the objective function expression (OBJ) in equation (1).

Costs include manure hauling and application costs (HAC), plus manure-incorporation costs and nutrient management plan charges. Costs for incorporation of applied manure (INC) are based on incorporation costs per acre and the share of manured acres treated. Nutrient management plan charges include manure testing and plan development costs for animal production facilities (NM1) and soil testing costs for acres manured (NM2). A penalty cost (ELA) ensures that all manure, net of quantities diverted for industrial use, is land applied subject to available land within the transport radius of the manure source (this penalty cost is removed from reported costs). Aggregate costs are adjusted to reflect cost savings due to reduced purchase and application costs for chemical fertilizers (FS).

Model equations include (i) balance equations that track stocks and flows of manure and manure nutrients; (ii) allocation constraints that fix the distribution of confined animal farms (manure sources), manure shares by storage and application technology, acreage shares by nutrient standard, and land availability for manure spreading; and (iii) cost accounting equations. Primary decision variables in the model involve the quantity of manure hauled, acres used for manure spreading, and manure hauling distance across CBW counties. In general, wet manure quantities are used to assess manure hauling and application costs, while manure-nutrient content and uptake determine the volume and direction of manure flows.

Manure transfers (M_TRAN) represent dry tons of manure hauled off the source farm and land-applied by county-level transfer. In equation (2), manure transfers are equal to the product of per-acre manure application rate (m_ap) for each county transfer and receiving acres (AC_SPR) in the destination county. Manure application rate is calculated based on (i) the average concentration of nitrogen (N) and phosphorus (P) in manure produced in the source county (ct); (ii) average nutrient removal rates for N and P in the destination county ($ct2$), weighted across crop and pasture acreage and yields for each of three farm types (nonanimal farms, nonconfined animal farms, and confined animal farms); (iii) nitrogen volatization factors, with and without incorporation; and (iv) the nutrient standard in effect. Data specification by county and farm type allows the model to capture potential variation in manure-nutrient concentrations and land assimilative capacity, with resulting differences in applied manure.

Nutrient standards are an important policy focus of the model. A nitrogen standard requires that applied manure-N may not exceed the nitrogen needs of the crop, while the more restrictive phosphorus standard limits manure-P to crop phosphorus uptake. The effect of the standards is to restrict applied manure per acre, thus increasing acreage and hauling requirements for a given quantity of manure. The share of acreage requiring a nitrogen (sh_n) or phosphorus (1-sh_n) standard may vary depending on soil-P concentrations and federal and state regulations in effect.

Manure transfers are linked to costs through the type of manure and distance hauled. Equation (3) sets county-level manure transfers (M_TRAN) equal to the sum of individual manure hauls (M_QTY) by source county grid (gr), manure system (sy), and hauling distance interval (ds). Moisture content of manure by species and system type, and associated hauling technology by system and distance interval, are important determinants of per-unit costs for manure hauling and land application. Equations (2) and (3) together ensure that total manure land-applied is equal to the quantity of manure hauled from the various sources and that costs of manure hauling capture variation in animal species, system types, and hauling technologies across the watershed.

Hauling distances for manure transferred off the farm are computed based on equations (4) and (5). In equation (4), average hauling distance (DS) from source county (ct) and grid (gr) is calculated as a function of spreadable acres in the destination county ($ct2$), based on GIS-derived area-to-distance relationships. Off-farm hauling distance by manure transfer is computed based on the destination county acreage receiving manure from a source county (AC_SPR)—above a fixed acreage on confined animal farms accounting for on-farm manure use (ac_onf) (see Figure 2). Intercept α and slope coefficient β are the GIS-derived functional relationships for within-county and out-of-county transfers.[5] The intercept term, representing linear hauling distance from the source farm for out-of-county transfers, is adjusted (δ^1) for selected county-to-county transfers to reflect significant natural barriers (e.g., large bodies of water). In addition, a circuity parameter (δ^2) is used to convert linear distance to road miles.[6] Thus, equation (4) establishes the key linkage in the model between (i) acreage accessed for manure spreading and (ii) average hauling distance within and between counties, with values of each GIS-derived endogenously across county-transfer combinations.

In equation (5), average hauling distances DS derived in equation (4) are simultaneously set equal to the weighted average of off-farm manure hauls (DST), based on dry tonnage of manure by system type (sy) and distance interval (ds) by county-level transfer. Hauling distance (DST) is an endogenously derived continuous variable, falling within one of three intervals ds (0.5–2 miles, 2–10 miles, and more than 10 miles) used in specifying hauling technology and per-unit hauling charges for manure hauls by system type (M_QTY). Equations (4) and (5) together effectively integrate (i) the costs of manure transport, based on tonnage hauled by manure system type and distance; and (ii) GIS-derived area-to-distance relationships that link average manure hauling distance with land area accessed for manure spreading.

In equation (6), manure hauling and application costs (HAC) are computed for manure moved off-farm, for within-county and out-of-county transfers. Costs reflect loading, unloading, and application costs per ton hauled (c1), hauling cost per ton-mile (c2), distance hauled (DST), and dry tons of manure hauled (M_QTY), 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. The model simulates a stepwise cost function for manure hauling/application cost, with cost coefficients defined by system type (lagoon, slurry, and dry) and distance interval hauled.

6. Assessing the importance of spatial considerations. As part of a broader ERS analysis of manure air-quality controls and potential cost implications for federal manure management policy, regional costs were estimated in a case-study of the CBW (Aillery et al. [2005b]). Policy scenarios were defined based on the share of farms assumed to meet nutrient application standards for water quality and/or ammonia-N controls for air quality. The scenarios assume an N-based standard for applied manure and landowner acceptance of manure on 30% of cropland and pastureland. Regional costs of manure land application ranged from $30 to $196 million, with costs varying depending on the extent of farm coverage and policy coordination across water-quality and air-quality policies.

Transporting manure for land application—both on and off the source farm—represented the largest component of annual manure management cost in the watershed, with 20% to 75% of the manure produced in the basin to be land applied (or otherwise disposed of) off the farm, depending on the policy scenario. Total regional hauling costs ranged from $30 to $136 million. However, aggregate regional transport costs mask substantial variability in local cost conditions, as most of the region's out-of-county costs accrue in a relatively few counties with significant surplus manure relative to the local land base.

A comparison of subregions within the CBW illustrates the importance of spatial relationships involving animal production and land resources on manure hauling requirements. Six multicounty subregions were defined, based on county-level ratios of excess manure production (manure N that exceeds crop requirements on the source farms) to land available locally for manure spreading (Figure 4). Three subregions (SR1–SR3) represent areas where production of confined animals is heavily concentrated and land for manure spreading is relatively limited. In these areas, an average of less than two acres of cropland and pastureland were available per ton of excess manure. Three additional subregions (SR4–SR6) represent areas with lesser concentrations of manure production relative to spreadable area. In

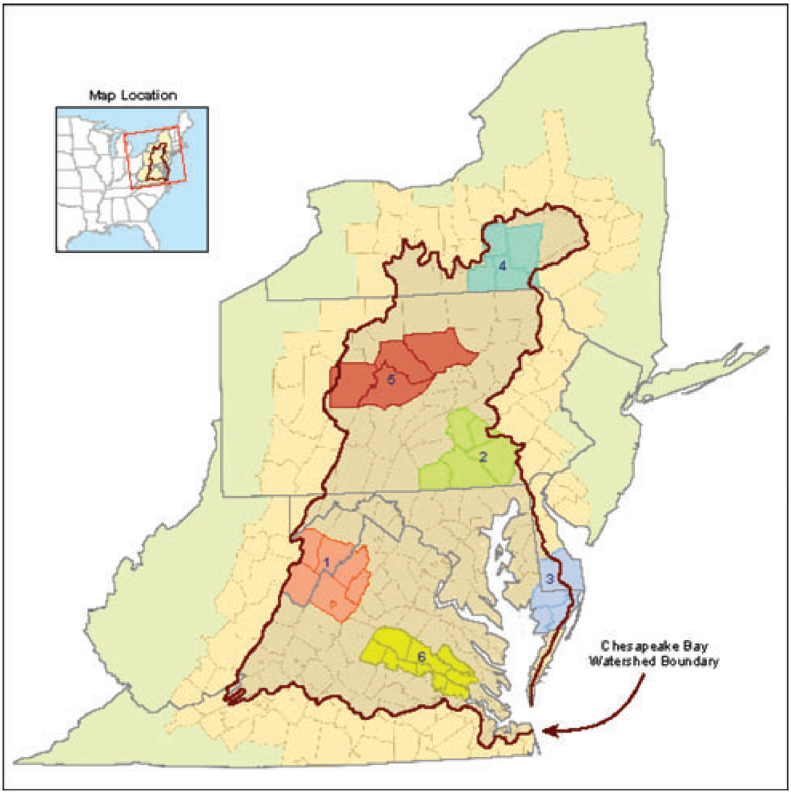

FIGURE 4. Model subregions, Chesapeake Bay Watershed.

these areas, there were more than 25 acres available per ton of excess manure.

Average manure hauling distances are evaluated under four hypothetical policy settings (Table 1). Scenarios reflect alternative assumptions on both the share of confined animal operations required to meet a nutrient standard for land-applied manure and landowner willingness to accept manure on their fields. The scope of the policy (share of farms covered) considers two options—“large farms only” and “all animal farms.” “Large farms only,” corresponding roughly with CAFO farms exceeding 1,000 animal units in size, account for most of the excess

TABLE 1. Effect of competition for spreadable land on average manure hauling distance by subregion, CBW.**

Selected subwatershed areas with lower and higher concentrations of excess manure nutrients	Spreadable land area per ton of excess manure production (N standard)	Large farms only meeting N standard for applied manure		All animal farms meeting N standard for applied manure	
		30% WTAM	70% WTAM	30% WTAM	70% WTAM
	acres/dry-ton	miles	miles	miles	miles
Lower manure-nutrient concentrations					
Subregion 4 (south-central NY)	61.0	0.4	0.4	0.5	0.4
Subregion 5 (north-central PA)	28.4	1.6	0.8	0.4	0.3
Subregion 6 (central VA)	40.1	1.2	0.5	1.8	0.9
Higher manure-nutrient concentrations					
Subregion 1 (northwest VA/ eastern WV)	0.5	54.6	6.3	77.2	44.5
Subregion 2 (southeast PA)	1.7	2.8	1.7	2.7	1.5
Subregion 3 (southeast MD/ southern DE)	1.1	3.1	1.8	10.6	3.3

**Values reflect the effect of a nitrogen standard for "large farms only" (CAFO farms exceeding 1,000 animal units in size) and "all animal farms," with landowner willingness to accept manure (WTAM) of 30% and 70%.

manure, and may be subject to existing federal manure regulations for water-quality control. For each of the policy options, two levels of landowner willingness to accept manure (WTAM) are considered—30% and 70% of available cropland and pastureland by county.

Average manure hauling distances for land-applied manure, weighted over on-farm and off-farm application for manure produced within the subregion, were computed for each of the CBW subregions. Average hauling distances are generally low for confined animal operations in subregions 4, 5, and 6, characterized by lower concentrations of confined animal production. In these areas, the majority of manure produced is used on the source farm and limited excess manure is hauled relatively short distances as competition for available land for manure spreading is generally low. Under the base case condition, with "large farms only" meeting an N standard for applied manure and an assumed WTAM of 30% of acres, average hauling distances ranged from 0.4 to 1.6 miles over the three subregions. Average hauling distances were generally shorter in subregions with higher spreadable land area per ton of manure excess, with the shortest hauling distance in south-central NY and somewhat longer hauling distances in central VA and north-central PA.

In contrast, average hauling distances are considerably higher for subregions 1, 2, and 3, where excess manure nutrients often exceeds the assimilative capacity of the local landbase. Competition for available spreadable land under base-case assumptions resulted in average hauling distances ranging from 2.8 miles to 54.6 miles. As with subregions 1–3, average hauling distance varied inversely with spreadable land area per ton of manure excess. The greatest hauling distances occurred in subregion 1 (northwest VA/eastern WV), reflecting very low land to manure ratios and comparatively low nutrient uptake rates (i.e., lower rates of applied manure under a nutrient standard) on area farmland. Lower hauling distances in subregion 2 (southeast PA) reflect higher nutrient uptake rates on area farmland. In subregion 3 (southeast MD/southern DE), local industrial processing of manure in combination with higher levels of nutrient uptake on area farmland reduced hauling distances for land-applied manure.

Policy adjustments to the base case may have a differential impact on producer costs, depending on spatial relationships involving manure and land. A hypothetical increase in landowner incentives to accept manure—expanding the supply of spreadable land to 70% of farm acres—would reduce hauling distances in virtually all areas.[7] However, the impact is much more significant in subregion 1 where competition for land is greatest, with average distance declining from 54.6 miles to 6.3 miles. Changes in landowner willingness to accept manure would have a comparatively small impact in subregions 2, 4, 5, and 6. Consideration of subregional spatial considerations may be important in effective targeting of incentives to enhance landowner acceptance of land-applied manure on cropland.

Similarly, policy adjustments that require "all animal farms" to meet land application standards may affect the animal sector differently across subregions. Such a broadening of policy would have little measurable effect on average hauling distances for subregions 2, 4, 5, and 6, where competition for land is limited. However, broader policy coverage resulted in substantially higher costs in subregions 1 and 3 due to increased concentrations of confined animal production. The greatest change occurred in subregion 1 (northwest VA/eastern WV), where an increase in the number of farms would substantially expand hauling distances under both the 30% and 70% assumptions for manure acceptance. In general, where competition for land is strong, an increase in landowner acceptance of manure can help to offset the effect of an expansion in farms required to meet land application standards.

Substantial differences in estimated hauling distances presented here underscore the importance of off-farm competition in assessing costs of federal guidelines and regulations for manure land application. The findings suggest that farm-level analysis that does not explicitly account for competition for available land resources may understate actual costs faced by animal producers in areas where land is limiting. For more discussion of these issues and associated findings, see Aillery et al. [2005b] and Ribaudo et al. [2003].

7. What have we learned? In developing the model presented in this paper, several insights on the use of spatial relationships within an optimization framework may be relevant to a broad range of agricultural policy issues. Our analysis suggests that it is possible to construct a regional model with a "firm-level perspective" that draws predominantly on national data series. The integration of farm-level census data, Landsat data in GIS-derived functional expressions, and local technology data capture considerable subregional variation in farm resource settings and potential policy responses. The framework provides a unique perspective on the spatial distribution of production enterprises and land resources, and may be preferable to a representative-case model or national-sector model for certain empirical questions when spatial considerations are important.

Findings from our application on the costs of manure management suggest that spatial relationships in land and production matter. Competition for spreadable land results in increased hauling distances, with the most significant cost effects observed in sub-watershed areas where the ratio of animal production to farmland is greatest. Indeed, it would be difficult to accurately assess manure hauling costs in many animal-producing areas of the country without considering the spatial relationship of animal operations and available landbase off the farm.

As in any modeling activity, measures to improve model tractability and convergence may introduce some bias in reported results. In integrating GIS spatial data and census data, it was somewhat difficult to assess the degree of bias (or net bias, considering factors jointly) in functional expressions of manure transport distance and costs. A key GIS data-integration issue involved allocation procedures for animal operations within a county, absent comprehensive locational data at a watershed scale. Improved spatial data specification, involving enterprise size and location, would be useful in refining distributional impacts. Making available spatial data operational within the optimization model was an additional concern. Aggregating spatial data on manure sources, limiting the maximum transport radius for manure hauls, and linearizing spatial functions are all operational decisions that help to achieve model convergence, trading locational precision for computational ease. More research is required to gain insight on the value and costs of additional spatial information, and tradeoffs in model precision and model performance.

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 for meeting federal environmental standards and illuminate several areas for policy consideration to mitigate costs. Although the application of GIS spatial data within an optimization framework represents a potentially powerful tool for policy analysis, model data development and computational requirements can be significant.

ENDNOTES

1. A full description of the modeling approach implemented by ERS is beyond the scope of this article. A technical documentation of the basic model may be found in Aillery et al. [2005a].

2. Changes in the profitability of animal production are not assessed because output prices and substitution possibilities are not considered. As with any model, modeled costs may not reflect the actual costs faced by all animal operations in the region.

3. Our analysis meets all respondent confidentiality requirements of the published Census of Agriculture values.

4. Model costs do not include 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. For within-county manure transfers, the intercept term of the area-to-distance relationship is zero.

6. A fixed circuity parameter of 1.2 reflects an average of state-level parameters reported for the Chesapeake Bay watershed region (U.S. Department of Commerce [1978]).

7. Measures to increase landowner willingness to accept manure might involve education on the value of manure as a nutrient source and soil amendment, development of private markets for manure use, and public cost-sharing for manure storage and handling systems.

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