Optimal Regional Regulation of Animal Waste

Antti Iho *, Natural Resources Institute Finland (Luke)
Doug Parker, Division of Agriculture and Natural Resources, University of California
David Zilberman, Department of Agricultural and Resource Economics, UC Berkeley

Abstract
Large animal facilities generate more manure than needed on their own feed production areas. Excessive nutrient applications deteriorate groundwater (nitrogen) and surface water quality (nitrogen and/or phosphorus). Due to differences in environmental and economic characteristics, adjacent regions may have differing objectives towards controlling nitrogen and phosphorus surpluses from manure applications. We consider jointly and separately optimal nutrient policies of an upstream agricultural and a downstream recreational region. We show that, depending on the environmental and economic characteristics, tightening upstream regulation with respect to the loading of one nutrient might increase the downstream loading of the other. We differentiate the impacts of manure regulation between the livestock farms and the adjacent crop production farms and show how this impacts nitrogen and phosphorus loading due to changes in nutrient application, crop uptake and changes in application areas. We allow regional differences in abatement objectives and identify locally and globally optimal policies.
Keywords Manure, Transboundary Pollution, Phosphorus, Nitrogen, Regulation, Externality

1 Introduction

Animal waste is a poster child of the complexity of environmental regulation. It is a multiagent, multi-pollutant and multiregion problem. Animal farms generate manure that they can use on their fields as a fertilizer or export for application on surrounding crop farms. Over application of manure may contribute to a variety of environmental problems. Most notably, phosphorus and nitrogen can contribute to surface water eutrophication and nitrogen also impairs ground water quality. Nutrient loadings emitted in one location may have environmental consequences far away downstream. Environmental pressures within regions may emphasize nitrogen and phosphorus differently, depending on whether surface or ground waters are more vulnerable. Due to these differences, solving an inboundary externality problem may cause or aggravate transboundary pollution. We postulate a two-agent, two-pollutant, two-region animal waste model and show how regional and isolated governance may create suboptimal solutions compared to inter-regional solutions.

Eutrophication—overenrichment of nutrients—is a severe problem in many surface waters. Toxic blooms of blue green algae in particular are linked to phosphorus loading as their growth is not limited by nitrogen: they are able to utilize molecular nitrogen diluted from the atmosphere. Events such as the fish kills in the Chesapeake Bay in the 1990's; the frequent nuisance of blue green algal blooms in the Baltic Sea; or the Do Not Drink order the city of Toledo issued in August 2014 due to algal toxins from the lake Erie draw a lot of attention. In addition to the blooms, eutrophication has more persistent and economically more severe symptoms such as permanent changes in fish stock or turbidity of water. Water clarity, for instance, has been shown to markedly influence property prices (see e.g., (Poor et al., 2001; Gibbs et al., 2002)). Altogether, the annual costs of freshwater eutrophication in the United States are estimated to be around $2.2 billion (Dodds et al., 2009). The economic benefits of restoring the water quality of the Baltic Sea was estimated at around $5.9 billion by a recent and extensive survey by **?**.

In many watersheds, agriculture is the most important source of man made phosphorus loading. It comprises, for instance, about 48 per cent of the loading to the Chesapeake Bay. About half of this is attributed to manure applications on cropland (EPA, 2009). Large animal facilities rely on imported feeds. The excreted manure is applied close to facilities because high transportation costs erode its value as a crop nutrient. This leads the soils close to animal facilities to receive too much nutrients in comparison to crop uptake. This surplus eventually contributes to pollution of surface and ground waters. The difference in the relative nutrient content in manure and relative agronomic needs of crops further leads to over application of one nutrient even though the other would be properly applied. Manure applications are typically based on nitrogen content of manure and nitrogen need of the crops, leading to excessive phosphorus application even in fields with precise nitrogen applications. This gradually accumulates soil phosphorus which leads to surface water enrichment. Freshwater ecosystems and coastal areas are often considered sensitive to phosphorus loading, open sea areas to nitrogen (Schindler, 2012).[1] In the United States animal waste is

[1] The issue is, however, highly disputed among hydrologists and ecologists, particularly concerning estuaries and coastal areas (see for instance the debate launched by Conley et al. (2009)).

also the predominant source of nitrogen to coastal waters (Howarth et al., 2002). In Chesapeake Bay it comprises about 46 per cent of all nitrogen loading (EPA, 2009).

Generation and application of manure simultaneously determines nitrogen and phosphorus surpluses (see, e.g. Schnitkey and Miranda (1993) and Innes (2000). Environmental regulation of animal agriculture is focused on nutrient surpluses, though typically on either nitrogen or phosphorus. Abatement actions can be divided into those lowering both surpluses (e.g. having less animals or swithing to a crop with higher agronomic needs) and those elevating one surplus while lowering the other (e.g. altering the ratio of N and P in manure by feed choices, manure storage or application methods or switching to a crop with an alternative N:P ratio).The nutrient abatement measures may thus be substitutes or complements as determined by Moslener and Requate (2007).

Nutrient pollution to surface waters is transboundary: Phosphorus or nitrogen emitted upstream may impair water quality at the source areas or at any location along the river or at the sea. The environmental damage at affected locations depends on the aquatic ecosystems, and on the distance between the source and the receptor area. Regions differ in the sensitivity of their water towards nitrogen and phosphorus. Groundwater problems are linked to nitrogen surpluses, surface water problems to either nitrogen or phosphorus, or both. The Mississippi River, for instance, carries pollutants from its immense basin to northern parts of the Gulf of Mexico. Regions with groundwater issues are likely to be more concerned about nitrogen than regions with large freshwater areas whose regulation is likely to focus on phosphorus. Transboundary character of nutrient loading makes optimal polices within regions differ from optimal policies between the regions.

There is one more crucial aspect in manure management. Manure can be applied on the fields of the animal farm (henceforth: on-farm) and on the fields of the surrounding crop farms (henceforth: off-farm). Economically and legally these are independent operators. The animal farm is typically liable for the animal waste it produces and applies to its own fields. Crop farms use manure as a substitute for synthetic fertilizers. Both on- and off-farm, the negative externalities to surface and groundwater are ultimately caused by the nutrient balance: the difference of phosphorus (nitrogen) applied to the field and phosphorus (nitrogen) biologically uptaken by the crop.

The earliest papers on animal waste regulation didn't differentiate between on-farm and off-farm application (or regulation), but included an outside disposal area. It was assumed to take care of manure with certain costs without environmental externalities (Moffitt et al., 1978) and (Hochman and Zilberman, 1979). The assumption of safe disposal areas has not held in practice. The regional dairy management plan of San Jacinto, California, for instance, states that dairy farmers cannot know whether the hauling contractors actually apply the manure appropriately or whether they dump it illegally. The report also suggests that illegal dumping indeed takes place (San Jacinto, 2009). Huang et al. (2005) assume that livestock farms lease the extra land needed for manure application, in which case they are also covered by on-farm regulation. The models by Schnitkey and Miranda (1993) and Innes (2000) quantify the excess application of manure as a function of the number of animals and the distance from the facility. They do not allow for outside disposal areas and assume that regulation applies to on- and off-farm similarly.

The other alternative is to view on-farm and off-farm applications separately. Regulation applies to animal farms who may respond by altering their on-farm operations or by increasing off-farm export of manure. The on-farm responses might include changing the number of production animals, altering the nutrient composition of manure or manure handling and application practices, or changing the crop. These choices either alter the amount of nitrogen and phosphorus generated on-farm, the amount made available to crops or the amount uptaken by crops. Implicitly or explicitly, all papers, to our knowledge, assume in these cases that off-farm applications are done according to either agronomic needs of crops, as a perfect substitute for chemical fertilizers (see, for example, (Fleming et al., 1998); (Kaplan et al., 2004) or (Baerenklau et al., 2008)). Hence, the economic decision making for off-farm choices is not modeled explicitly.

We extend the literature by combining three elements into manure regulation models: setting apart and being explicit about on-and off-farm manure application choices and regulation; having the farms' choices simultaneously determine the phosphorus and nitrogen surpluses; and making regions' surface water quality partly dependent on other regions' choices. As seen above, each of these has been considered separately. There are, however, no models that combine all three in the context of animal manure and water quality regulation.

We develop a stylized model comprising two regions. One is the source of nitrogen and phosphorus loading affecting both regions' water quality negatively but differently. We solve for optimal regulation from the perspective of the source region and from the perspective of both regions. Our results show that the lack of available land on-farm may lead to costly regulation that has at its worst no environmental benefits; that focusing on nitrogen surpluses may even increase phosphorus loading; and regional orientation in regulation in worst cases may lead to an overall decline in social welfare. Furthermore, we show how regionally defined nutrient management plans transmit these eddects into regional and global nutrient surpluses and welfare.

The rest of the paper is organized as follows. We first present the model and derive the necessary optimality conditions. We then analyze the instruments, focusing on regional second-best instruments and their implications. The third section concludes and discusses the policy implications.

2 The model

Consider two regulatorily independent regions with connected surface waters: an agricultural and a recreational region (figure 1). Agricultural region consists of two farms: a representative animal farm which has its own feed production area, and a representative crop farm. Their border is denoted by the horizontal line at distance $\underline{d}$. Both farms' fields are assumed rectangular and one unit wide. Manure is generated at the facility located along the rear edge of the animal farm (along d_0). Manure can be applied on-farm and exported and applied off-farm.[2]

FIGURE 1 ABOUT HERE.

[2] All crop farm's fields are assumed to be suitable for manure application. Assuming a smaller fraction to be suitable would change the link of the application distance and acreage. This has trivial effects on the results and will thus not be further considered here.

Manure can lead to loading of residual nutrients to surface and ground waters.[3] Both phosphorus and nitrogen residuals impair surface water quality of both regions. Nitrogen residuals also affect the groundwater quality of the agricultural region. A given, nutrient specific fraction (illustrated by the narrow part of the *Surface water externality* in figure 1) of the loading is carried over to the recreational region. The sensitivity of the surface waters towards phosphorus and nitrogen may be different in the two regions. The residual nutrients are defined as the differences of nutrients excreted by animals and nutrients utilized by crops:

Definition 1. *Residual nitrogen* $\left(r^N\right)$ *and phosphorus* $\left(r^P\right)$ *are given by*

$$r^N = \alpha qa - \gamma^k d_{on} - \gamma^j \left(d_{off} - \underline{d}\right)$$
$$r^P = \beta qa - \delta^k d_{on} - \delta^j \left(d_{off} - \underline{d}\right).$$

where α and β are the nitrogen and phosphorus concentrations of manure, q the amount of manure generated by one animal in one year, a the number of animals, γ and δ crop specific agronomic needs for nitrogen and phosphorus per acre, k and j the crop choices on- and off-farm, and d_{on} and d_{off} the hauling distances on- and off-farm.[4] Our model allows off-farm manure application even if there were no or only some on-farm application. That is, it is possible that $d_{off} > \underline{d}$ even if $d_{on} = 0$

In our model, the hauling distance unambiguously determines the quantity of manure nutrients applied along that distance. The manure is applied exactly according to crop's needs for the relatively more scarce nutrient. If the relatively scarce nutrient is nitrogen, phosphorus will be applied excessively on the application area and vice versa. The crop growth does not respond to nutrient application exceeding the agronomic need. Hence, the application distance, crop choice and the nutrient content of manure together determine the quantity of manure applied.

Definition 2. *The quantity of manure applied on-farm* (M_{on}) *and off-farm* $\left(M_{off}\right)$ *are given by:*

$$M_{on} = \max\left\{\frac{d_{on}\gamma^j}{\alpha}, \frac{d_{on}\delta^j}{\beta}\right\}$$
$$M_{off} = \max\left\{\frac{\left(d_{off}-\underline{d}\right)\gamma^j}{\alpha}, \frac{\left(d_{off}-\underline{d}\right)\delta^j}{\beta}\right\}$$

It can be seen from definitions 1 and 2 that our model has two origins for residual nutrients. Part of them are generated by the mismatch of nutrients in manure and those needed by crops. However, this only generates residuals of either phosphorus or nitrogen. The other source is dumping which adds to both residual phosphorus and residual nitrogen. Manure that is generated by production animals but not applied to crops (or in the real world: applied in excess of crops' needs to either of the nutrients) is defined as dumped. If, for instance, one unit of manure was applied according to crop's need for either

[3]To highlight the problems related to manure, we assume that chemical fertilizers are applied precisely according to crops' needs. Only manure may thus be the source of residual phosphorus and nitrogen.

[4]Agronomic nutrient needs may differ from nutrient uptake of crops. Soybeans, for instance, can bind most of the nitrogen it needs from atmospheric nitrogen. We define residual nutrients as differences between actual applications and application requirements.

phosphorus or nitrogen, but two units of manure were excreted, we would consider one unit dumped.[5] Dumping on-farm (x_{on}) and off-farm (x_{off}) has identical environmental effects. Profit maximization guarantees that dumping may occur only on-farm, on the shortest distance possible (i.e. at $d = 0$). We include the possibility for off-farm dumping (x_{off}) because as we will see, it may be an optimal response to regulation.

Definition 3. *The total quantity of manure dumped on-farm (x_{on}) and off-farm (x_{off}) is given by:* $x_{on} + x_{off} = qa - M_{on} - M_{off}$

We consider four alternative decision makers: (1) the animal farmer, (2) the crop farmer, (3) the rural social planner, and (4) the global social planner. The global social planner maximizes the sum of profits from farming, net of environmental damages in both regions. The rural social planner considers the environmental damage in the agricultural region only, and crop and animal farmers ignore externalities altogether. To highlight the characteristics of manure as an economic good, we begin by modeling the choices of the crop farm.

2.1 Optimization problem of the crop farm

To keep the model tractable, we assume fixed, crop specific yields, agronomic nutrient requirements and prices. If available, the crop farm may substitute chemical fertilizers with manure. It takes the price of manure as given. The crop farm maximizes profits by choosing the crop and the combination of manure and chemical fertilizers. Henceforth, we will use the index j to denote the crop farms crop choice, and k to denote the animal farms crop choice (the choices may, of course, be identical):

$$\begin{aligned} &\underset{j,d_{off}}{\text{Max}}\, \pi_{off} = y^j p^j \left(\bar{d} - \underline{d}\right) - \left(\gamma^j p^N + \delta^j p^P + g\right)\left(\bar{d} - d_{off}\right) - p^M M_{off} \\ &s.t.\ d_{off} \geq \underline{d}. \end{aligned} \tag{1}$$

The farmer chooses the crop (j) and the amount of manure imported (or equally: the distance of manure application: d_{off}).[6] The per acre crop yield is y^j, its net price (including variable costs other than fertilization costs) $\left(p^j\right)$, and the total field acreage $\left(\bar{d} - \underline{d}\right)$. Costs from chemical fertilizers are given by $\left(\gamma^j p^N + \delta^j p^P + g\right)\left(\bar{d} - d_{off}\right)$, where p^N and p^P are prices of nitrogen and phosphorus, and g is the per-acre cost of application. The more manure applied, i.e. the longer the hauling distance $\left(d_{off}\right)$, the higher the savings from chemical fertilizer costs.

Crop farm's optimal manure import and crop choice

Writing a Lagrangian and taking the first-order conditions yields

[5] The counterpart of dumping in models by Innes (2000) or Schnitkey and Miranda (1993) is the excessive manure application which is monotonically decreasing with the distance from the animal facility, until becoming zero at the critical distance $\bar{r}$. Their crop response functions are increasing and concave, ours is a linear response and plateu, simplified to a fixed yield and fixed need of nutrients. Externalities in both models are due to the sum of over application. Therefore, we do not need to define the exact location for dumping, as long as it's either on-farm or off-farm.

[6] Hauling distance is a common metric for crop and livestock farmer. For tractability, we denote hauling distances with subscripts. That is, if the crop farm's hauling distance is equal to the boundary of the animal and crop farm $\left(d_{off} = \underline{d}\right)$, it does not import manure.

$$\begin{aligned}&\left(\gamma^j p^N + \delta^j p^P + g\right) = p^M \max\left\{\frac{\gamma^j}{\alpha}, \frac{\delta^j}{\beta}\right\} + \lambda_c \\ &\lambda_c \geq 0, \left(d_{off} - \underline{d}\right) \geq 0, \lambda_c \left(d_{off} - \underline{d}\right) = 0.\end{aligned} \tag{2}$$

For a given crop, all terms in (2) are exogenous for the crop farmer. For positive import quantities $\left(d_{off} > \underline{d}, \lambda_c = 0\right)$, a price the crop farmer is willing to pay is

$$p^M = \frac{\left(\gamma^j p^N + \delta^j p^P + g\right)}{\max\left\{\frac{\gamma^j}{\alpha}, \frac{\delta^j}{\beta}\right\}}. \tag{3}$$

Given fertilizer prices, crop choice, and manure nutrient concentration, the price (3) is constant. That is, the crop farmer is always willing to use manure for the entire suitable crop land or not at all. The result does thus not contradict the fact that actual crop farms that apply manure also tend to use chemical fertilizers (see, e.g., (Feinerman et al., 2004)). In our model the animal farm is willing to sell and haul manure only to distances where the price (3) covers the costs. That is, the amount manure applied on crop farm will be jointly determined by both farms' first-order conditions.

The price (3) is increasing in nutrient concentration of the relatively scarce nutrient and insensitive toward the other nutrient. However, the price is affected by prices of both nutrients as chemical fertilizers. The numerator in (3) gives costs in dollars per acre of chemical fertilization, which is influenced by both nutrients and the application costs. The denominator gives the amount of manure one needs to cover the nutrient requirements of an acre of land. Hence, the unit of (3) is dollars per unit of manure.

Note that the crop farmer makes the crop choice irrespective of the manure application decision.

2.2 Optimization problem of the animal farm

The animal farm chooses the number of animals, manure application on own land, manure export and the cultivated crop to maximize profits:

$$\begin{aligned}\underset{a,d_i,x_{off},k}{\text{Max}} \pi_{on} = {} & p^a a + p^M M_{off} - f(a) - \left(\gamma^k p^N + \delta^k p^P + g\right)\left(\underline{d} - d_{on}\right) \\ & - p^k\left(\xi^k a - y^k \underline{d}\right) - h\left(M_{on}, d_{on}\right) - h\left(M_{off}, d_{off}\right) - c\left(x_{off}\right)\end{aligned} \tag{4}$$

s.t.

$$\left(qa - M_{on} - M_{off}\right) \geq 0 \qquad \left(\underline{d} - d_{on}\right) \geq 0 \qquad \left(d_{off} - \underline{d}\right) \geq 0$$
$$\left(\overline{d} - d_{off}\right) \geq 0 \qquad a, d_{on} \geq 0$$

Primarily, the revenues are obtained from production animals (a). Potentially, there may also be revenues from selling manure $\left(d_{off}\right)$ and feed grown in animal facility's own fields (given production exceeds the needs of production animals). Substituting fertilizers with manure also creates savings. Life-cycle revenues from a single animal are given by p^a. Depending on the type of production animal, these may comprise average per-unit revenues from selling milk, meat, eggs etc. Manure $\left(M_{off}\right)$ is sold with a price $\left(p^M\right)$, which is determined in (3). Fertilizer savings from applying manure on d_{on} are given by $d_{on}\left(\gamma^k p^N + \delta^k p^P + g\right)$.

Production costs (f) comprise of annualized investment costs and operation costs excluding feed costs. The cost function satisfies $f'(a) > 0$ and $f''(a) > 0$.[7] Feeding (a) animals requires $\left(\xi^k a\right)$ units forage. The forage requirement depends on the animal and on the crop. Own crop production $\left(y^k \underline{d}\right)$ may be higher or lower than this. The needed (excess) units of feed will be bought (sold) at price p^k.

Hauling and application costs (h) depend on the distance and the quantity of manure hauled. In our model, the latter is determined by distance and crop choice. Following conventional assumptions (see, for instance (Fleming et al., 1998)) we assume that the costs of hauling a unit are increasing in distance and thus total hauling costs are increasing and convex.[8] The function is identical for on- and off-farm hauling, but off-farm hauling starts from a distance $\underline{d}$.

The costs of dumping (c) on own land are assumed to be zero and, on the crop farm, $c\left(x_{off}, \underline{d}\right) \equiv x_{off}\frac{\partial h(\underline{d})}{\partial d}$. Constraints in (4) limit the amount of manure applied on a livestock farm to the manure excreted by animals in total $\left(qa - M_{on} - M_{off}\right) \geq 0$, the availability of land for manure application on both farms, and the choice variables to be positive.

Optimal animal numbers, crop choice and manure utilization and export

The first-order conditions (excluding, for brevity, the standard nonnegativity constraints) for the continuous choice variables are

$$p^a + \lambda_1 q = f'(a) + p^k \xi^k \tag{5}$$

$$\frac{\partial h}{\partial d_{on}} = \left(\gamma^k p^N + \delta^k p^P + g\right) - \lambda_1 \max\left\{\frac{\gamma^k}{\alpha}, \frac{\delta^k}{\beta}\right\} - \lambda_2 \tag{6}$$

$$\frac{\partial h}{\partial d_{off}} = p^M \max\left\{\frac{\gamma^k}{\alpha}, \frac{\delta^k}{\beta}\right\} - \lambda_1 \max\left\{\frac{\gamma^k}{\alpha}, \frac{\delta^k}{\beta}\right\} + \lambda_3 - \lambda_4 \tag{7}$$

$$\lambda_1 \geq 0, qa - M_{on} - M_{off} \geq 0, \lambda_1\left(qa - M_{on} - M_{off}\right) = 0$$

$$\lambda_2 \geq 0, \underline{d} - d_{on} \geq 0, \lambda_2\left(\underline{d} - d_{on}\right) = 0$$

The optimal number of animals (5) balances the marginal benefits and costs of having one more animal. The marginal benefits consist of sales revenues (p^a) and cost savings from using manure $(\lambda_1 q)$. If manure is scarce, i.e. $\lambda_1 > 0$, it would be applied more if available. If manure is excessive, $(\lambda_1 = 0)$, benefits

[7] Think of f as a simplification from a concave-convex cost function. The sufficient (second-order) conditions tell that the relevant part of the curve must have a positive second derivative.

[8] We could also assume linear or even concave hauling costs. This would make the optima characterized by some binding constraints. Analysis would be qualitatively unchanged.

accrue from sales revenues only. The marginal costs consist of marginal production costs $(f'(a))$ plus feed costs for one animal $\left(p^k \xi^k\right)$, i.e. a linear and decreasing function.[9]

The optimal hauling distance on-farm (6) balances the marginal savings in mineral fertilizers $\left(\gamma^k p^N + \delta^k p^P + g\right)$ and the marginal costs of hauling. If manure quantity and area constraints are not binding, marginal costs are $\frac{\partial h}{\partial d_{on}}$. Since the hauling costs are increasing (and convex), positive shadow prices imply lower application distances. In case no interior solution were found, the complementary slackness condition sets the hauling distance to zero. If manure is applied on the entire farmland controlled by the livestock farm, the area constraint is binding and $\lambda_2 = \left(\gamma^k p^N + \delta^k p^P + g\right) - \frac{\partial h}{\partial d_{on}} > 0$.

Conditions for optimal hauling distance off-farm (7) are similar except that the marginal benefit is the price received from the crop farmer (3). If crop choices on and off farm are identical, the shadow value of the land constraint is the negative of the shadow value for the animal farm's land $(\lambda_3 = -\lambda_2)$.[10] If the land constraint on crop farm is binding $(\lambda_4 > 0)$, the entire agricultural region is not sufficiently large to absorb generated manure nutrients. The opposite is not true however. Even though the region would not be enough to absorb all generated nutrients, the land constraint might not be binding.

Combinations of binding and non binding manure and land constraints on- and off-farm generate eight different cases. The optimality conditions simplify differently for each of them. As we next consider the social planners problems, we narrow our focus on the most policy relevant cases: The manure is excessive, i.e., $\lambda_1 = 0$; nitrogen is the relatively scarce nutrient; and the livestock farm utilizes at least some of the manure and may or may not export it to the crop farm.

2.3 Optimization problem of the rural social planner

The rural social planner maximizes private profits from operations on- (π_{on}) and off-farm (π_{off}) net of externalities at the agricultural region to ground $\left(E_A^G\right)$ and surface waters $\left(E_A^S\right)$.[11]

$$\underset{a,d_i,x_i,j,k}{\text{Max}} \pi_{on}(a,k,d_i,x_i) + \pi_{off}\left(j,d_{off}\right) - E_A^S\left(r^N,r^P\right) - E_A^G\left(r^N\right) \tag{8}$$

Optimal animal numbers, crop choices and manure utilization

Denoting the shadow values with λ_i^A, the rural social planner's first order optimality conditions are:

$$p^a = f'(a) + p^k \xi^k + \left(\frac{\partial E_A^S}{\partial r^N} + \frac{\partial E_A^G}{\partial r^N}\right)\frac{\partial r^N}{\partial a} + \frac{\partial E_A^S}{\partial r^P}\frac{\partial r^P}{\partial a} \tag{9}$$

$$\frac{\partial h}{\partial d_{on}} = \left(\gamma^k p^N + \delta^k p^P + g\right) - \lambda_2^A - \left(\frac{\partial E_A^S}{\partial r^N} + \frac{\partial E_A^G}{\partial r^N}\right)\frac{\partial r^N}{\partial d_{on}} - \frac{\partial E_A^S}{\partial r^P}\frac{\partial r^P}{\partial d_{on}} \tag{10}$$

[9] Note that the farmer marginally loses $\left(p^k \xi^k\right)$ whether the farmer is a net importer or exporter of feed. If the farmer produces more than the production animals need, increasing the number of animals reduces the sales revenues. If the farmer has to buy the additional feed needed, the input costs increase by the same amount.

[10] This would be different if the animal farm did not retrieve all the surplus from the crop farm in selling manure: its gains from both land applications are identical

[11] For tractability we assume $\frac{\partial^2 E_A^S}{\partial r^P \partial r^N} = 0$.

$$\frac{\partial h}{\partial d_{off}} = \left(\gamma^j p^N + \delta^j p^P + g\right) + \lambda_3^A - \lambda_4^A - \left(\frac{\partial E_A^S}{\partial r^N} + \frac{\partial E_A^G}{\partial r^N}\right)\frac{\partial r^N}{\partial d_{off}} - \frac{\partial E_A^S}{\partial r^P}\frac{\partial r^P}{\partial d_{off}} \tag{11}$$

$$x_{off} = 0; x_{on} \geq 0 \tag{12}$$

Given that the rural planner chooses the same crops as the private farmers, the optimal number of animals decreases: the two last terms in 9 are positive, $f'(a) > 0$ and other terms are constant. Changes in hauling distances (10 and 11) are slightly different as they are influenced by the border of crop and animal farms. This is one of our inputs to traditional animal waste models. Proposition 1 establishes the result:

Proposition 1. *If the marginal social benefits from manure utilization at the crop and animal farm's border are below marginal hauling and application costs; and if the animal farm fully utilizes its land application area in private optimum, rural planner's solution does not increase manure utilization. That is, if $\lambda_3^A > 0$ and $\lambda_2 > 0$ then $d_{on} = \underline{d}$ and $M_{off} = 0$ for both private and social optima*

Figure 2 illustrates the proposition.

FIGURE 2 ABOUT HERE

The horizontal axis denotes the hauling distance, the marginal gains and costs from manure application are on the vertical axis. The dotted vertical line at $d_{on} = \underline{d}$ denotes the border of the animal and crop farm. The increasing curve denotes the marginal hauling costs h'. The lower horizontal line on the left of the dotted vertical line denotes the private marginal benefits from manure application on-farm $\left(\gamma^k p^N + \delta^k p^P + g\right)$. More manure would be spread on-farm if more land was available. Hence, the shadow price for land on-farm (λ_2) is positive. Introducing externalities (the upper horizontal line) puts more pressure on utilizing manure on-farm, but as all land is already used for manure application, the only effect is for the shadow price for on-farm land to increase $\left(\lambda_2^A > \lambda_2\right)$. Off-farm, no manure is applied in the private optimum, i.e. $\left(\gamma^j p^N + \delta^j p^P + g\right) < h'$ and $\lambda_3 > 0$. Rural planner's solution sees the shadow price of crop land $\left(\lambda_3^E\right)$ decrease close to zero but the utilization of manure does not change in the agricultural region as the hauling distances remain unchanged. To sum up, externalities increase the need for higher utilization of manure nutrients but the availability of on-farm land may result in unchanged manure utilization levels. Of course, if the crop choices on- and off-farm were the same, the marginal social benefits of manure application would be identical on- and off-farm. Therefore, an increase in marginal damage would always lead to longer hauling distances.

In our parsimonious model, there is no reason for the animal and crop farm to choose their crops differently. In practice, however, this is often the case. Furthermore, there are other features encountered in real world that would be associated with differences in marginal benefits from manure application on- and off-farm—even if the crop choices were identical. There might be discontinuities in hauling distances or disutility from accepting the manure due to odor, flies, etc. Proposition 1 thus presents a simple and general result underlining the impacts of scarcity of land available for manure applications on-farm, and a different economic environment off-farm.

The externalities from dumping manure either on the livestock farm or on the crop farm are identical. Since the costs of dumping on-farm are assumed to be zero, the rural planner chooses trivially, $x_{off} = 0$. The optimal dumping on farm is defined by the other optimal choices: $x^*_{on} = qa^* - M^*_{on} - M^*_{off} \geq 0$. That is, even though the rural planner generates less residual nutrients of interest, the excessive manure – if it is socially optimal to have some – is applied as close to the facility as possible.

Optimal solutions get an interesting twist if the privately and socially optimal crop choices differ. Denote the crop choices by *k* and *m* and profits associated with rural planner's choices by π_A. For clarity, assume that the animal farm does not export manure in either optima. Proposition 2 shows that in some cases regulation may lead to increasing production, i.e., higher optimal animal numbers when compared to the unregulated case:

Proposition 2. *If acknowledging the externality induces a change in crop into one with higher nutrient uptake, the social optimum might have more production animals than the private optimum. That is, if*

i) $p^m\xi < p^m\xi + \left(\frac{\partial E^S_A}{\partial r^N} + \frac{\partial E^G_A}{\partial r^N}\right)\frac{\partial r^N}{\partial a*} + \frac{\partial E^S_A}{\partial r^P}\frac{\partial r^P}{\partial a*} < p^k\xi$
ii) $\pi^k > \pi^m$
iii) $\pi^{k*}_A < \pi^{m*}_A$
$\Rightarrow a^*_A > a^*$.

Proposition 2 states that the rural planners' optimal solution includes more production animals than the animal farmer's privately optimal solution $(a^*_A > a^*)$ if conditions $(i)-(iii)$ hold. Conditions (ii) and (iii) state that the animal farmer and the rural planner gain highest welfare when choosing crops *k* and *m*, respectively. Condition (i) follows from the optimality conditions for the number of animals. It states that the privately optimal number of animals for crop *m* is higher than for crops *k* but that the rural planner's optimal number of animals for crop *m* is higher than the privately optimal for crop *k* (but lower than the privately optimal amount under crop *m*). The proof as well as a graphical presentation is given in the Appendix.

Naturally, it is always the case that for any given crop, the rural planner chooses less animals at the optimum than the private farmer. What Proposition 2 states is that it may be the case that taking externalities into account may induce a change in crop from *k* to *m* to increase the uptake of either of the nutrients and, hence, reduce residual nutrients. And, while the rural planner always chooses less animals than the private farmer for any given crop, the planner might choose a higher number of animals than the private farmer if the crop choices are different. There may thus be cases where regulation increases the production intensity. However, it is always the case that regulation decreases the generation of those externalities that initially trigger regulation and decreases private profits. This, however, is the point where the regional conflict steps into play. To see that, let us look at the optimal solutions of the global planner.

2.4 Optimization problem of the global planner and welfare comparisons

The global social planner maximizes profits net of the sum of externalities in the agricultural region ($E_A^S + E_A^G$) and in the recreational region (E_R^S):

$$\underset{a,d_i,x_i,j,k}{\text{Max}} \pi_{on}(a,k,d_i,x_i) + \pi_{off}(j,d_{off}) - E_A^S(r^N,r^P) - E_R^S(\omega_N r^N, \omega_P r^P) - E_A^G(r^N) \tag{13}$$

The parameters ω_N and ω_P denote the fractions of nitrogen and phosphorus residuals that are carried over to the recreational region.[12] The socially optimal number of animals satisfies:

$$\begin{aligned} p^a = f'(a) + p^k \xi^k + \left(\frac{\partial E_A^S}{\partial r^N} + \frac{\partial E_A^G}{\partial r^N} + \omega_N \frac{\partial E_R^S}{\partial r^N}\right)\frac{\partial r^N}{\partial a} \\ + \left(\frac{\partial E_A^S}{\partial r^P} + \omega_P \frac{\partial E_R^S}{\partial r^P}\right)\frac{\partial r^P}{\partial a} \end{aligned} \tag{14}$$

Conditions for globally optimal hauling distance on- and off-farm (not presented here) include the same partial derivatives of recreational region's externalities, weighted with the carry over fractions. If $\omega_i \frac{\partial E_R^S}{\partial r^i} > 0$ for either $i = N$ or $i = P$ global and rural planners' optimal choices are different. That is, if the surface waters in the recreational region are sensitive towards a nutrient, of which a positive fraction is carried over to the region, globally optimal solution differs from the rural planner's optimum. If, on the other hand, $\omega_i \frac{\partial E_R^S}{\partial r^i} = 0$ for both $i = N$ and $i = P$, solutions to (13) and (8) coincide. The optimality condition for dumping (12) is always identical for both planner's: it's never optimal to dump off-farm.

Naturally, all effects describe in the previous section apply for the global planner if the optimality conditions are identical. Proposition 1 and the ensuing discussion hold for the global planner even though the solutions were not identical. Looking at the figure 2, the global planner's solution—given $\omega_i \frac{\partial E_R^S}{\partial r^i} > 0$—would shift the horizontal line associated with crop j higher. There would, however, still be cases where discontinuities in marginal benefits from manure applications off-farm would cause the consideration of externalities in no improvements in manure utilization.

We have thus three types of solutions: Private optimum that does not consider externalities, rural planner's optimum that solves the inboundary externality but ignores the transboundary pollution and the global planner's optimum that maximizes the overall welfare. Let us compare the rural planner's optimum with the private optimum. We show that, depending on the environmental sensitivity of the regions, rural planner's solution may even increase transboundary pollution to recreational region and hence decrease its welfare; and that it may decrease the total welfare of the two regions. We first make the following notational definitions:

Definition 4. *Denote by $\Delta r^N = r_A^N - r^{N*}$ the difference in nitrogen residuals associated with the rural planner's and private farmers' optima;*

[12] For simplicity, we assume the fractions are exogenous. In reality, they reflect the amount of externalities in the agricultural region: algae growth, for instance, reduces the amount of nutrient residuals that are eventually carried over to recreational region's surface waters. Intensive algae growth in the agricultural region would decrease both ω_N and ω_P.

denote by $\Delta r^P = r_A^P - r^{P*}$ *the difference in phosphorus residuals associated with the rural planner's and private farmers' optima;*
denote by $\Delta E_R^S = E_R^S\left(\omega_N r_A^N, \omega_P r_A^P\right) - E_R^S\left(\omega_N r^{N*}, \omega_P r^{P*}\right)$ *the difference in environmental damage in the recreational region associated with the rural planner's and private farmers' optima.*

Remark 1. *For nutrient i emphasized by the rural planner, it holds that* $\Delta r^i < 0$.

In other words, rural planner's regulation always decreases the externalities in the agricultural region, and hence the residual of at least the nutrient towards which its environment is more sensitive to. The following two propositions establish the regional conflict.

Proposition 3. *Assume that rural planner's intervention reduces nitrogen residuals. It may, however, result in an increase in phosphorus residuals in which case* $\Delta r^N \times \Delta r^P < 0$. *Then, for each* Δr^N, *there is some* $\overline{\Delta r^P}$ *and some damage function parametrization for which* $\Delta E_R^S > 0$.

Proposition 3 states that, if reductions in nitrogen residuals are associated with increases in phosphorus residuals carried over to the recreational region, the externalities in the recreational region may increase as a result of rural planner's intervention. If there is a trade off in nitrogen and phosphorus residuals, and if the sensitivity of the environment is different in the two regions, there is some threshold after which rural regulation makes the recreational region worse off. This is one of the the key messages of the article.

What are the conditions for $\Delta r^N \times \Delta r^P < 0$? First, the crop choices between the rural planner and the private farmers must be different. If they are identical, the residuals move in same directions. The rural planner always generates less (here) nitrogen residuals than the private farmers (see Proof of Proposition 2). If the per-acre crop uptakes are unchanged, the phosphorus residual has to decrease too.

Second, the differences in nitrogen and phosphorus uptakes of the crops must be high enough to offset the potentially longer hauling distances and the potentially decreasing number of production animals. It is thus not the absolute phosphorus uptake that matters. If the rural social planner switches to a crop with a significantly higher nitrogen uptake and with a slightly higher phosphorus uptake, the per-acre phosphorus residual increases in the manure application area. That is, whenever
$\left(\beta q a_A^k - \delta^k d_{on_A} - \delta^k d_{off_A}\right) > \left(\beta q a*^{l*} - \delta^{l*} d_{on*} - \delta^{l*} d_{off*}\right)$,
the rural planner's solution increases the phosphorus residual in both regions.

Whether residual moving to opposite directions actually increases environmental damage downstream $\left(\Delta E_R^S > 0\right)$ depends on the ecological characteristics of the surface waters. Phosphorus may be the only determinant of eutrophication or it might have no effect on algae growth or anything between the extremes. The more important it is relative to nitrogen, the more likely it is that the rural social planner's policies will deteriorate the environmental quality downstream. In addition to this, the higher the ratio $\frac{\omega_P}{\omega_N}$, the more likely the aforementioned outcome. The absolute levels of the coefficients are not important as long as they are nonzero. The same does not hold for the following proposition:

Definition 5. *Denote by* $\Delta\pi = \pi_A - \pi^*$ *the difference in profits associated with the rural planner's and private farmers' optimum;*

denote by $\Delta E_A = E_A^G\left(r_A^N\right) + E_A^S\left(r_A^N, r_A^P\right) - E_A^G\left(r^{N*}\right) - E_A^S\left(r^{N*}, r^{P*}\right)$ *the difference in environmental damage in the agricultural region associated with the rural planner's and private farmers' optimum;*
denote by $\Delta W = \Delta\pi - \Delta E_A - \Delta E_R^S$ *the difference in global social welfare associated with the rural planner's and private farmers' optimum.*

Proposition 4. *If* $\Delta r^N \times \Delta r^P < 0$ *and* $\Delta E_R^S > 0$*, there is some threshold increase in rural welfare* ($\Delta\pi - \Delta E_A$) *that has to be achieved for rural social planner's intervention to increase global welfare.*

Proposition 4 compares the cases of no intervention and rural intervention from the global planner's perspective. If the rural planner's solution increases one of the nutrient surpluses while decreasing the other ($\Delta r^N \times \Delta r^P < 0$); and if the environmental sensitivity of the recreational region is such that the surface water quality decreases as a consequence of this ($\Delta E_R^S > 0$), the rural planner's optimal solution may decrease global welfare. In this case, the no intervention case outperforms the rural intervention, from the global planner's perspective. Note that the rural planner always increases welfare and environmental quality in the agricultural region, i.e., $\Delta\pi - \Delta E_A > 0$. But if it simultaneously increases environmental damages in the recreational region, the welfare improvement in agricultural region must offset this effect. As the coefficients ω_P and ω_N become smaller, a decrease in global welfare becomes less likely. For the individual elements of welfare changes, discussion in Propositions 2 and 3 apply.

The results established in Propositions (2)-(4) bear similarities with Walls and Palmer (2001). Their theoretical model considers a single product with multiple externalities during its life cycle. The main outcome of their model is the need to consider all externalities from a single product simultaneously. The results are also related to the game theoretical model of Martin and Stahn (2013) who illustrate a conflict between agricultural and ground water managers, drawing from their differing definitions of externalities. And even though we have not analyzed policy instruments so far, the results also hint towards the Tinbergen rule (Tinbergen, 1952) which states that economic policy must include as many instruments as targets. After all, the ultimate reason for the regional conflict is the different role of nutrients in the environmental damage in the two regions, which in the extreme case is the complete lack of one of the externalities in the rural planner's optimization problem.

It is well understood that interstate coordination within Mississippi river basin is needed in protecting the Northern Gulf of Mexico (see, e.g. (Task Force, 2001, 2008)). Chesapeake Bay watershed has been suggested as a model of policy coordination for the Mississippi basin (see, e.g. (of the National Academies, 2009). Even at the Chesapeake Bay, however, there are substantial differences in how states emphasize nitrogen and phosphorus in manure regulation. This is implicitly expressed in defining the P-index threshold for mandatory phosphorus standard. After crossing the threshold, animal farms may no longer follow the nitrogen standard. Maryland, for instance, has a stricter (i.e. lower) threshold for using a phosphorus standard than Pennsylvania (Pennsylvania, 2011; Maryland, 2014).[13] Hence, state regulations treat the two main nutrients causing eutrophication differently within the Chesapeake Bay watershed.

[13] Operators in Maryland must follow nitrogen standard at fertility index values (FIV) of 150 and above. This corresponds to Mehlich III soil test value of about 136 ppm. In Pennsylvania, nitrogen standard can be followed until Mehlich III values of 200 ppm, i.e. the threshold is about 47 per cent higher than in Maryland.

3 Instrument analysis

By definition, any global sub-optimality of rural planner's policies will carry over with first-best instruments imposed on farmers. The situation is different with second-best instruments, of which we analyze Nutrient management plans (NMP) and a tax on nitrogen fertilizer. NMPs are by far the most important instruments used to regulate large animal facilities in the United States. Similar, nutrient balance based approached are also widely used in other countries. Tax on nitrogen fertilization is an economic instrument that could be considered for nutrient regulation – and it has been used in, for instance, Austria, Finland and Sweden (Rougoor et al., 2001). We analyze these from the rural social planner's perspective and examine how the unintended increase in phosphorus loading to recreational region carries over when using either of the instruments.

3.1 Nutrient Management Plans

In the United States, NMPs are the most widely used regulatory instrument to curtail nutrient loading from animal production. Plans may be based either on a nitrogen or phosphorus standard. Under the nitrogen standard, the animal farm may apply nitrogen with manure only up to the level of nitrogen uptake of the crop.[14]

Assuming nitrogen is also the relatively scarce nutrient, it is easy to introduce the nitrogen standard for livestock farms into our model. It simply requires that $x_{on} = 0$. Note that our hauling distance (d_i) has a unique counterpart in field acreage on which manure is applied exactly according to crop requirements, i.e., in accordance with the nutrient standard.

Technically, such an instruments adds a constraint into the livestock farmer's optimization problem 4. The associated first-order conditions are presented in the Appendix. Let us denote by λ_5 the shadow price of the constraint. It depends on the marginal hauling costs at the farms' border: $\lambda_5 = \frac{\partial h(b_{on})}{\partial d}$. By the very need to impose the instrument, we assumed that $\lambda_1 = 0$ and $\lambda_2 > 0$.

The situation changes if the NMP is based on phosphorus standard and if nitrogen is still the relatively scarce nutrient. The constraint $x_{on} = 0$ remains, but the maximization problem changes. The manure can replace only part of the nitrogen needed. The savings in phosphorus fertilization still read $d_{on}\delta^k p^P$ when applying $\frac{d_{on}\delta^k}{\beta}$ units of manure. The hence applied amount of nitrogen is $\alpha\frac{d_{on}\delta^k}{\beta}$, and the cost savings in offsetting chemical nitrogen fertilization are p^N times this. The fixed acreage costs of fertilization (g), however, are not saved since nitrogen must be applied to the entire acreage. The fertilization costs after into taking account the savings from manure thus read $\left(\gamma^k b_{on} - \frac{d_{on}\alpha\delta^k}{\beta}\right) p^N + \delta^k p^P \left(b_{on} - d_{on}\right) + g b_{on}$.

With fixed manure handling and application technology and regulation covering only the animal farm, the effects of an NMP are presented in the following proposition. Denote the optimal choices under nitrogen standard with the superscript *NMPN*, under phosphorus standard with *NMPP* and under private optimum with $\star$:

[14]Not all manure nitrogen is in plant-available form. Part of plant-available nitrogen is also lost during the various phases that manure must undergo before it is actually uptaken by crops. Therefore, the nitrogen standard actually sets a lower bound for the ratio of applied and uptaken nitrogen. In California, for instance, this ratio is 1.42. That is, the farmer is allowed to apply 1.42 units of nitrogen in manure per each unit of nitrogen harvested with crops.

Proposition 5. *Under NMP, with nitrogen as the relatively scarce nutrient, it holds for any given crop that*
i) $a^{NMPP} = a^{NMPN} < a^*$
ii) $d_{off}^{NMPP} = d_{off}^{NMPN} = d_{off}^*$
iii) $x_{off}^{NMPP} > x_{off}^{NMPN} < x_{on}^*$
iv) $\pi^{NMPP} < \pi^{NMPN} < \pi^*$.

The first point (i) follows directly: Each animal generates q units of manure. If the NMP constraint is binding, each animal incurs thus an extra marginal cost equal to the cost of dumping the manure off farm.

The second point (ii) is one of the key results of the paper. It states that neither of the standards increases the off-farm utilization of manure. That is, they do not increase the hauling distance off-farm. This is because the marginal costs and benefits of off-farm hauling are unchanged. Furthermore, the regulatory standard concerns only the animal farm. Because of the standard, manure has to be shipped away from the animal farm. But the area where it is applied according to crops' nutritional needs is unchanged, which is to say that dumping off-farm must increase.

There are differences in the two standards in how much is dumped off-farm as shown by the third point (iii). It states that the amount of manure dumped off farm under phosphorus standard is higher than under the nitrogen standard, both being lower than dumping under no regulation. This is an important result concerning the differences between the two standards. Recall that, even though the constraint of $x_{on} = 0$ still remains, the maximization problem changed slightly when moving to a phosphorus standard. It turn out that less manure will be applied on-farm and as off-farm hauling is unchanged, the number of animals is lowered identically by both standards, off farm dumping must increase. The costs increase with fertilization costs and increased dumping to the farm border, the result referred to in (iv) above.

There are two more features to be noted. First, NMPs incentivize switching to a higher nitrogen or phosphorus uptaking crop, depending on the standard. Therefore, insights of Propostition 2 apply also here. Second, even though the phosphorus standard will increase crop-specific dumping, we do not know its total environmental or welfare effects: The crop switch affects these as well as parametrizations of the relevant functions. That is, Propositions 3 and 4 apply here too.

Proposition 2 contradicts with Kaplan et al. (2004) who find that binding nutrient constraints reduce phosphorus loading significantly. The difference stems from the modeling assumptions: our model assumes that an animal farm follows either nitrogen or phosphorus standard – as is the case with actual CAFO regulation. Furthermore, our model assumes that the animal farm may comply by exporting all surplus manure off-farm, i.e. export and apply more than is paid for. In the partial equilibrium model by Kaplan et al. (2004), the crop farm accepts only the amount of manure required by crops. Hence, the differences in how binding the regulation is on-farm and off-farm changes the results drastically.

The substitution between phosphorus and nitrogen surpluses is similar to that of air and water pollution in Aillery et al. (2005). In their model, applying manure without incorporating it to soil reduces nitrogen surpluses contributing to ground water pollution but increases air pollution, both topical problems in California. Effectively, this is the same effect as that brought by switching the crops in our model in terms of phosphorus and nitrogen surpluses. Also Baerenklau et al. (2008) consider cross-effects of air and ground-water pollution but not those of phosphorus and nitrogen.

3.2 Nitrogen tax

We analyze a tax on mineral nitrogen fertilizer in the simplest possible setting: the animal farm applies manure according to nitrogen needs, it dumps some of the manure it generates and it does not export any manure before or after the tax. Furthermore, to gain analytically insightful results, we parametrize the hauling costs as $h = M\varphi d$ where φ is some parameter. As nitrogen is the relatively scarce nutrient, hauling costs are given by $h = \varphi M d_i = \frac{\varphi d_i^2 \gamma^i}{\alpha}$, i.e. increasing and convex in distance and decreasing in the concentration of the relatively scarce nutrient.

Because the model contains continuous and discrete variables, we analyze the effects of a tax in two steps. First, we examine how it would change the farmer's optimal choices regarding the number of animals and hauling distance. Then, we examine what kind of incentives it creates for crop choice.

A nitrogen tax increases the price of nitrogen fertilizers. Comparative statics reads:

$$\underbrace{\begin{bmatrix} -f'' & 0 \\ 0 & \frac{-2\varphi\gamma^k}{\alpha} \end{bmatrix}}_{A} \times \begin{bmatrix} \frac{da}{dp} \\ \frac{dd_{on}}{dp} \end{bmatrix} = \begin{bmatrix} 0 \\ -\gamma \end{bmatrix} \tag{15}$$

yielding $\frac{da}{dp} = 0$ and $\frac{dd_{on}}{dp} = \frac{\alpha}{2\varphi} > 0$. An increase in the price of nitrogen increases the hauling distance at the rate of the ratio of nitrogen concentration in manure and marginal hauling costs. Hence, it decreases the residuals of both nutrients, given that there are no changes in crop choice. What kind of incentives does a tax on nitrogen create for crop choice? A tax increases the per-acre costs of chemical fertilization and, therefore, makes it profitable to haul and apply manure on a larger area. The higher the crop requirement for nitrogen, the higher the marginal effect of fertilizer price increase on profits. That is, increasing nitrogen fertilizer prices creates incentives to change the crops to those requiring less nitrogen. The rural social planner—trying to lower the nitrogen residual—does not want to see the farmer to switch to crops that require less nitrogen. This would increase the nitrogen residuals from the given manure application (the effect on phosphorus residuals depends on the phosphorus uptake of the new crop). The rural social planner is thus willing to set a tax (τ) on a range $0 \leq \tau < \tau_k$, where τ_k is given by the equality of any alternative crop choice (s) such that

$\pi_\tau^k - \pi^s = 0 \Leftrightarrow -\left(\gamma^k\left(p^N + \tau_k\right) + \delta^k p^P + g\right)\left(\underline{d} - d_{on}\right) - p^k\left(\xi^k a - y^k \underline{d}\right) - h\left(M_{on}^k, d_{on}^k\right)$
$+\left(\gamma^s p^N + \delta^s p^P + g\right)\left(\underline{d} - d_{on}\right) + p^s\left(\xi^s a - y^s \underline{d}\right) + h\left(M_{on}^s, d_{on}^s\right) = 0.$

That is, the tax is bound from above at the level where the farmer is indifferent between switching the crops. For a given crop, a tax does not incentivize increasing (or decreasing) the number of animals or encourage a transition to a more nitrogen uptaking crop. Hence, it eliminates both sources of the regional conflict. However, its effectiveness might be limited. The feasible bounds of the tax depend on the nitrogen and phosphorus uptakes of the crop alternative that would be chosen next instead of the privately optimal choice. How useful the nitrogen tax is in the presence of livestock production is therefore an empirical question. However, it is a qualitatively robust result that the tax does not generate a regional conflict.

Schnitkey and Miranda (1993) suggests that an increase in fertilizer price increases both manure application and the number of production animals. The difference with our model stems from the crop response specification. They assume that marginal impact of increase in nutrients is always positive. In our model with fixed crop yields, a price increase affects only the hauling distance (when manure is excessive). Contrasting both these models, Smith et al. (2006) find that a 56 percent increase in nitrogen price does not affect manure utilization in crop production.

4 Discussion and policy implications

Animal waste is a prominent example of complex environmental problem, where not having all ducks in a row results in a suboptimal solution. Our analysis demonstrates the importance of scale in evaluating an environmental problem. Private optimum is different than regional optimum and global optimum. This has significant implications for policy making and institutional design. For instance, a strong regional government may over regulate nitrogen surpluses compared to phosphorus, leading to eutrophication far away from the source of pollution. Regional integration and globalization may lead to shift in environmental priorities and policies and tension between the center and the regions.

We developed a two-agent, two-pollutant, two-region animal waste management model, recognizing the difference between manure application on animal vs. crop farms, and considering simultaneously phosphorus and nitrogen surpluses and identifying possibility of conflicts between farming and non farming regions with shared body of water. We assessed the implication of regulation using the popular nutrition management plan in addition to financial incentives. We showed that governance design crucially affects the outcomes of environmental regulation.

There are two insights provided by the on-farm off-farm division. Firstly, increasing pressure to reduce nutrient surpluses does not always lead to more efficient manure utilization. If the animal farm's fields are already fully utilized, introducing (or increasing) the environmental damage associated with nutrient surpluses does not necessarily lead to increased hauling distances.

The second insight is related to Nutrient Management Plans (NMP) as a regulatory instrument. NMPs provide binding nutrient surplus constraints to on-farm applications. The marginal incentives for manure utilization off-farm, however, do not change. NMPs do foster record keeping and information guidance for crop farmers utilizing manure (see. e.g., Pennsylvania code 83.343) The effectiveness of education or information as a regulatory instrument, however, is questionable (see, e.g., (Ribaudo and Horan, 1999)). At its worst, NMPs might induce crop production areas to be used to get rid of excessive manure at application rates higher than agronomic recommendations. Hence, excessive manure applications might be simply shifted from one region to another, with minor benefits to environment but with increased hauling costs.

Our analysis indicates the existence of a trade off in nitrogen and phosphorus surpluses. Could this be of practical relevance? In the U.S. about 90 percent of hogs and pigs and about 66 percent of milk cows are in operations classifiable as CAFOs (USDA, 2012).[15] Obviously, any environmental regulation that affects CAFOs' generation and application of manure has substantial consequences on nutrient loading on nation's surface and ground waters.

Our analysis has potential implications for regulating transboundary pollution to the Gulf of Mexico. The Gulf suffers from a persistent hypoxia area caused by eutrophication. During the last decades, its size has fluctuated around 15,000 square kilometers (Task Force, 2013). It causes huge direct losses to fisheries but is also contributes to the eutrophication itself by disallowing phosphorus to be trapped in bottom sediments. Nutrients to the gulf are brought by the Mississippi, and Atchafalaya Rivers, collecting waters from over thirty states. Previously, nitrogen was considered the most important cause of eutrophication in the Gulf of Mexico (see, e.g., (Rabalais et al., 2002)). In the first Action Plan of the Mississippi River/Gulf of Mexico Watershed Nutrient Task force (Task Force, 2001) it was explicitly stated that the excessive algal growth was primarily driven by nitrogen. Even though phosphorus and local water quality concerns were mentioned, the two priorities chosen to combat dead zones were linked to nitrogen loading. This, in turn, might have influenced the nutrient management plans the states in the basin adopted. Our results suggests that if NMP are based on a nitrogen standard, phosphorus loading from large animal facilities may increase for a variety of reasons.

Current understanding suggests that both nitrogen and phosphorus have important roles in driving eutrophication in the gulf (Scavia and Donnelly, 2007; Quigg et al., 2011). This is also recognized in the action plan: the latest version emphasizes both phosphorus and nitrogen abatement (Task Force, 2008). The 2013 progress report shows that the five year average nitrogen loading to the Northern Gulf of Mexico has remained at its 1997 level, whereas phosphorus loading has increased by about 30 per cent (Task Force, 2013). Obviously, an increase of this magnitude is bound to have negative effects on the water quality of the Gulf of Mexico. We know that during this period, point-sources have further curtailed their pollution, the sales of mineral phosphorus fertilizers has not systematically increased and that the agglomeration and intensification of animal operations has continued.[16] It seems plausible that manure management practices as described in the current paper could be behind this increase. To empirically verify this, we would need econometric analysis of crop prices and choices, fertilizer prices, manure standards followed, amounts of imported and exported manure, etc.

The third feature of our model was the regionally independently regulated, transboundary pollution. In the United States, the Environmental Protection Agency guides federal-level policies while the states have primacy in implementation and enforcement of regulations, such as the Clean Water Act. Sigman (2005) proposes that this decentralization has, to some extent, lead to free riding by states. We show that regulation focusing on a single region and a single nutrient may lead to similar results as free riding, even in first-best optimum.

[15]CAFO definitions vary by state and do not match perfectly the classes of Agricultural Census data; 90 percent of hogs and pigs are on farms that have more than 2000 heads and 66 percent of milk cows are on farms with more than 200 heads.

[16]see, e.g., http://www2.epa.gov/nutrient-policy-data/commercial-fertilizer-purchasedtable2

Transboundary pollution is often analyzed under the framework of environmental federalism. It analyzes benefits and drawbacks of local versus federal regulation. The basic result suggests that regions with independent environmental regulation tend to be driven toward overly lax environmental policies—the race to the bottom hypothesis (see, for instance (W.Oates, 2002) and (List and Mason, 2001)). Distortion from efficient levels of environmental protection are typically a result of strategic reasoning (local level regulation) or the lack of environmental precision and other informational shortcomings (federal level regulation). By introducing two tightly linked pollutants, our model generates similar outcomes under full information and without strategic play between the regions. So far, all theoretical frameworks on transboundary pollution and environmental federalism, starting from Tietenberg (1980) and Baumol and Oates (1988) as well as later developments, such as Mäler and de Zeeuw (1998) and Fernandez (2002) focus on a single pollutant. This is hardly suitable for water quality issues driven by one macro nutrient in one place and by a combination of both in the other.

There are obvious extensions to our analysis. We could explicitly assume only an endogenous fraction of cropland suitable for manure application. There are technical and crop-specific reasons for suitability but also reluctance of crop farmers to apply manure on their crops. An often cited reason for farmers' unwillingness to accept manure is their uncertainty regarding the nutrient concentration of manure and the plant availability of these nutrients. Crop farmers' willingness to accept manure is often found to be crucial for livestock farmers' compliance costs (Ribaudo and Agapoff, 2005) and (Kaplan et al., 2004). An interesting extensions of the model would be to allow for heterogeneous beliefs about the nutrient needs of crops. It would also be interesting to consider extending the NMPs to cover the areas importing manure — and to allow this regulatory extension to influence the willingness to accept manure.

We argue that allowing the farmer to alter the nutrient concentration of manure by feed choices, manure storage, and application techniques would provide qualitatively similar results as the crop choice in the current model. Empirically, however, it would be interesting to analyze how the farmer would optimally increase or decrease the nutrient concentration of manure within the feasible range for each production animal. Increasing nutrient concentration reduces hauling costs of a nutrient unit and makes it more competitive against mineral fertilizers.

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Figures

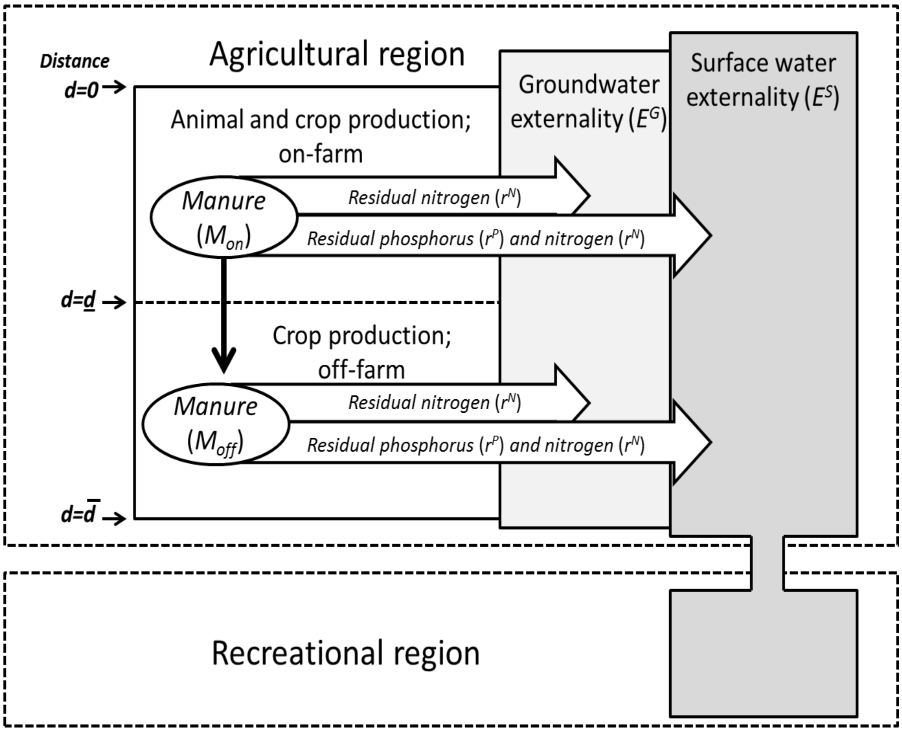

Figure 1: Conceptual model of the recreational and agricultural regions

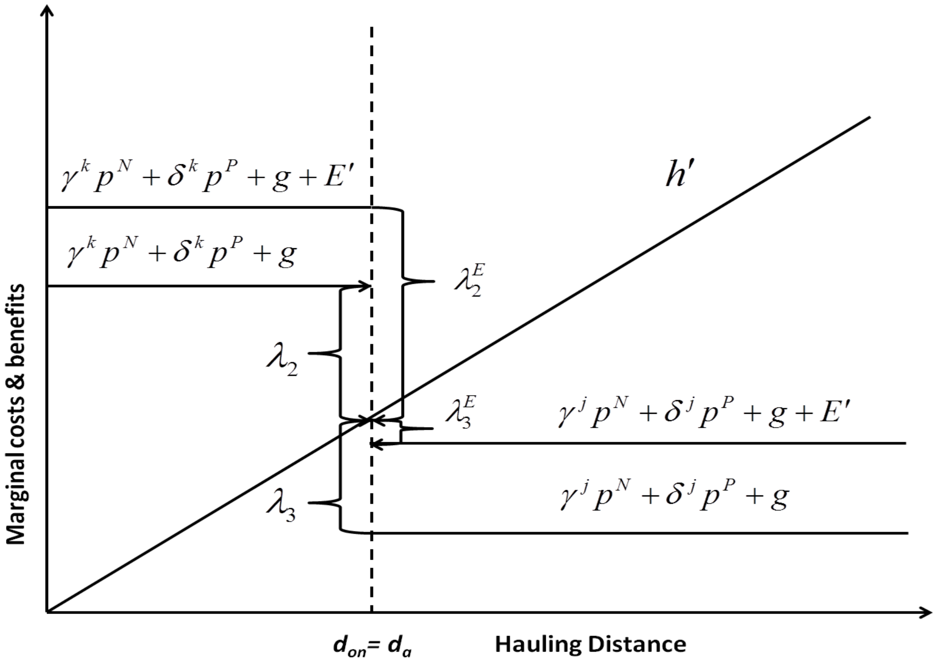

Figure 2: Optimal hauling distances on and off farm

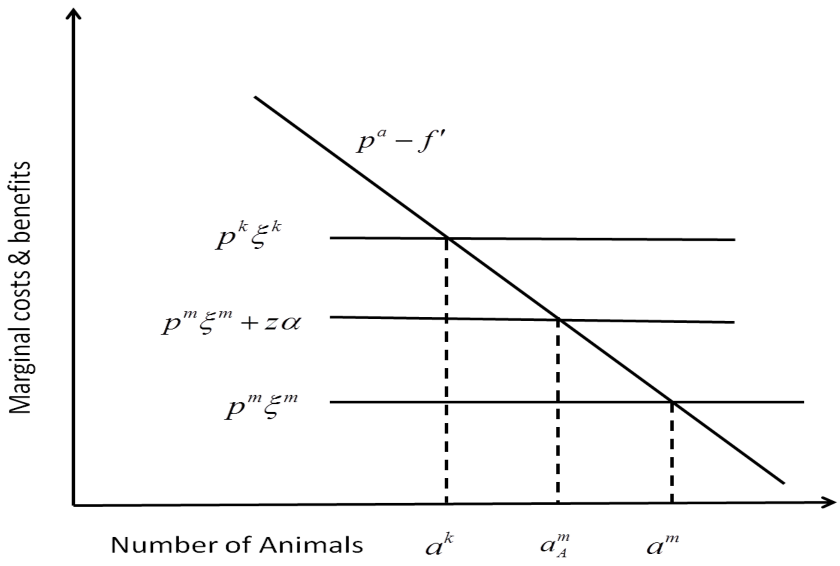

Figure 3: Rural social planner's solution may increase the number of production animals

A Appendix

A.1 Proof and Graphical Presentation of Proposition 2

1. We first show that $p^m\xi^m < p^k\xi^k \Rightarrow a^k < a^m$. By continuity, we always have $p^m\xi^m \neq p^k\xi^k$. Set $p^m\xi^m < p^k\xi^k$. By first-order conditions, we have

   $$\begin{cases} p^a - f^{'}(a^m) - p^m\xi^m = 0 \\ p^a - f^{'}\left(a^k\right) - p^k\xi^k = 0 \end{cases} \Leftrightarrow f^{'}\left(a^k\right) - f^{'}(a^m) = p^m\xi^m - p^k\xi^k < 0 \Rightarrow a^k < a^m.$$

   The implication follows from $f^{''} > 0$.

2. Next, we show that, for any given crop (l), $a_A^l > a^l$.

   $$\begin{cases} p^a - f^{'}\left(a_A^l\right) - p^l\xi^l - \frac{\partial E}{\partial a} = 0 \\ p^a - f^{'}\left(a^l\right) - p^l\xi^l = 0 \end{cases} \Leftrightarrow f^{'}\left(a^l\right) - f^{'}\left(a_A^l\right) = \frac{\partial E}{\partial a} > 0 \Rightarrow a_A^l < a^l \forall l.$$

3. Then, show that $\frac{\partial E}{\partial a_A^m} < p^m\xi^m - p^k\xi^k \Rightarrow a_A^m > a^k$

   $$\begin{cases} p^a - f^{'}\left(a_A^m\right) - p^m\xi^m - \frac{\partial E}{\partial a_A^m} = 0 \\ p^a - f^{'}\left(a^k\right) - p^k\xi^k = 0 \end{cases} \Leftrightarrow f^{'}\left(a^k\right) - f^{'}\left(a_A^m\right) = \frac{\partial E}{\partial a} - p^k\xi^k + p^m\xi^m$$

   $$\Leftrightarrow \frac{\partial E}{\partial a_A^m} < p^m\xi^m - p^k\xi^k \Rightarrow a_A^m > a^k.$$

4. It remains to be shown that it is possible that the rural social planner's crop choice is *m* and the livestock farmer's choice is *k*

   $$\begin{cases} \pi_A^m - E_A^m > \pi_A^k - E_A^k \\ \pi^m < \pi^k \end{cases} \begin{cases} \pi_A^k - \pi_A^m < E_A^k - E_A^m \\ \pi^m - \pi^k < 0 \end{cases},$$

   which requires that the difference in environmental damages under the two crops outweighs the difference in the associated profits. Set the nitrogen uptake γ^m to generate $E_A^m = 0$. Then, for any difference in profits $\pi_A^k - \pi_A^m$, one can find a damage parametrization satisfying $\pi_A^k - \pi_A^m < E_A^k$. That is, it is always possible to find a case where the rural planner's solution increases the number of production animals.

Figure 3 illustrates the case where only nitrogen loads are harmful and where the damage function is linear with marginal damage equal to z.

FIGURE 3 ABOUT HERE

The downward sloping curve in Figure 3 denotes the slope, $p^a - f'(a)$, i.e., the marginal profit of production animal before feeding costs. The slope does not depend on environmental damages or the crop choice. The horizontal lines denote the marginal feeding costs. The intersection of the downward sloping curve and the highest horizontal line denotes the privately optimal number of animals under crop choice k. The lowest horizontal curve corresponds to a private solution under crop m. The intersection with the horizontal line in the middle denotes the optimal number of production animals associated with the rural social planner and crop m. In addition to feeding costs, it includes the marginal environmental damages of a production animal.

A.2 First-order conditions with Nutrient Management Plans

With nitrogen as the relatively scarce nutrient, with excess generation of manure and by denoting the shadow price of NMP with λ_5, the first-order condition for optimal number of animals reads

$$p^a - f^{'}(a) = p^k \xi^k + \lambda_5 q. \tag{A.16}$$

For any crop, introducing a binding NMP unambiguously reduces the number of animals. In Figure 3 the last term in (A.16) would elevate the horizontal line, moving the intersection of the two curves to left.

Assuming that the livestock farm's own land is already fully utilized, introducing a NMP only affects the shadow price of land. Interestingly, it lowers the shadow price by the term $\lambda_5 \frac{\gamma_{on}^k}{\alpha}$, i.e., the marginal costs of dumping on the border of the crop and livestock farm times the per-acre nutrient uptake–concentration ratio.

The first-order conditions for off-farm hauling and dumping are

$$\begin{aligned} &\frac{2\varphi d_{off}\gamma_{off}^k}{\alpha} = \rho\left(\gamma_{off}^k p^N + \delta_{off}^k p^P + g\right) + \lambda_3 - \lambda_4 - \rho\lambda_5 \frac{\gamma_{on}^k}{\alpha} \\ &\frac{\partial c}{\partial x_{off}} = \lambda_5 = \frac{2\varphi b_{on}\gamma_{on}}{\alpha}. \end{aligned} \tag{A.17}$$

The situation changes if the NMP is based on a phosphorus standard and if nitrogen is still the relatively scarce nutrient. The constraint $x_{on} = 0$ is still valid, but the maximization problem changes slightly. The manure can replace only part of the nitrogen needed. The savings in phosphorus fertilization still reads $d_{on}\delta_{on}^k p^P$ when applying $\frac{d_{on}\delta_{on}^k}{\beta}$ units of manure. The hence applied amount of nitrogen is $\alpha\frac{d_{on}\delta_{on}^k}{\beta}$, and the cost savings in offsetting chemical nitrogen fertilization are p^N times this. The fixed acreage costs of fertilization (g), however, are not saved since nitrogen must be applied to the entire acreage. The fertilization costs after taking into account the savings from manure thus read $\left(\gamma b_{on} - \frac{d_{on}\alpha\delta}{\beta}\right) p^N + \delta p^P (b_{on} - d_{on}) + g b_{on}$.

Reversing the nutrients (phosphorus standard, phosphorus relatively scarce; nitrogen standard, phosphorus relatively scarce), the results would be mirror images of the cases above.