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A linear optimisation model for animal farm manure transports in regions with high intensity animal farming

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Abstract: In several districts of a high intensity animal farming region in north-west Germany, animal farm manures are in surplus to what can sustainably be used on the existing farm land. Export to other districts is necessary but costly, especially for manures with high water contents. In another part of north-west Germany, intensive arable farming requires input of energy-intensive and expensive mineral fertilizers.

Thus, the aim of this study is to develop a model capable in optimizing the distribution and transports of the animal farm manures in and between the districts of Lower Saxony at lowest costs. The model aims at avoiding manure over-application in the surplus districts and at the same time making use of the fertilizer value in districts with lower animal densities.

Data used for the modelling are the actual numbers of farm animals as well as land use data within each district. The specific average nutrient contents in the different animal farm manure are considered, too, as are average nutrient demands of the different land uses. The modelling language is GAMS. The model is linked to an Excel template serving as an interface for data input and result visualization. Scenarios can be defined by setting constraints on manure nutrient application. The constraints impact on the extent of manure distribution across the districts in Lower Saxony and the exports from surplus districts which are involved in the optimized distribution. The kind of manure that is exported and the distance over which it is transported is a result of the manure nutrient contents, the manure mass and of the distances between the districts.

The modelling of individual scenarios is supposed to reveal the impacts of changing constraints on the overall optimal solution of animal farm manure transports in Lower Saxony (e.g. impacts of national policies or of selected good farming practices). Thus, the model allows the definition of a pool of most efficient animal farm manure management options.

The newly developed linear optimization model has proven capable in simulating the optimization of animal farm manure flows to the available agricultural acreage on a regional level while considering a set of constraints. Additional features of the model will include processing steps altering the composition of the manures (e.g. biogas production, manure separation techniques). In a future step, the model will be modified to be used by policy makers and extension workers. Consequently, based on this explorative model, a regional material flow management for farm manures in general will enable a reasonable substitution of often expensive, limited and energy-intensive mineral fertilizers with animal farm manures in districts with little animal farming. At the same time, environmental problems caused by manure over-application will be diminished. Hence, the model setup can contribute considerably to environment and climate protection.

Keywords: *Linear optimization, spatial modelling, manure nutrients*

1. INTRODUCTION

In Lower Saxony, a federal state in Germany comprising 2.6 million hectares of agricultural acreage, two major agricultural production zones can be distinguished. While intensive arable farming prevails in the federal state's south-east and east, the north-western part of Lower Saxony is dominated by dairy farming and high intensity animal agriculture. Here, farm animal densities are high and so are nutrient quantities from animal farm manures.

Long-term over-application of animal farm manure in those districts resulted in massive nitrogen leaching from soils to groundwater and surface water and to phosphorous (P) enrichments in soils. Since fertilizer use on the farm level has been regulated by the German Fertilizer Ordinance which implements the European Nitrates Directive, a threshold limit exists for the application of animal farm manures equivalent to 170 kg of nitrogen (N) per hectare per year (DüV, 2007). Surplus animal farm manures in the high intensity animal farming areas are now exported to farms in areas with lower animal densities (Warnecke et al., 2008). Relocation of manure nutrients is particularly costly for slurries with high water contents. Logistics are expensive, too.

While there is a nutrient surplus problem from manures in the animal farming region, arable farming requires large quantities of nutrients. The demand is currently either covered by mineral fertilizers or limited sources in the soils themselves. The global phosphorous sources are finite and the quality of the mineral phosphorous fertilizers is partially deteriorating. The production of mineral nitrogen fertilizers is highly energy demanding, making them expensive and a considerable factor with respect to climate change. Hence, the situation of Lower Saxony's agriculture, like many other regions around the globe, exhibits a distribution problem of valuable fertilizer nutrients due to a spatial imbalance in demand and availability.

Thus, the aim of this study is to develop a model capable in optimizing the distribution and transports of the animal farm manures in and between the districts of Lower Saxony at lowest costs. The model aims at avoiding manure over-application in the surplus districts and at the same time making use of the fertilizer value in districts with lower animal densities. Unlike many other models that deal with manure surpluses on the farm level, de Mol and Beek (1991) presented a modelling approach for the regional level. However, they did not consider any actual transport distances. Besides the distance and the nutrient issues, our modelling of individual scenarios is supposed to reveal what impacts most on the overall extent of animal farm manure transports in Lower Saxony (e.g. impacts of national policies or of selected good farming practices). Additionally, the model acts as a step towards a regional material flow management of animal farm manures as opposed to the current farm-individual manure management.

2. METHODS

On basis of Biberacher (2007) and Warnecke et al. (2008), a linear optimization model is developed to solve the following distribution problem: various animal farm manures are to be distributed to different agricultural crop lands and grasslands in individual spatial units of a model region. The modelling language is GAMS (General Algebraic Modelling System). GAMS is a system for mathematical programming and optimization for dealing with large scale problems. The model is linked to an Excel template for data input and result visualization. The constraints for manure distribution are individually defined for single scenarios. The model output is the optimal manure distribution to the agricultural land and the minimal manure transports between all spatial units at lowest overall costs. This also leads to the definition of manure nutrient deficient or surplus spatial units. For this study, the model was applied to the federal state of Lower Saxony, Germany.

2.1. Notation and Units

Indices, variables and parameters considered in the model are outlined in Table 1.

Table 1. Notations for indices, variables and parameters as used in the relations and equations of the model.

Indices	
s :	spatial unit
r :	spatial unit different from spatial unit (s)
n :	nutrient
c :	crop class
h :	farm animal class
Variables	
$\boldsymbol{d}_{s,c,h}$:	application of manure of farm animal class (h) on crop class (c) in spatial unit (s)
$\boldsymbol{t}_{s,r,h}$:	transport of manure of farm animal class (h) from spatial unit (s) to another spatial unit (r)
$\boldsymbol{ex}_{s,h}$:	global export of manure of animal class (h) from spatial unit (s) beyond the model region (slack variable)
Parameters	
$l_{n,c}$:	specific nutrient (n) constraint for crop class (c)
$a_{s,c}$:	total area of crop class (c) in spatial unit (s)
$b_{h,n}$:	specific nutrient (n) content of manure of farm animal class (h)
$u_{s,h}$:	number of animals in farm animal class (h) in spatial unit (s)
m_h:	annual amount of manure of one unit of farm animal class (h)
$w_{s,r}$:	distance between spatial units (s) and (r)
k:	specific transport costs (costs per distance unit and mass unit)
p:	global specific transport costs (costs per mass unit) for transports beyond model region

Table 2. Basic model assumptions (a and b) and the interrelation of assumptions and results (c) (notations of expressions used in the model equations and relations in '…' – also refer to Table 1)

a) Each spatial unit can provide nutrients (nitrogen, phosphorous) from animal husbandry:	b) Each spatial unit comprises areas of various land uses:	c) The extent to which the manures are transported depends on:
• The model has 29 'farm animal classes' with corresponding animal farm manures ('manures'). • Manures form a stock of local nutrients and can be used to cover some or all of the local crop nutrient demand. The term *local* refers to the crop class or farm animal class with its manure in an individual district.	• Land use is described as 'crop classes', containing both grasslands (2 classes) and the crops grown on arable land (14 classes). • 'Crop classes' are given as area per district. • Each 'crop class' has an individual specific nutrient demand. The model considers nitrogen and phosphorous demand.	• Local manure production, • Scenario constraints regarding manure nutrients application defined in the model, and • Manure availability after transportation between districts as depending on scenario constraints.

2.2. Input parameters

Prior to the actual modelling, the relevant factors generally impacting on animal farm manure transports and their costs were determined. These are quantity and quality (nutrient and water content) of the manures produced and the capacity of land use systems to utilize manure as fertilizer.

Data and information on the factors with a dominant impact on manure amount and composition were derived from various sources and integrated into an Excel-based data base. Data considered were district level data on number of farm animals sorted by species, use, age, and weight (LSKN, 2004, TSK, 2008), and additional federal state level information on farm animal productivity, intensity of animal husbandry, and feeding strategy. The data were then combined with the general reference values on nutrient excretion of farm animals (LWK, 2007). The average amount of manure produced by the animals in the different categories was also taken from LWK (2007). A simplifying assumption was made for the type of manure produced: all pig and all cattle manure was considered being slurry, all poultry manure was considered being solid manure. Small ruminants are not considered in this setup of the model.

Information on land use was taken from district level data sets from official agro-statistics (LSKN, 2008a). A combination of the land use data with federal state level average yield levels of the individual crops and grasslands (LSKN, 2008b) and fertilizing advice regarding nitrogen and phosphorous (LWK, 2008) resulted in the determination of nutrient demand of the crop land and grasslands. Like the modelling itself, the input parameters were determined for the district level and for the years 2007/2008.

2.3. Assumptions for the modelling

The model aims at optimising animal farm manure distribution in and transport between spatial units (districts) in a model region (federal state). It considers constraints for the application of manures to agricultural acreage as well as transportation costs. The model assumptions are listed in Table 2.

2.4. Relations and equations: Manure distribution and transports

The model is implemented as linear optimisation model. The relations and equations in the model use the notation shown in Table 1. Relation (1) describes the combination and amount of manure applied to each of the crop classes in each of the spatial units. It prevents exceeding constraints for manure nutrient application. The constraints can be defined and altered for individual scenarios.

$$\Sigma_h\ (\boldsymbol{d}_{s,c,h} * b_{h,n}) \leq l_{n,c} * a_{s,c} \qquad \text{for all } s, n, c \quad (1)$$

For each spatial unit in the model region, equation (2) equates locally available manures and manures imported from other spatial units with local manure application, manures exported to other spatial units and manure transports beyond the model region (***ex***). The latter is only accounted for if total regional manure production exceeds total regional manure application capacity which is determined by the model constraints.

$$\Sigma_r\ (\boldsymbol{t}_{r,s,h}) + u_{s,h} * m_h = \Sigma_c\ (\boldsymbol{d}_{s,c,h}) + \Sigma_r\ (\boldsymbol{t}_{s,r,h}) + \boldsymbol{ex}_{s,h} \qquad \text{for all } s, h \quad (2)$$

The objective of the model is to find a cost optimised solution for the whole model region (sum over all spatial units (s)). The objective function (3) of the model sums up all costs that are considered in the model setup.

$$\text{Min}\ \ \Sigma_{s,r,h}\ (\boldsymbol{t}_{s,r,h} * w_{s,r} * k) + \Sigma_{s,h}\ (\boldsymbol{ex}_{s,h} * p) \quad (3)$$

Costs considered so far are the 'specific transport costs', consisting of a distance element (represented by the centroidal distances between the districts) and a mass element (represented by the mass of manure). This enables the model to weight transportation between spatial units. Since the optimisation model

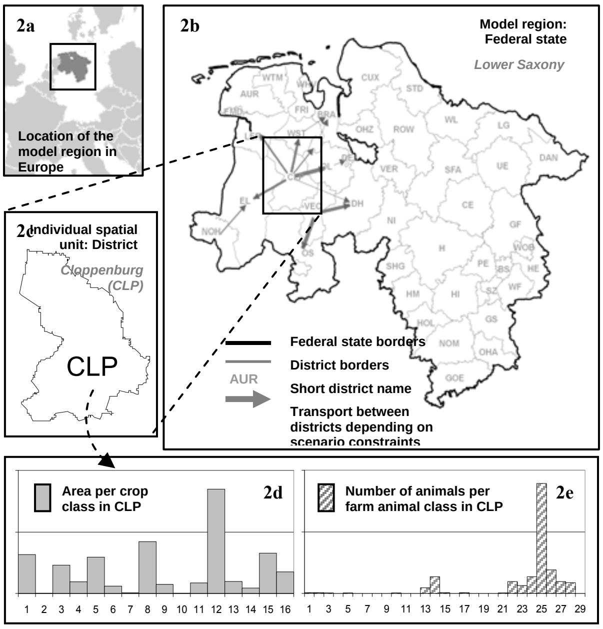

Figure 2. Spatial setup of the model. Model region is the federal state of Lower Saxony, north-west Germany (2a, 2b), with its administrative districts forming the individual spatial units of the model (2c). Input data per district are the acreage of ‘crop classes’ (2d) and number of animals per ‘farm animal class’ (2e). Model results after scenario definition are manure flows from manure nutrient surplus to deficient districts (2b).

is linear and no real costs have yet been determined for the objective function (3), an arbitrary value >0 was chosen. Global transport costs for transport beyond the model region (***ex***) are the costs for any ‘global export’ of manure beyond the region. The ‘global export’ keeps the model feasible for scenarios which, by fulfilling the constraints, lead to excess manure nutrients in all spatial units of the model region. Therefore, these costs (p) are set extremely high compared to the transport cost between spatial units in the model region.

Running the model according to the constraints results in an output file that lists the two elements involved in achieving a cost-optimization:

- manure distribution over the crop classes in each spatial unit
- manure transports between the spatial units.

The model has been applied for the federal state of Lower Saxony in Germany. The spatial units are the 45 administrative districts of Lower Saxony, each with a maximum of 16 ‘crop classes’ and 29 ‘farm animal classes’ serving as input data for the model (Figure 2).

3. RESULTS

3.1. Constraints

Two scenarios were developed and calculated for this study:

SCENARIO 1 serves as a reference scenario. Constraints are basic and reflect minimum good farming practices and minimum legal standards:

- Animal farm manure nitrogen may not exceed the application limit of 170 kg N ha^{-1} defined by the German Fertilizer Ordinance.
- Nitrogen and phosphorous demand of the individual crop classes may not be exceeded by animal farm manure nitrogen and phosphorous.

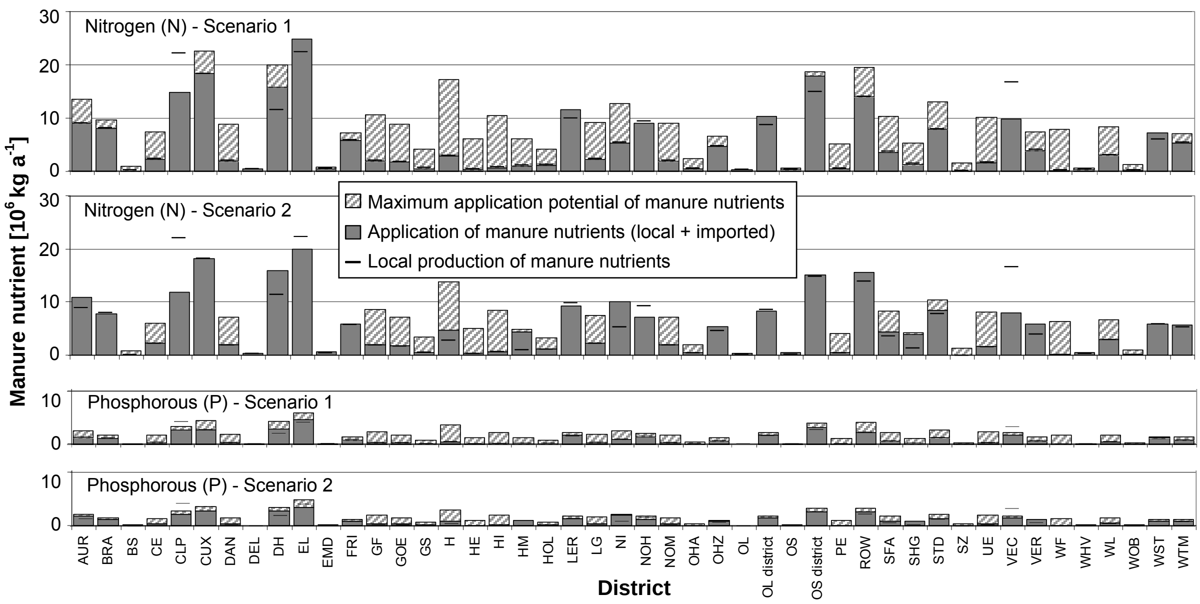

Figure 3. Maximum manure nutrient (N, P) utilization capacity of each district (dashed bars) and manure nutrient distribution resulting from the cost-optimized manure distribution and transports (filled bars) as defined by both scenarios. Local manure nutrient production (not affected by scenarios) is also shown (horizontal lines).

Covering 100% of the crop nutrient demand by organic manure nutrients is not a sensible option from many viewpoints, e.g. regarding plant nutritional or nutrient leaching aspects.

SCENARIO 2 allows for a coverage of 80% of the nitrogen and phosphorous demand of the individual crop classes by manure nutrients. Compliance with the legal limit of 170 kg N ha^{-1} remains, as well.

After running the model according to the constraints of the two scenarios, the results in the output file show the impacts on manure distribution and manure transports in the districts of Lower Saxony.

3.2. Manure distribution

Manure distribution at optimized costs for both scenarios is shown in Figure 3. The gap between the two parts of each bar shows the remaining capacity of each district to use manure nutrients for fertilizing its local crops under the scenarios' constraints. Additionally, Figure 3 indicates the local manure nutrient availability (horizontal lines). For Cloppenburg (CLP), for example, the horizontal lines for both nitrogen and phosphorous show that local manure nutrients, are in excess to what can be used locally according to the constraints of either of the two scenarios, resulting in exports to other districts. Cloppenburg district serves also as an example for one nutrient constraint being fully covered (nitrogen) while the other is not (phosphorous). The maximum manure nutrient utilization capacity of each district is decreased considerably by the constraints of SCENARIO 2 in comparison to SCENARIO 1. As local manure nutrient production is not affected by the scenarios, less manure can be used locally. This results in an increased number of districts with a greater share of manure nutrients from manure due to imports from surplus districts. At the same time, an increased number of districts exports manures (Figure 4a and 4b).

3.3. Manure transports

Restricting animal farm manure nutrient application to an equivalent amount of 80% of the crop nutrient demand results in extensive manure transportation activities (Figure 4b). Manure distribution in SCENARIO 2 involves transportation from 19 to 23 districts as compared to transportation from 6 to 9 districts SCENARIO 1 (Figure 4a and 4b). In total, 1 252 662 t and 2 945 511 t of manure are being transported in SCENARIO 1 and 2, respectively. In both scenarios the majority of nutrients are exported with poultry manure. However, at increased constraints on manure nutrient application, even cattle and pig slurry with far lower nutrient contents are exported. The model gives preference to the closest districts to receive water rich slurries.

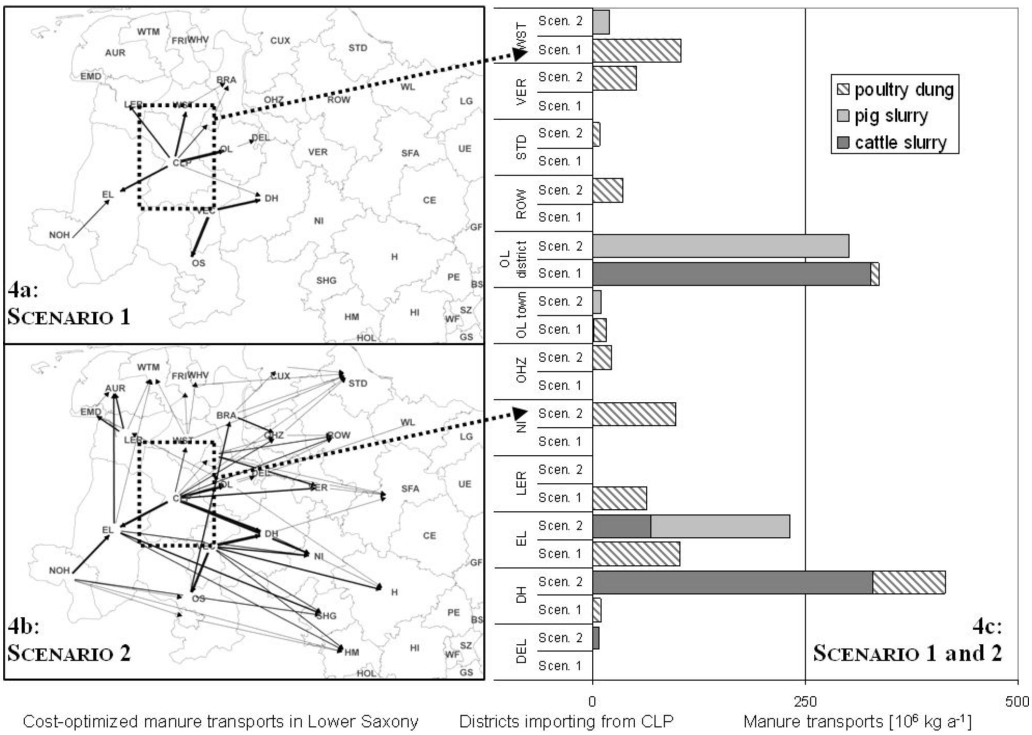

Figure 4. Manure transports in SCENARIO (Scen.) 1 (4a) and SCENARIO (Scen.) 2 (4b) and comparison of type of manures exported from Cloppenburg district (CLP) to adjacent districts in both scenarios (4c). The cumulative expressions 'poultry dung', 'pig slurry' and 'cattle slurry' sum up all manures from the respective farm animal classes.

4. DISCUSSION

The modelling is aimed at delivering a distribution of animal farm manures which is optimal under defined constraints and leads to a minimization of transport costs between districts or beyond Lower Saxony. The problem of high intensity animal farming and locally surplus manure – however surplus has been defined over the past decades – is not new (e.g. de Mol and Beek, 1991**,** Wossink et al., 1992). Most analyses regarding excess manure were conducted on the farm level. Wossink et al. (1992) analyzed on-farm manure processing techniques. Lauwers et al. (1998) analyzed how policies impact on farm setups which in turn impact on farm level manure production. Modelling approaches on regional levels have not yet been elucidated on actual distances. The problem of transportation effort by de Mol and Beek (1991) did present an optimisation approach which included manure processing steps and distances. But de Mol and Beek (1991) did not consider real transport distances as presented in this paper.

The primary focus of previous publications is the export of manure from surplus farms or regions – as opposed to really make use of their fertilizer value in areas where it is really useful. Hence, in our approach, we particularly aim at actual transport distances. In the current model setup, they are rough and simplified, but still valid and can be extended in the future. Secondly, we place emphasis on manure composition and how this relates to transport distances to tackle the problem of fertilizer value of manures in low animal density regions.

Since different manures contain individual nutrient contents the transportation distance is of particular importance with respect to minimizing cost. Allocation of one kg of nitrogen or phosphorous is less costly in dungs than in slurries. Hence, manures with high nutrient contents are the first choice for long distance transports, while slurries with low nutrient contents are to be used in the immediate surroundings of their production. This situation is exactly reflected by the model results, in degree obviously depending on the constraints. What is exported first and at longest distances is manure with high nutrient contents (e.g. dried dung from laying hens), while the model keeps slurry in the closest adjacent district to a surplus district.

Managing manure flows in a way the model is able to could, in practise, improve the distribution of valuable fertilizer nutrients from manures across Lower Saxony. However, modifications in the model setup are required before that. These include the integration of biogas production, as it impacts considerably on regional agricultural material flows. Biogas production introduces additional nutrients by the digestion of renewable raw materials and also all sorts of agricultural wastes. A further weak point in the model is that costs are not yet considered as actual costs, as well as no monetary values has been attributed to the fertilizer value of the manures. This will also be adjusted in a future model. Yet, the model presents a first step in providing an explorative tool to support development of a regional material flow management for optimal spatial organic manure distribution with minimal transportation effort.

5. CONCLUSION

On basis of our results we conclude that the newly developed linear optimization model has proven capable in simulating the optimization of animal farm manure flows to the available agricultural acreage on a regional level while considering a set of constraints. Additional features of the model will include processing steps altering the composition of the manures (e.g. biogas production, manure separation techniques). In a future step, the model will be modified to be used by policy makers and extension workers. Consequently, a regional material flow management for farm manures in general based on this explorative model will enable a reasonable substitution of often expensive, limited and energy-intensive mineral fertilizers with animal farm manures in districts with little animal farming. At the same time, environmental problems caused by manure over-application can be reduced. Hence, the model setup can contribute considerably to environment protection.

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