Optimal Regional Policies to Control Manure Nutrients to Surface and Ground Waters

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Abstract:

Current day large animal facilities generate more manure than they need 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 for nitrogen and phosphorus abatement. We postulate an analytical model of upstream agricultural and downstream recreational regions, and analyze optimal policies that consider both regions. We show that depending on the environmental and economic characteristics, tightening upstream regulation with respect to loading of one nutrient only might increase the downstream loading of the other. As the prevailing regulatory tool for livestock production is the Nutrient Management Plan based on nitrogen standard; and because livestock production is the main source of man-made nutrient loads to environment, the model is of high importance. Our model contributes to literature by i) differentiating (the impacts of) manure regulation between the livestock farm and the adjacent crop production farm ii) showing how this differentiation is carried over to relative and absolute amounts of nitrogen and phosphorus loading due to changes in nutrient application and uptake; and due to changes in application areas iii) allowing for regional differences in abatement objectives.

Keywords Manure, Transboundary Pollution, Phosphorus, Nitrogen, Regulation, Externality
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1 Introduction

Transboundary pollution spreads between regions with varying effects on natural environments. There may also be regional differences in citizens' valuation for environmental quality. Furthermore, the jurisdiction over environmental regulation may be partly or completely shared between the regions or it may be completely isolated. These features may lead to region specific abatement goals and policies to meet them. Since the environmental quality of regions sharing a transboundary pollutant is interconnected, allocation of resources and actions to determine and achieve the goals should be done in cooperation.

Most of the academic work on transboundary pollution has focused on international environmental agreements. Due to diverging objective and absence of international enforcement, agreements often either ratify what has already been accomplished or fail in achieving their targets.[1]

In US, the environmental protection agency guides federal level policies while the states have primacy in implementation and enforcement of regulations such as Clean Water Act. [14] proposes that this decentralization has to some extent lead to free riding of states. While free riding might be an important issue, we think that lack of understanding between the effects of regulation on one region to another together with diverging objectives are more important obstacles to efficient environmental policies.

All theoretical frameworks on transboundary pollution, starting from [15] and [3] as well as later developments such as [10] and [**?**] focus on a single pollutant. When applied to water pollution, this choice imposes substantial limitations to policy analysis. Eutrophication of surface waters is mainly driven by excessive loads of two macro nutrients, nitrogen and phosphorus. Nitrate nitrogen also contributes to impairments in ground water quality. That is, water quality in any region is driven by the combination of phosphorus and nitrogen. A region suffering from groundwater problems but

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[1] An example of the former is the Montreal protocol [12] and of the latter the protection of the Baltic Sea which has experienced various declarations and treaties since the Helsinki convention signed in 1974, all with negligible effects on countries' abatement decisions [5].

not having an issue with surface waters is likely to focus its efforts in abating nitrogen loads. If algae growth in surface waters is limited by the same (combination of) nutrients in source areas as downstream, both areas are interested in mitigating the same pollutants. [2]

Agriculture as a major source of nutrients exhibits trade-offs between phosphorus and nitrogen abatement. Together with differences in regional responses in environmental quality and objectives regarding it, these features bring about previously unrecognized pitfalls in decentralized regulation. Because significant, agricultural intensive pollution source areas, such as Chesapeake Bay or Mississippi basins, are characterized by partially independent regions and different focuses on phosphorus and nitrogen, unintended outcomes of regional policies may be dramatic.

What makes this particularly important is the fact that livestock production is one of the most important individual sources of nitrogen and phosphorus loads in US and in Europe. Concentration of livestock production to certain regions and increase in average number of animals per farm are ongoing trends. Therefore, the need to understand drivers of pollution on a regional scale is of utmost practical relevance.

Ultimately, the excess nutrient loading related to livestock production originates from the high hauling costs of manure relative to its nutrient content, the suboptimal nitrogen phosphorus ratio; and increased concentration of livestock production to certain regions which has lead to scarcity of manure application area. Without regulation, manure will not be hauled long distances and will thus be over applied in livestock production regions.

Livestock farm can – and has been – made liable for the animal waste it produces and applies to cropland under its own control. Surrounding crop areas can accept manure but they don't have to. Regulation tends to differentiate between manure applications in the area controlled by livestock operation, and those on the surrounding crop

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[2] Inland lakes are often considered phosphorus limited, rivers and estuaries sensitive to nitrogen or both nutrients and open sea areas to nitrogen. There is, however, no consensus among hydrologists on this issue (see e.g. the debate launched by [**?**]). Even without consensus among scientist, political decisions are by large based on the above generalizations.

production area.Literature has addressed this feature with two alternative approaches. The first one sees livestock and crop production areas equal in terms of regulation, the other separates on- and off-farm regulation.

The earliest papers assumed regulation to cover both on-farm and off-farm application similarly, but also included an outside disposal area which was assumed to take care of manure with certain costs, without environmental externalities [11] and [6]. [7] assume that livestock farms lease the extra land needed to manure application in which case they are also covered by on-farm regulation. [13] and [8] further develop the theoretical framework of manure applications. Their models quantify the excess use of manure as a function of the number of animals and the distance from the facility. They do not allow for outside disposal areas but do assume that regulation can reach manure application similarly, regardless of land being operated by the livestock farmer or the crop farmer. That is, they do not differentiate between on-farm and off-farm manure application.

The other alternative is to treat on-farm and off-farm applications separately. Regulation hits livestock farmers who may react by altering their on-farm operations or by increasing off-farm export of manure. Implicitly or explicitly, all papers to our knowledge assume in these cases that off-farm applications are done according to either agronomic needs or as a substitute for chemical fertilizers (see, e.g. [4]; [9] or [2]).

Considering practical policy limitations, this assumption might have important implications. In US, about 17% of corn producers and 8% of soybean producers use manure as a substitute for chemical fertilization (USDA-ERS 2003). These crop farmers are not covered by nutrient management plans that prohibit applying manure above agronomic needs of crops. Such difference in manure regulation 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 in worst case be simply shifted from one region to another, with minor benefits to environment, but with increased hauling costs.

We contribute to literature firstly by formalizing a transboundary pollutant model with two pollutants, interlinked both at the source and in the environment. Secondly, we model the cross effects between on- and off-farm regulation and manure applications, allowing for area constraints.[3] As in [8] our production region consists of livestock production facilities and land on crop production that can be used for manure application. But unlike their model, we separate between land under the control of livestock farms and crop farms.

We develop a stylized model comprising two regions. Pollution originates from one of them but both incur economic losses according to region specific damage functions. We solve for optimal regulation within the source region as a decentralized and centralized control problem. We show that regional orientation in regulation may lead to overall decline in welfrare. We also analyze instruments to see how the outcomes of regional policies are carried over when using different instruments to incentivize the policies.

The rest of the paper is organized as follows. We first present the model conceptually and analytically and derive the necessary optimality conditions. We then analyze the instruments, focusing on regional second best instruments and their implications. Third section considers how endogenous choice of manure nutrient concentration would affect the main results. The fourth section concludes.

2 The conceptual model

Consider two regions with independent regulatory policies: an agricultural region and an adjacent, recreational region.[4] The surface waters of the regions are connected. Nitrogen and phosphorus loading that impairs surface water quality originates from

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[3] [1] and [2] consider joint regulation of air and water emissions from livestock production. Interestingly, there are no analyses on joint regulation of phosphorus and nitrogen regulation, even though they contribute to a single environmental externality: eutrophication, and originate from the same economic activity.

[4] The recreational region may also include agricultural activities, externalities and their regulation. The difference is that its pollution (regulation) does not affect the welfare of agricultural region while the pollution (regulation) of the agricultural region does affect the welfare of the recreational region. That is, the only economic activity on the recreational region that enters our model is the suffering from eutrophication.

applying nutrients with manure in excess of crops agronomic needs. To highligh the chracteristics in nutrient surpluses emerging particularly in animal husbandry we assume that chemical fertilizers are applied precisely according to agronomic needs of crops and that their contribution to pollution is marginal. Furthermore, we assume that the precise location of excess manure application within a farm or even a within a region (if located on a single watershed) does not matter for the environment— only the total phosphorus and nitrogen surplus does. This implicitely assumes that loading is linearly dependent on nutrient residuals, and that the retention of nutrients is uniform within the watershed. Residual nitrogen also affects groundwater quality in the agricultural region. The agricultural region consists of a land area controlled by livestock production (on-farm) and the area under crop production (off-farm).

Both regions have unique damage functions whose arguments are nitrogen and phosphorus loading. The model is static, i.e. the damage is inferred directly from the flow of nutrients. Figure 1 presents the model schematically.

The model embeds optimization problems of four agents: 1) the livestock farmer, 2) the crop farmer, 3) the rural social planner taking into account profits and damages in livestock and crop production areas, denoted jointly as agricultural region (A) and 4) the global social planner acknowledging profits and damages in both agricultural and recreational regions. For the ease of exposition, we assume that the width of the land area is 1. The livestock facility is located at the outer edge of the rectangular land area under the control of the livestock farm. The distance and the acreage from the facility is denoted (d_{on}). The boundary between the livestock and crop farms is denoted (b_{on}) and the rear boundary of the crop farm$\left(b_{off}\right)$.

The livestock farmer maximizes profits by choosing the number of animals (a), the cultivated crop or crop rotation (k_{on}), the distance manure is hauled and applied on own land (d_{on}), the amount of manure exported to crop production area $\left(M_{off}\right)$, and the amount dumped on either own land (x_{on}) or on the crop production area $\left(x_{off}\right)$. The manure is applied on the distance (d_{on}) according to either phosphorus or nitrogen needs of crops. Potential over application is captured in (x_{on}). The crop choice de-

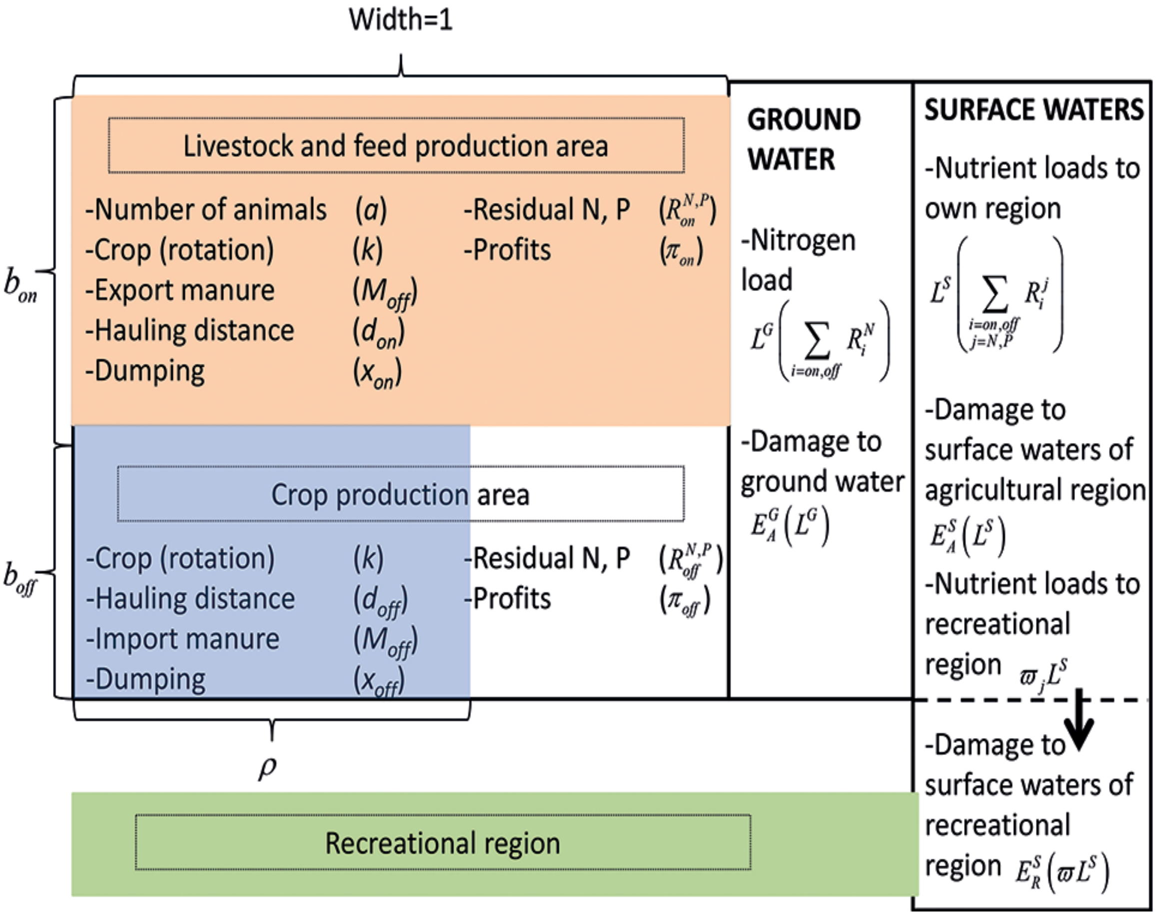

Figure 1: Recreational region and agricultural region comprised of crop and livestock production areas

termines the per acre nitrogen and phosphorus requirements, which together with the manure nutrient concentration and hauling distance determine the quantity of manure applied (M_{on}).

A single crop farmer (or a continuum of crop farmers totaling 1) operates the crop production area. She chooses the crop $\left(k_{off}\right)$ and the amount of manure imported from the livestock production area (M_{off}). Only a given exogenous fraction $\rho \in (0,1)$ of cropland is feasible for manure application.

Hauling costs for manure are convex in hauling distance which must lie within the boundaries of the respective farming areas$(d_i \leq b_i)$. Hauling distance is a common metric for crop and livestock farmer. For tractability, we denote hauling distances with subscripts. That is, if the crop farmer's hauling distance is equal to the boundary of the livestock and crop farm$\left(d_{off} = b_{on}\right)$, she does not import manure. The hauling and application of manure is operated by the livestock farmer.

Residual nutrients from both production areas generate damages in ground- and surface waters of the agricultural region and surface waters of the recreational region. Damage on groundwater depends on the sum of residual nitrogen (nitrates) from livestock and crop production areas $\left(\sum_{i=on,off} R_i^N\right)$ as defined by physical load functions$\left(L^i\right)$. In what follows, we assume a linear relationship between the residuals and loads. Therefore, the damage functions can be expressed as functions of residuals directly. A residual is determined as the differences between the applied and uptaken nutrient. Only a nutrient specific fraction $(\varpi_{N,P})$of residual nutrients from the agricultural region are carried to the recreational region. Damage on surface waters is driven by both nutrients, defined region specifically by the damage function$\left(E_l^S(N,P)\right)$. Surface water quality may be sensitive towards nitrogen, phosphorus or both. In what follows, the arguments of the damage function are R^N and R^P for the agricultural region, and $\varpi_N R^N$ and $\varpi_P R^P$ for the recreational region.

2.1 The Optimization Problems of Alternative Agents

All optimization problems can be obtained from global social planner's problem by omitting certain elements. The rural social planner omits the damage on surface waters in the recreational area; and farmers omit externalities altogether. The global social planner's problem in general form is given by:

$$\underset{a,k_i,d_i,x_i}{\text{Max}}\ \pi_{on}\left(a,k_{on},d_i,x_i\right)+\pi_{off}\left(k_{off},d_{off}\right)-\sum E_l^j\left(\sum R_i^j\right)-E^G\left(\sum R_i^N\right), \qquad (1)$$

Above, i denotes either livestock farm (on) or crop farm (off, k_i denotes the crop

Table 1: First Order Conditions for the Four Decision Makers

Global Social Planner	$\frac{d}{ds}\pi_{on} + \frac{d}{ds}\pi_{off} = \frac{d}{ds}E_A^S + \frac{d}{ds}E_R^S + \frac{d}{ds}E_A^G$
Rural Social Planner	$\frac{d}{ds}\pi_{on} + \frac{d}{ds}\pi_{off} = \frac{d}{ds}E_A^S + \frac{d}{ds}E^G$
Livestock farmer	$\frac{d}{ds}\pi_{on} = 0$
Crop farmer	$\frac{d}{ds}\pi_{off} = 0$

choice, j denotes either nitrogen (N) or phosphorus (P) and l either the agricultural area (A) or the recreational area (R). The first order conditions for any choice variable s for the four decision makers are collected in Table 1:

For each choice variable, the global social planner balances the marginal private profits $\frac{d}{ds}\pi_{on} + \frac{d}{ds}\pi_{off}$, marginal damages from deteriorating surface and groundwater quality in the agricultural region $\frac{d}{ds}E_A^S + \frac{d}{ds}E_A^G$ and surface water quality in the recreational region $\frac{d}{ds}E_R^S$. The rural social planner omits the last term and considers only the externalities experienced in the agricultural region. Livestock and crop farmers' objectives are to maximize their profits.

Upon choosing, livestock farmer takes into account the crop farmer's decision rule for manure imports; and social planners take into account both farmers' optimal choices. Therefore, we start analyzing the optimality conditions in more detail from crop farmer's perspective.

2.2 Optimization problem of the crop farmer

The crop farmer chooses a single cultivated crop and the amount of manure imported from the livestock production area for an exogenously given fraction $\rho \in (0,1)$ of her farmland. We assume that she is always willing to substitute chemical fertilizers with manure if the cost of satisfying the crop's agronomic needs with manure is less than or equal to doing the same with chemical fertilizers.[5] In this case, the optimization problem of the crop farmer is given by:

$$\begin{aligned}
&\underset{k_{off},d_{off}}{\text{Max}} = \pi_{off}\rho\left(y^k p^k\left(b_{off}-b_{on}\right)-\left(\gamma^k_{off}p^N+\delta^k_{off}p^P+g\right)\left(b_{off}-d_{off}\right)\right.\\
&\left.-p^M\max\left\{\frac{\left(d_{off}-b_{on}\right)\gamma^k_{off}}{\alpha},\frac{\left(d_{off}-b_{on}\right)\delta^k_{off}}{\beta}\right\}\right) \qquad (2)\\
&s.t.\ d_{off}\geq b_{on}
\end{aligned}$$

The fixed gross revenue from the potential application area is $\rho y^k p^k\left(b_{off}-b_{on}\right)$, where the net price $\left(p^k\right)$ includes variable costs except for fertilization costs. The agronomic needs for nitrogen and phosphorus for crop (k) are $\left(\gamma^k_{off},\delta^k_{off}\right)$, respectively.[6] The farmer thus optimizes over the combination of manure and chemical fertilizers, not over the amount of nutrients. Chemical fertilizers are applied on acreage $\rho\left(b_{off}-d_{off}\right)$. If no manure is imported, i.e $\left(d_{off}=b_{on}\right)$, chemical fertilizers will be applied in the entire crop production area. The per acre fertilizer costs are $\left(\gamma^k_{off}p^N+\delta^k_{off}p^P+g\right)$, where p^N and p^P are prices of nitrogen and phosphorus as chemical fertilizers and (g) is the per acre cost of application. The costs of manure (hauled and applied by the livestock farmer) is given by the per unit price $\left(p^M\right)$ times the units applied $M_{off}=\rho\max\left\{\frac{\left(d_{off}-b_{on}\right)\gamma^k_{off}}{\alpha},\frac{\left(d_{off}-b_{on}\right)\delta^k_{off}}{\beta}\right\}$. This quantity is given by the application acreage times the manure needed per acre. This is defined by the crop's need for the relatively scarce nutrient. If, for instance, satisfying nitrogen requirements requires more manure per acre than satisfying phosphorus needs, it is the nitrogen that drives the application rate — and phosphorus is applied excessively.[7]

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[5] We are not able to quantify the bergaining power of the two parties. As the focus of the present analysis is on designing and assessing regulatory policies, we assume for tractability that the crop farmer takes the price as given and all potential surplus manure trade goes to the livestock farmer. If entry and exit were considered, higher profits for the livestock producers would give incentives for new entrepreneurs to enter the market, increasing the total number of animals.

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

[7] This is an assumption supported by economic reaoning and a bulk of economics literature: applying according to the relatively more condensed nutrient would require applying chemical fertilizer in addition to satisfy the needs of the other nutrient. Furthermore, it would require applying manure at low rates which is

First order conditions for the crop farmer

Writing a Lagrangean and taking the first order conditions yields:

$$\begin{aligned} &\left(\gamma_{off}^{k} p^{N} + \delta_{off}^{k} p^{P} + g\right) = p^{M} \max\left\{\frac{\gamma_{off}^{k}}{\alpha}, \frac{\delta_{off}^{k}}{\beta}\right\} + \lambda_c \\ &\lambda_c \geq 0, \left(d_{off} - b_{on}\right) \geq 0, \lambda_c \left(d_{off} - b_{on}\right) = 0, \end{aligned} \tag{3}$$

For a given crop, all terms in (3) are exogenous for the crop farmer. For positive import quantities $\left(d_{off} > b_{on}, \lambda_c = 0\right)$ the price the crop farmer is willing to pay is:

$$p^{M} = \frac{\left(\gamma_{off}^{k} p^{N} + \delta_{off}^{k} p^{P} + g\right)}{\max\left\{\frac{\gamma_{off}^{k}}{\alpha}, \frac{\delta_{off}^{k}}{\beta}\right\}} \tag{4}$$

Given fertilizer prices, crop choice and manure nutrient concentration, the price (4) is constant. That is, the crop farmer is always willing to use manure for the entire suitable crop land or not at all. The amount eventually applied will be determined by the livestock farmer's first order conditions. The price (4) is increasing in nutrient concentration of the relatively scarce nutrient and insensitive towards the other nutrient. However, the price is affected by prices of both nutrients as chemical fertilizers. Prices of both nutrients affect the costs of applying them on a unit of land. The numerator in (4) gives costs in dollars per acre of chemical fertilization which is influenced by both macro 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 (4) is dollars per unit of manure.

Note that the overall profits are not affected by using manure. Hence, the crop farmer makes the crop choice irrespective of the manure application decision.

2.3 Optimization problem of the livestock farmer

The optimization problem of the livestock farmer is given by:

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technically challenging (see e.g. Lazarus and Kohler 2002).

$$\begin{aligned}
&\underset{a,d_i,k_{on},x_{off}}{\text{Max}} \quad \pi_{on} = p^a a - f(a) + p^M M_{off} - \left(\gamma_{on}^k p^N + \delta_{on}^k p^P + g\right)(b_{on} - d_{on}) - p^k \left(\xi^k a - y_{on}^k b_{on}\right) \\
&-h(M_{on}, d_{on}) - h\left(M_{off}, d_{off}\right) - c\left(x_{off}\right) \\
&\text{s.t.} \\
&\left(qa - M_{on} - M_{off}\right) \geq 0, (b_{on} - d_{on}) \geq 0, \left(d_{off} - b_{on}\right) \geq 0, \left(b_{off} - d_{off}\right) \geq 0 \\
&a, d_{on} \geq 0
\end{aligned} \tag{5}$$

with

$$\begin{aligned}
&M_{on} = \max\left\{\tfrac{d_{on}\gamma_{on}^k}{\alpha}, \tfrac{d_{on}\delta_{on}^k}{\beta}\right\}; M_{off} = \rho \max\left\{\frac{\left(d_{off} - b_{on}\right)\gamma_{off}^k}{\alpha}, \frac{\left(d_{off} - b_{on}\right)\delta_{off}^k}{\beta}\right\} \\
&x_{on} = qa - M_{on} - M_{off} - x_{off} \\
&R_A^N = \alpha qa - d_{on}\gamma_{on}^k - \left(d_{off} - b_{on}\right)\gamma_{off}^k \\
&R_A^P = \beta qa - d_{on}\delta_{on}^k - \left(d_{off} - b_{on}\right)\delta_{off}^k
\end{aligned}$$

The livestock farmer has five decision variables. The number of animals (a), the distance manure applied on and off farm (d_i) (which together with the composition of the manure and crop choices also determine the manure quantities (M_i)), the crop choice (k_{on}) and the amount of manure dumped to the crop production region, i.e hauled and applied in excess of the crop's needs $\left(x_{off}\right)$[8]. The last two equations define the sum of residual nutrients in the livestock and crop production regions.

The two sources of revenues are animals and manure. Selling animal products yields sales revenue; lifecycle revenues from one animal are given by (p^a). Depending on the type of production animal, these may comprise average per unit revenues from selling milk, the meat, eggs etc. Substituting own chemical fertilizer use with manure creates savings at the rate $\left(\gamma_{on}^k p^N + \delta_{on}^k p^P + g\right)$, and selling manure creates revenues $\left(p^M M_{off}\right)$, where the price is given by (4). Potentially, there are also sales revenues from selling forage from own crop production area.

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[8] There is no crop response to excessive manure application. Therefore, the crop farmer is not willing to pay anything for excessive manure. Because hauling is costly the livestock farmer always chooses $\left(x_{off}\right) = 0 \forall i$ without regulation. That is, potential excessive manure will be dumped on livestock farm with zero costs.

Production costs (f)

Production costs comprise of annualized investment costs and operation costs excluding feed costs. The costs are expressed as a function of the number of production animals with a second order polynomial with $f'(a) > 0$ and $f''(a) = C > 0$, where C denotes some constant.[9] Feed costs are defined separately because the crop choices play a special role in our model. Feeding (a) animals requires $\left(\xi^k a\right)$ units forage. The forage requirement depends on the animal and on the crop. Own forage production $\left(y^k_{on} b_{on}\right)$ may be higher or lower than this. The needed (excess) units of feed will be bought (sold) at price$\left(p^k\right)$.

Hauling costs (h)

Hauling and application costs are determined by the distance and the quantity of manure hauled. As application follows the agronomic needs, the quantity of manure has a unique counterpart in hauling distance for each crop and manure type. Following conventional assumptions (see e.g. 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.[10] The hauling costs function is identical for on- and off-farm hauling. However, the minimum distance for off-farm hauling is (b_{on}). To make things concrete, consider hauling costs given by $M\varphi d$ where φ is some parameter. If nitrogen would be the relatively scarce nutrient, hauling costs were given by: $h = \varphi M d_i = \varphi \rho \frac{d_i^2 \gamma^i}{\alpha}$. This simple formulation makes hauling costs increasing and convex in distance, and decreasing in the concentration of the relatively scarce nutrient.

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[9] Think of (f) as a simplification from a concave-convex cost function. The share of investments per production animal is high with low number of animals, given rise to the sharply rising production costs in the beginning. As the number of production animals increase, returns to scale make production costs increase more slowly. But as the number of animals increases further, the costs start to increase more rapidly again. The sufficient (second order) conditions tell that the relevant part of the curve must have positive second derivative. That is, the convex part of production costs is relevant for our optimization problem. These together with linearly increasing costs can be approximated with a second order polynomial.

[10] We could also assume linear or even concave hauling costs. This would make the optima always characterized by some binding constraints, never by interior solutions. Analysis would be otherwise unchanged.

Dumping costs (c)

Manure that is applied excessively regarding crops' agronomic needs for either of the nutrients (x_i) adds in its entirety to residual nutrients. We assume that dumping costs depend on the quantity of manure and the distance at which they are dumped. The costs of dumping on own land are assumed zero and on the crop farm $c\left(x_{off}, b_{on}\right) \equiv x_{off}\frac{\partial h(b_{on})}{\partial d}$. If nitrogen is the relatively scarce nutrient, this becomes $x_{off}\frac{2\varphi b_{on}\gamma}{\alpha}$.

Constraints in (5) limit the amount of manure applied on 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.

2.3.1 Optimal behavior of the livestock producer

Below, we give the first order conditions (excluding for brevity the standard non negativity constraints) for the continuous choice variables. We give them both in general form as well as for the case where nitrogen is the relatively scarce nutrient:

$$p^a + \lambda_1 q = f^{'}(a) + p^k \xi^k \tag{6}$$

$$\begin{aligned} \frac{\partial h}{\partial d_{on}} &= \left(\gamma_{on}^k p^N + \delta_{on}^k p^P + g\right) - \lambda_1 \max\left\{\frac{\gamma_{on}^k}{\alpha}, \frac{\delta_{on}^k}{\beta}\right\} - \lambda_2 \\ \underset{\text{N-scarce}}{\Rightarrow} \frac{2\varphi d_{on}\gamma_{on}^k}{\alpha} &= \left(\gamma_{on}^k p^N + \delta_{on}^k p^P + g\right) - \frac{\lambda_1 \gamma_{on}^k}{\alpha} - \lambda_2 \end{aligned} \tag{7}$$

$$\begin{aligned} \frac{\partial h}{\partial d_{off}} &= p^M \rho \max\left\{\frac{\gamma_{off}^k}{\alpha}, \frac{\delta_{off}^k}{\beta}\right\} - \lambda_1 \rho \max\left\{\frac{\gamma_{off}^k}{\alpha}, \frac{\delta_{off}^k}{\beta}\right\} + \hat{\lambda}_3 - \hat{\lambda}_4 \\ \underset{\text{N-scarce}}{\Rightarrow} \frac{2\varphi d_{off}\gamma_{off}^k}{\alpha} &= \left(\gamma_{off}^k p^N + \delta_{off}^k p^P + g\right) - \frac{\lambda_1 \gamma_{off}^k}{\alpha} + \lambda_3 - \lambda_4 \end{aligned} \tag{8}$$

$$\lambda_1 \geq 0, qa - M_{on} - M_{off} \geq 0, \lambda_1\left(qa - M_{on} - M_{off}\right) = 0 \tag{9}$$

$$\lambda_2 \geq 0, b_{on} - d_{on} \geq 0, \lambda_2\left(b_{on} - d_{on}\right) = 0 \tag{10}$$

The optimal number of animals (6) balances marginal revenues and costs of having one more animal. The marginal change in revenues consists of sales revenues (p^a) and cost savings from using manure $(\lambda_1 q)$. If $(\lambda_1 > 0)$ manure is scarce. That is, it would be applied more and hence it would generate more costs savings if available. A production animal excretes q units of manure. If manure is generated excessively compared to its application, its shadow value is zero $(\lambda_1 = 0)$. The marginal costs are the marginal production costs $\left(f^{'}(a)\right)$ plus feed costs for one animal $\left(p^k \xi^k\right)$, i.e. a linear and decreasing function. [11]

The optimal hauling distance (d_{on}) on the livestock farm (7) balances the marginal costs and savings. The marginal savings are the per acre nitrogen and phosphorus crop uptakes weighed with the prices of chemical fertilizers plus the per acre costs of applying them $\left(\gamma_{on}^k p^N + \delta_{on}^k p^P + g\right)$. If manure is not scarce and if the livestock farmer is not appying manure on all land area under her control, these marginal savings are balanced at the optimum with the marginal hauling and application costs $\left(\frac{\partial h}{\partial d_{on}}\right)$. 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, i.e. $\lambda_2 = \left(\gamma_{on}^k p^N + \delta_{on}^k p^P + g\right) - \frac{2\varphi d_{on}\gamma^k}{\alpha} > 0$, when nitrogen is relatively scarce and manure is excessive.

Figure 2 depicts the optimal hauling distance within the livestock farm for two alternative per acre costs for chemical fertilization. The illustrative cost differences are either due to fertilizer prices or different agronomic needs for nitrogen and phosphorus. Own land is not scarce, i.e. $\lambda_2 = 0$, manure may or may not be scarce, i.e. $\lambda_1 \geq 0$ and nitrogen is assumed to be the relatively scarce nutrient. Rearranging (7) we obtain $(2\varphi d_{on} + \lambda_1)$ on the left hand side. The right hand side $\left(\frac{\alpha\left(\gamma_{on}^k p^N + \delta_{on}^k p^P + g\right)}{\gamma_{on}^k}\right)$ denotes the implicit price of manure on the livestock farm cultivating crop k.

The figure illustrates the optimal hauling distance on-farm as well as the shadow

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

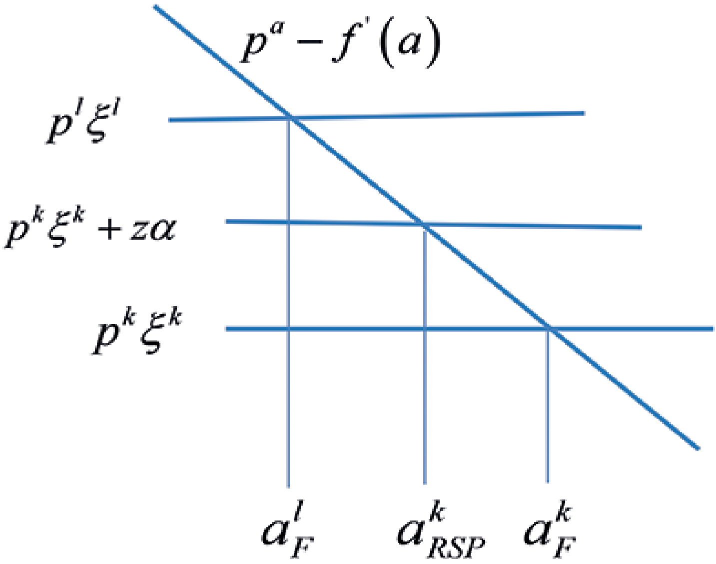

Figure 2: Optimal hauling distance within the livestock farm

price of manure (shadow price for land constraint could be determined in similar vain with slightly different interpretation). With crop choice 2, the hauling distance is d_{on}^2. With crop choice 1, the farmer would be willing to apply manure up to distance d_{on}^1 but there is not enough manure to do so: the quantity constraint sets the hauling distance to $\bar{d}_{on}$. The shadow price is given by the vertical shift of the marginal hauling cost curves to make it cross the (horizontal) marginal benefits at $\bar{d}_{on}$. It can be read directly from vertical axis.

Conditions determining the optimal hauling distance on the crop farm (8) resemble those on the livestock farm. The marginal benefit is the price obtained from manure, determined by the crop choices of the crop farmer. There are three shadow prices. The shadow price for the manure is the same as above and the shadow value of the land constraint is the negative of the land constraint for the livestock farmland ($\lambda_3 = -\lambda_2$). If a marginal increase in the land area controlled by the livestock farm increases livestock farmer's profits by λ_2, decreasing it by the same amount decreases the profits equally. If the land constraint on crop farm is binding, the entire agricultural land can not be sufficiently large to absorb generated manure nutrients (the opposite is not true however: even though the land area would not be enough to absorb all generated nutrients, the land constraint might not be binding); and $\lambda_4 > 0$.

Depending on scarcity of manure or land on- and off-farm, there are altogether eight different combinations. The optimality conditions simplify differently, depending on the case. We discuss all eight cases in the Appendix. Henceforth, we will focus on the cases with the highest political relevance. Such cases share the following features: 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.

2.4 Social Planners' Solutions

This section discusses the maximization problems and optimal solutions of the two alternative social planners. The global social planner takes into account externalitites in both regions. The rural social planner omits the effects on the surface water quality on the recreational region.

2.4.1 First order conditions

The first order conditions are presented in Table 2. With the optimal number of animals the rural social planner acknowledges the externalities on surface and groundwaters from the marginal increase of nitrogen residuals $\left(\frac{\partial E^S}{\partial R^N} + \frac{\partial E^G}{\partial R^N}\right)\frac{\partial R^N}{\partial a}$ and the effect of phosphorus residual on surface water quality $\frac{\partial E^S}{\partial R^P}\frac{\partial R^P}{\partial a}$. The global planner takes into account both regions, i.e. substitutes the term $\frac{\partial E^S}{\partial R^P}\frac{\partial R^P}{\partial a}$ with $\left(\frac{\partial E^S_A}{\partial R^P} + \frac{\partial E^S_R}{\partial R^P}\right)\frac{\partial R^P}{\partial a}$. The optimal choices of on- and off-farm hauling and application as well as for manure dumping are given in the similar fashion.

The externalities from dumping manure either on the livestock farm or on the crop farm are identical. Since the costs of dumping on the livestock farm are (assumed to be) zero, both planners choose trivially $x_{off} = 0$. The optimal dumping on farm is

Table 2: **Rural (RSP) and Global (GP) Planners' Optima.**

(a^*)	**RSP**	$p^a = f^{'}(a) + p^k \xi^k + \left(\frac{\partial E_A^S}{\partial R^N} + \frac{\partial E^G}{\partial R^N}\right)\frac{\partial R^N}{\partial a} + \frac{\partial E_A^S}{\partial R^P}\frac{\partial R^P}{\partial a}$
	GP	$\ldots + \left(\frac{\partial E_A^S}{\partial R^N} + \frac{\partial E^G}{\partial R^N}\right)\frac{\partial R^N}{\partial a} + \left(\frac{\partial E_A^S}{\partial R^P} + \frac{\partial E_R^S}{\partial R^P}\right)\frac{\partial R^P}{\partial a}$
(d_{on}^*)	**RSP**	$\left(\gamma_{on}^k p^N + \delta_{on}^k p^P + g\right) = \frac{2\varphi d_{on}\gamma^k}{\alpha} + \lambda_2 + \left(\frac{\partial E_A^S}{\partial R^N} + \frac{\partial E^G}{\partial R^N}\right)\frac{\partial R^N}{\partial d_{on}} + \frac{\partial E_A^S}{\partial R^P}\frac{\partial R^P}{\partial d_{on}}$
	GP	$\ldots\left(\frac{\partial E_A^S}{\partial R^P} + \frac{\partial E_R^S}{\partial R^P}\right)\frac{\partial R^P}{\partial d_{on}}$
$\left(d_{off}^*\right)$	**RSP**	$\left(\gamma_{off}^k p^N + \delta_{off}^k p^P + g\right) = \frac{2\varphi d_{off}\gamma^k}{\alpha} - \lambda_3 + \lambda_4 + \left(\frac{\partial E_A^S}{\partial R^N} + \frac{\partial E^G}{\partial R^N}\right)\frac{\partial R^N}{\partial d_{off}} + \frac{\partial E_A^S}{\partial R^P}\frac{\partial R^P}{\partial d_{off}}$
	GP	$\ldots\left(\frac{\partial E_A^S}{\partial R^P} + \frac{\partial E_R^S}{\partial R^P}\right)\frac{\partial R^P}{\partial d_{off}}$
(x_i^*)	**RSP**	$x_{off} = 0; x_{on} \geq 0$
	GP	$x_{off} = 0; x_{on} \geq 0$

defined by the other optimal choices: $x_{on}^* = qa^* - M_{on}^* - M_{off}^* \geq 0$.

For each potential crop, the decision maker defines the optimal choice variables. After this, she chooses the crop that produces the highest welfare at the optimum.

The asymmetry of damages between the regions and the discrete crop choice yields interesting results. Consider a situation where after optimizing, the private farmer and the rural social planner end up choosing differently out of two alternative crops, k and l. Proposition 1 shows that in some cases regional regulation may lead to increasing production, i.e. higher optimal animal numbers when compared to the unregulated case:

Proposition 1. *If*

i) $p^k\xi < p^k\xi + E_N R_a^{N*} + E_P R_a^{P*} < p^l\xi$

ii) $\pi_P^{l*} > \pi_P^{k*}$

iii) $\pi_{RSP}^{l*} < \pi_{RSP}^{k*}$

$\Rightarrow a_{RSP}^* > a_P^*$

Proposition 1 states that the Rural Social Planner's optimal solution has more pro-

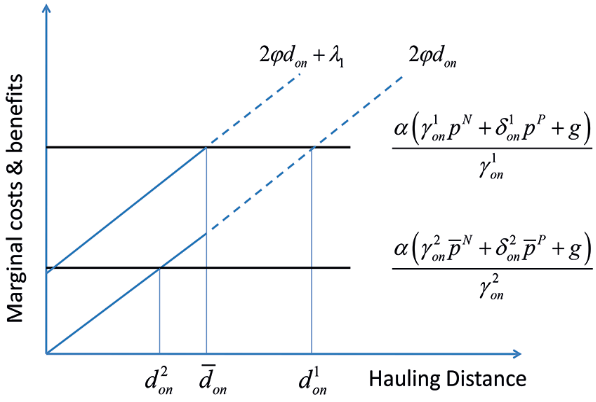

Figure 3: Rural Social Planner solution may increase the number of production animals

duction animals than the livestock farmer's privately optimal solution $\left(a^*_{RSP} > a^*_P\right)$ if conditions $i) - iii)$ hold. Conditions $ii)$ and $iii)$ state that the livestock farmer and the rural planner gain highest welfare when choosing crops l and k, respectively. Condition $i)$ follows from the optimality conditions for the number of animals. It states that the privately optimal number of animals for crop k is higher than for crops l, but that the rural planner's optimal number of animals for crop k is higher than the privately optimal for crop l (but lower than the privately optimal amount under crop k). The proof is given in the appendix.

Naturally, it is always the case that for any given crop, the social planner chooses less animals at the optimum than the private farmer. What proposition 1 states is that it may be the case that taking externalities into account may induce a change in crop from l to k to increase the uptake of either of the nutrients, and hence reduce residual nutrients. And whilst the rural social planner always chooses less animals than the private farmer for any given crop, she might choose higher number of animals than the private farmer if the crop choices are different. Figure 3 illustrates the situation for a case where the agricultural area suffers only from nitrogen loads; and where the damage function is linear with marginal damage equal to z.

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 l. The lowest horizontal curve corresponds to private solution under crop k. The intersection with the horizontal line in the middle denotes the optimal number of production animals associated with the rural social planner and crop k. In addition to feeding costs, it includes the marginal environmental damages of a production animal.

Proposition 1 presents an intriguing, even counterintuitive result: There may be cases where regulation increases the production intensity. In such a case, the social planner ends up choosing a crop with lower residuals of the nutrient of interest; lower profits for the farmer, but lower price for feed per one production animal. Why would the private farmer choose l over k if a unit of fodder based on the latter is less expensive? The marginal effect on animal numbers depends only on the price of buying (or selling) a unit of feed. The crop is chosen based on its effects on overall profits: it might for instance be that fertilizer costs outweigh the savings in per unit feed costs.

However, it is always the case that regulation decreases the generation of those externalities that initially trigger regulation, i.e. $E_{A,RSP} < E_{A,F}$ — and decreases private profits. The regional conflict emerges from the differences in how externalities affect the environmental quality. In extreme cases, the agricultural area is interested only in regulating nitrogen (phosphorus) while the recreational region would be only interested in regulating phosphorus (nitrogen). The following propositions establish the.

Definition 1. *Nitrogen and phosphorus loads to recreational region are given by*

$$R^N \equiv \varpi_N \left(\alpha qa - \gamma^k_{on} d_{on} - \gamma^k_{off} d_{off} \right)$$

$$R^P \equiv \varpi_P \left(\beta qa - \delta^k_{on} d_{on} - \delta^k_{off} d_{off} \right)$$

Remark 1. *Assume that nitrogen is both the focus of environmental protection in the agricultural region and the relatively scarce nutrient. Then it holds that:* $R^N_{RSP} < R^N_F$

Remark

Remark 2. *If crop choices of rural social planner and the private farmers are identical, it holds that:* $i) a_{RSP} < a_F$

That is, the residual nitrogen under rural social planner's solution is always lower than the residual nitrogen under private solution.

Proposition 2. *The rural planner's optimum may be associated with either higher or lower phosphorus residuals (in both regions) than the private farmers' optimum.*

Proof. If the crop choices are identical $k_{RSP} = k_F$, it always holds that $R^P_{RSP} < R^P_F$, i.e. the residual phosphorus in the recreational region is always lower under the rural social planner's solution. This follows from the fact that the rural planner always generates less (here) nitrogen residuals than the private farmers (see Proof of proposition 1). If the per acre crop uptakes are unchanged, the phosphorus residual has to decrease too.

With $k_{RSP} \neq k_F$ it is possible that $R^P_{RSP} > R^P_F$, even if the per phosphorus requirement of the rural planner's crop choice would be higher than private farmer's, i.e. $\delta_i^{k_{RSP}} > \delta_i^{k_F}$. Whenever $\left(\beta q a^k_{RSP} - \delta^k_{on_{RSP}} d_{on_{RSP}} - \delta^k_{off_{RSP}} d_{off_{RSP}}\right) > \left(\beta q a^l_F - \delta^l_{on_F} d_{on_F} - \delta^l_{off_F} d_{off_F}\right)$, the rural planner's solution increases the phosphorus residual in both regions. Whether this is the case depends on all above variables. It may, for instance, be the case that the rural planner's crop choice increases the nitrogen uptake and thereby increases the per acre application intensity. If the increase in nitrogen requirements is sufficiently higher than in the phosphorus requirements, the per acre residual may increas. Then it is up to the production intensity (number of animals increases or decreases) whether the total residuals increase.

□

Proposition 2 states that the Rural Social Planner's solution may be associated with higher residual phosphorus entering the recreational region. This, in turn, can lead to higher or lower environmental damage (E) in the recreational region, as stated in the following Proposition:

Proposition 3. *If $R^P_{RSP} > R^P_F$, either $E_R\left(R^N_{RSP}, R^P_{RSP}\right) < E_R\left(R^N_F, R^P_F\right)$ or $E_R\left(R^N_{RSP}, R^P_{RSP}\right) \geq E_R\left(R^N_F, R^P_F\right)$*

Proof. i) Direct calculation

□

Proposition 3 states that if the phosphorus residual increases in the Rural Social Planner's solution, it may or may not be associated with higher environmental damage in the recreational region than the private solution. This depends on the ecological characteristics of the surface waters. If eutrophication depends on phosphorus loading only, increasing residuals mean increasing damages. But it is also possible that increasing phosphorus loading decreases damages, if nitrogen loading decreases sufficiently at the same time.

Finally, if the environmental damage indeed increases, it may be the case that the overall welfare either increases or decreases as a consequence of the rural planner's optimal solution. Let us first define:

Definition

Definition 2. *The global social welfare is given by*
$\pi_{on} + \pi_{off} - E_A - E_R$
Denote the global welfare associated with the Rural Social Planner's and farmers' optimal choices by W_{RSP} and W_F

Proposition 4. *If $E_R\left(R^N_{RSP}, R^P_{RSP}\right) > E_R\left(R^N_F, R^P_F\right)$ either $W_{RSP} < W_F$ or $W_{RSP} \geq W_F$*

Proof. i)Direct calculation

□

It may thus be that rural planner's policy decreases the global welfare. This happenes if the increases in increased costs from environmental protection in the agricultural region and increased damages in the recreational region outweight the reductions in the damages experienced in the agricultural region. Whilst the second case could be made Pareto efficient with monetary transfers from the agricultural region to recreation region, in the third case this would not be possible: it represents a case where rural agri-environmental policies unambiguosly decrease the global welfare.

3 Instrument analysis

The first best instruments make farmers undertake the socially optimal actions. Under full information, the social planner may pose quantity restrictions on production animals, subsidies for manure hauling, taxes for manure disposed in excess of crop's needs (x_i) and mandate the optimal crop choices. In our model, the different objectives of the two social planners add an interesting twist to instrument analysis. Namely, if the rural planner chooses suboptimally from the global perspective in the first place, the same suboptimality will carry over with first best instruments. Situation is different with second best instruments. As it turns out, an instrument second best for the rural social planner (nitrogen tax) might be preferrable to rural planner's first best instrumtn from the global welfare perspective. This generates a very robust policy recommendation in favor of the tax: it erases the regional conflict while maintaining the regional primacy. However, the effectiveness of a fertilizer tax is limited for the same reason as before: the farmers may react by changing the crop. If all regions have identical damage functions, this handicap might become important.

We analyze two second best instruments: tax on nitrogen fertilizer and nutrient management plans. We analyze these from the rural planner's perspective and examine how the unindented increase in phosphorus loading to recreational region carries over when using either of the instruments. Both can be implemented on both on the livestock farm and on the crop farm. With current regulation, however, the (binding) nutrient management plans face only the livestock producers.

3.1 Nitrogen Tax

How would the rural social planner set the tax on nitrogen in chemical fertilizer? Again, all eight cases would provide technically different but qualitatively similar results. A nitrogen tax is similar for the livestock and for the crop farm. Therefore, we analyze the simplest case: the one where the livestock farmer applies manure on part of her own land, deposits some, does not export anything and applies manure on the basis of its nitrogen concentration.

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. This procedure can be used to find the boundaries where the rural social planner operates when setting the tax rate.

A nitrogen tax increases the price of nitrogen fertilizers. To conduct comparative statics, rename the livestock farmer's optimality conditions for the number of animals and for the hauling distance: $Q \equiv p^a - f'(a) - p^i \xi - z\alpha q = 0$ and $G \equiv \left(\gamma^i_{on} p^N + \sigma^i_{on} p^P + g - \frac{2\varphi d_{on}\gamma^i}{\alpha} + z\right)$ yielding

$$\underbrace{\begin{bmatrix} -f'' & 0 \\ 0 & \frac{-2\varphi\gamma^k}{\alpha} \end{bmatrix}}_{A} \times \begin{bmatrix} \frac{da}{dp} \\ \frac{dd_{on}}{dp} \end{bmatrix} = \begin{bmatrix} 0 \\ -\gamma \end{bmatrix} \tag{11}$$

We obtain $\frac{da}{dp} = 0$ 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? [12] The higher the crop recuirement for nitrogen, the higher the marginal effect of fertilizer price increase to profits. That is, increasing fertilizer prices creates incentives to change the crops to less nitrogen requiring ones. The rural

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[12] The direction could be seen directly from 2: a tax increases the per acre costs of chemical fertilization and therefore makes it profitable to haul and apply manure on a larger area.

social planner — trying to lower the nitrogen residual — does not want the see the farmer to switch to crops that recuire less nitrogen. This would increase the nitrogen residuals from 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

$$\pi_\tau^k - \pi^s = 0 \Leftrightarrow -\left(\gamma_{on}^k \left(p^N + \tau_k\right) + \delta_{on}^k p^P + g\right)\left(b_{on} - d_{on}\right) - p^k\left(\xi^k a - y_{on}^k b_{on}\right) - h\left(M_{on}^k, d_{on}^k\right)$$
$$+\left(\gamma_{on}^s p^N + \delta_{on}^s p^P + g\right)\left(b_{on} - d_{on}\right) + p^s\left(\xi^s a - y_{on}^s b_{on}\right) + h\left(M_{on}^s, d_{on}^s\right) = 0$$

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 and never incourages 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, is therefore an empirical question. It is, however, a qualitatively robust results that it doesn't allow for regional conflict. (David Doug: should that be made a proposition?)

3.2 Nutrient Management Plans

In U.S., nutrient management plans (NMP) are the most widely used regulatory instrument to curtail nutrient loading from animal production. Plans may be based either on nitrogen or phosphorus standard. Under nitrogen standard, the livestock farmer may apply nitrogen with manure only up to the level of nitrogen uptake of the crop. [13]

Assuming nitrogen as the relatively scarce nutrient, it is easy to introduce the nitrogen standard for livestock farms into our model: it simply requires that $x_{on} = 0$. To

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[13] Not all manure nitrogen is in plant available form. Part of plant available nitrogen is also lost during the various phases manure has to undergo before it is actually uptaken by crops. Therefore, the nitrogen standard actually sets a lower boud 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.

see this, 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. We defined dumping x_i, on the other hand, as the manure application in excess of crop nutrient requirements, reagrdless of its location within the livestock farm x_{on} or within the crop farm x_{off}. A nutrient management plan based on nitrogen standard imposed on a livestock farm where nitrogen is the relatively scarce nutrient thus imposes $x_{on,NMP} = 0$.

The most interesting — and most practically relevant cases — is one with scarcity on own land $(\lambda_2 > 0)$. In this case nitrogen residual on-farm is positive (i.e. $(x_{on} > 0)$, i.e. the livestock farmer overapplies manure on own land to some extent. The precise location of overapplication does not alter the quantity of residual nutrients generated, and hence does not influence the level of externalitites. Imposing a nutrient standard creates twofold incentives. Firstly, keeping the crop choice fixed, it incentivizes the livestock farmer to shift dumping to the crop production area, i.e. to choose $\left(x_{off,NMP} = x_{on}\right)$. There are no incentives to haul manure any longer distances, since the price paid by the crop farmer would not cover hauling costs.

Secondly, the nutrient standard incentivizes the livestock farmer to switch the crop. There might still be positive dumping off-farm but to a less extent. The livestock farmer is willing to face lower overall profits associated with a new crop with higher nitrogen uptake, if the decrease in profits is lower than costs of the alternative compliance strategy, dumping off-farm only. The following proposition summarizes the case with binding land constraint.

Proposition 5. *If imposing a nitrogen sandard under binding area constraint induces a change in crop, the phosphorus loading from agricultural region either increases or decreases. If the standard induces no switch, it does not affect either nitrogen or phosphorus loading but only lowers the profits of the livestock producer.*

Proof. $i)$Unfinished

□

The intuition of proposition is the same as with rural planner's solution. In what comes to increases in phosphorus loading in recreational region, environmental damage in recreational region or overall welfare in both regions as a result of imposing NMP, propositions 2 — 4 apply

4 Extension to manure management and handling technologies

Obviously, the nutrient concentration of manure is not exogenous. Feed choices, manure handling, storage and application technologies would all affect (α) and (β). The common feature for all these choices is that they may change both the absolute and relative amounts of nutrient concentration in manure.

Depending on the production animal, there is some feasible range of phosphorus and nitrogen the manure contains when it is excreted by the animal. To some extent, these concentrations can be altered by feed choices. After the manure is excreted, there are several ways to again alter the concentration. Certain separation techniques, for instance, can be used to increase the nutrient concentration of the manure (separate water from manure); leaving the manure unincorporated while applying it will decrease the nitrogen concentration as part is lost to atmosphere etc. The farmer may thus increase or decrease the nutrient concentration of manure within the feasible range characteristics for each production animal. Increasing nutrient concentration reduces hauling costs of a nutrient unit and makes it more competitive against mineral fertilizers.

Without explicitly defining the means to do it, we assume that all these measures can be arranged into a production animal specific implicit cost function for choosing nutrient concentration of manure. We need to assume that such functions are convex, continuous and twice differentiable. The simplest candidate is a second order polynomial with a positive second order coefficient. The minimum point of the function can be scaled to yield zero costs. This way, any other nutrient concentration will be costly for the farmer. The higher the change in nutrient concentration in either direction, the more costly it will be for the livestock farmer. For simplicity, we assume that the cross derivatives are zero. We show the modified optimization problem in the appendix and present here only the proposition summarizing the results:

Proposition 6. *Under no regulation, there are no incentives for the livestock farmer to alter the nutrient concentration of the nutrient* ***not*** *relatively scarce. When utilizing manure, the farmer has incentives to increase the nutrient concentration. The optimal concentration is given by (here for nitrogen, similar solutions for phosphorus):*

$$\frac{\partial t}{\partial \alpha} = \lambda_1 \left[\frac{d_{on}\gamma^i_{on}}{\alpha^2} + \frac{d_{off}\gamma^i_{off}}{\alpha^2} \right] + \frac{\partial h}{\partial M_{on}} \frac{d_{on}\gamma^i_{on}}{\alpha^2} + \frac{\partial h}{\partial M_{off}} \frac{d_{off}\gamma^i_{off}}{\alpha^2}$$

proof *Appendix*

The optimal nutrient concentrations depened on which of the two nutrients is relatively scarce. If nitrogen is relatively scarce, there are no incentives to alter the phosphorus concentration of manure from its default level and vice versa. Since the conditions are symmetric it is enough to discuss the one defining the optimal nitrogen concentration. Marginal costs of changing the nitrogen concentration are $\left(\frac{\partial t}{\partial \alpha}\right)$. The marginal benefits are due to changes in hauling costs. It takes less manure per acre to satisfy crops' needs for the relatively scarce nutrient with higher concentrations. The marginal savings are collected from both areas if manure is applied there. Whether the constraint of, say, arable land under the control of the livestock farm (b_{on}) is binding or not does not affect the optimal nutrient concentration. The marginal savings in hauling costs are capitalized regardless of the constraints on land. The intuition of the shadow price term is unclear. If manure is scarce, incentives to elevate the concentration increase.

5 Discussion and Policy implications

We have posteluated a model which highlights caveats in regionally non coordinated regulation of manure nutrients. We have shown that tightening regulation in upstream region may increase nutrent loading in the downstream region; it may increase externalities in the downstream regiona and it may even lower the total welfare of upstream and downstream regions. Taxes on chemichal fertilizer provide a means to regulate residua nutrients without this conflict, but the feasible bounds of taxes may limit the efficiency of regulation. Nutrient management plans shows serious weaknesses: they may be completely ineffective is area constraints are binding, and if the nutrient standards are confined to livestock farms.

Despite the fact that there are ways to commensurate nitrogen and phosphorus loading into a single component according to their effect on eutrophication, (most widely used the Redfield ratio (Wetzel 2001)), there have been no analyses to combine these two pollutants in manure regulation. The ratios are watershed specific. For instance, similar nitrogen loading rates to the Potomac River and Narragansett Bay are associated with very different water qualities in the mesohaline portions of the receiving waters (Magnien et al 1990, Nixon et al 1986).

There are obvious extensions to our analysis. We assumed that a fraction ρ of cropland is suitable for manure application. There are technical and crop specific reasons for suitability, but also reluctancy of crop farmer's to apply manure on their crops. An often cited reason for farmers' unwillingness to accept manure is their uncertainty regarding nutrient concentration of manure and the plant availability of the nutrients it contains. Crop farmers' willingness to accept manure is often found crucial for livestock farmers' compliance costs (Ribaudo and Agapoff 2005; Kaplan et al 2004).There are, however, only few quantitative estimates on crop farmers' willingness to substitute commercial fertilizers with manure (Norwood et al 2005 on swine manure one of the few). An interesting extensions of the model would be to allow for heterogenous believes about nutrient needs of crops. In this case, the actual application rates would vary. Also, setting the nutrients standard, i.e. κ would affect the farmer's willingess to accept manure if NMP would constrain manure usage on crop farms. If κ would be lower than the farmer considers necessary to cover the nitrogen needs, the farmer would accept manure only if its price would be low enough to allow for treating the same areas with additional chemical fertilizers, unless this were also forbidden. In either case, the willingness to accept manure would effectively become a function $\rho(\kappa)$. Be tightening the standard (lowering κ) the regulator would decrease the ratio of cropland suitable for manure, thereby increasing compliance costs even without any effects on crop yields (standards set too low to enable the livestock farmer to generate sufficient yileds would be another source of compliance costs). This would creaste welfare losses and also increase to incentives for noncompliance.

The principals of livestock production and the problem of excess nutrients are fairly identical in developed countries. The detrimental effects of the nutrient loads in the receiving environments, however, are very different in different regions. If the problems are primarily in groundwater quality or on surface waters sensitive to nitrogen, policies have focused on nitrates but if they are related to eutrophication in phosphorus sensitive areas, the focus has been on phosphates in manure. There are two things that make this feature interesting. Firstly, most of the commonly used measures to reduce nitrogen in manure increase its relative phosphorus concentration, i.e. do not change its phosphorus content. If restrictions for land applications of manure are based on nitrogen and they are binding, nitrogen abatement increases accumulation of phosphorus. Secondly, there are areas with overlapping problems. Areas which might need to be analyzed using our framework include the Baltic Sea with many surrounding countries, Chesapeak Bay an northern part of the Gulf of Mexico.

All appendices available upon request from the corresponding author

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