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In: Journal of Environmental Planning and Management 53 (8), 1011-1030, 2010.

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The EU Nitrate Directive has spurred many countries to regulate manure production and manure application. Farmers have three allocation options: spreading manure on their own land, transporting manure to other farmers' land, or processing manure. The manure problem can be seen as an allocation problem. To better understand this allocation problem, we have developed the spatial mathematical programming multi-agent simulation (MP-MAS) model. This model has been applied in Flanders, Belgium, a region with a high livestock concentration. The model evaluates the cost efficiency of policy intervention in the manure market through obliged processing. We propose to further optimise the policy using a regionally differentiated manure pressure indicator, which is directly derived from the dual outcome of the mathematical program. This indicator increase transparency in the manure and processing market, leading to better decision support about location and type of manure processing.

Keywords: multi-agent-simulation, mathematical programming, manure abatement, Flanders, spatial allocation

1 Introduction

Excess manure has become a significant problem in livestock production in many West-European countries in recent decades. Manure is seen as a "bad" thing (Lewis, 2008) or as an undesirable by-product of livestock production (Huhtala and Marklund, 2008). In countries with very concentrated animal production, e.g. the Netherlands, Belgium (mainly in Flanders) and parts of France and Italy, more manure is produced per unit of farmland than legally allowed. In Flanders, the case for this research, more than 260 kg of nitrogen (N) was produced per hectare of land in 1991 (Vervaet *et al.*, 2004). By 2006, N-production had dropped to 200 kg per hectare of land, thanks to policy interventions.

This high concentration in livestock production had become possible due to the import of feed compounds from elsewhere in the world. The inexpensive availability of imported feed has favoured the growth of the livestock production in regions close to sea-ports (Feinerman and Komen, 2005). This dependency of livestock production on sea-ports has given rise to two regions with highly concentrated animal production in Flanders. One is located in western Flanders (province of West-Flanders), adjacent to the sea-port of Ghent (further served by tranships to the inland port of Roeselare, the centre of the livestock production area).

The other region is the northern part of Flanders (province of Antwerp), close to the sea-port of Antwerp.

Before 1991, without any policy intervention, the nutrients in the form of animal manure were mostly disposed of on the farmers' own land. The farmers did not face incentives to bear the extra cost of transporting manure to other regions. They even benefitted from the increased crop yield, due to the very high fertilisation based on manure (Nesme *et al.*, 2005). Both the excessive manure application and the limited nutrient uptake by crops increased the nutrient concentration in the soil. Nitrate and phosphate leaching from the soil polluted surface- and groundwater (Withers and Haygarth, 2007).

In 1991, the European Nitrates Directive (91/676/EEC)[1] introduced the 50 mg nitrate per litre water standard and required the regional or national governments to take action against excessive application of manure and other fertilisers. This water quality standard led many countries to set fertilisation standards. Livestock farms have now three ways to allocate their produced manure: (1) using the manure on his own land, (2) transporting it to other (deficit) farms or (3) processing manure. The fertilisation standards limit use of the first and second option. As a result, the quantity of manure which could not be disposed of on land, must be processed.

Manure transport is operating at maximum limits. Processing capacity, however, is as yet insufficient to solve the manure problem. Processing capacity must expand, but this is hampered by uncertainty about the evolution of the manure surplus and related disposal costs. Further, huge spatial differences exist in the demand for manure processing due to regional concentration of animal production and high transportation costs. The interplay between transportation and processing determines future demand for processing capacity. Various models exist to describe this interplay (De Mol and Van Beek, 1991; Lauwers, 1993; Lauwers et al., 1998). However, these models were mostly too aggregated (e.g., manure transport was simulated at the regional level) and normative and ignored insights in the actual fertilisation behaviour of the farmers.

This paper presents a comprehensive manure allocation model that combines choice of location of processing plants with individual farmers' observed behaviour on manure production, manure disposal, manure transport and manure supply to possible processors. The methodology of this paper is based on Mathematical Programming-based Multi-Agent Systems (MP-MAS), applied to a dataset containing the complete farm population of Flanders (38,777 farms). This approach improves upon previous models and approaches by first, avoiding aggregation errors, and second, using actual manure application data.

The paper is structured as follows. First, we explain the modelling aspects of the manure allocation problem. This includes a detailed description of all aspects of manure production, manure disposal, manure processing and manure transport. Next, we describe the dataset and present our results. We end by presenting our conclusions about the model and discussing the results further. Particular focus goes to a discussion of the strengths and weaknesses of spatial mathematical programming for supporting environmental and regional planning decisions, as based on the case of the optimal location of manure processing capacity in the manure-saturated region of Flanders.

2 Modelling the manure allocation problem

2.1 Description of the manure allocation model

Most environmental problems such as the manure surplus involve decisions at different levels, namely at the farm and regional level. At the micro or farm level, the farmer decides to produce manure and to use, transport or process it. The aggregation of these numerous decisions results in a manure supply and demand at the macro or regional level. The decisions at the micro-level both influence and depend on the conditions at macro or regional level. In other words, manure supply and demand at the aggregated level influence and depend on micro-level decisions to either transport or process surplus manure. The interaction between farms, i.e., competition for manure disposal space, thus becomes important, as is spatial differentiation. The manure production and the availability of land to dispose of the manure are regionally diverse and create completely different conditions for micro-level decision makers (agents) depending on their location. In our modelling approach, agents are the model representatives of the real-world farmer.

Mathematical programming models that fail to capture the interaction between agents are not able to simulate farmer behaviour in a heterogeneous environment (Berger, 2001; Boulanger and Brechet, 2005). We have thus chosen the multi-agent simulation (MAS) approach to model the manure allocation problem. MAS allows interaction between agents and can account for differences in the agents' environment. MAS makes it possible to construct artificial micro worlds in which both micro- and macro-level parameters can be controlled in a spatial context (Courdier *et al.*, 2002). The micro-level part of the MAS- system is represented by Mathematical Programming (MP), which simulates the decisions of individual agents while taking legal and other constraints into account. The use of MP at the core of the decision-making procedure captures agent heterogeneity and economic trade-offs while simultaneously focusing on policy-relevant constraints (Berger *et al.*, 2006; Schreinemachers *et al.*, 2007).

Several other researchers have integrated MP in MAS, namely Berger (2001), Becu *et al.* (2003), Schreinemachers *et al.* (2007) and Valbuena *et al.* (2008). Berger (2001) and Becu *et al.* (2003) have applied MAS to the water management problem. Schreinemacher *et al.* (2007) have used a bio-economic MAS to simulate changes in soil fertility and poverty in Uganda. Valbuena *et al.(*2008) have simulated changes in land use with MAS. All these applications have dealt with the similar problem of individuals making decisions about using limited resources, where resource use by one decision maker affects the availability of that resource for other decision makers.

There are differences between our research and these aforementioned studies. First, their studies were all on a small scale. To the authors' knowledge, the MP-MAS approach has not yet been applied to a simulation with a large population of more than 38,000 individual decision makers. The successful application to this sample size illustrates that MP-MAS can also be used for large scale applications. Two, we make use of a normative approach whereas Berger (2001) and Schreinemachers *et al.* (2007) calibrated the model to a base situation (positive modelling approach)[1]. As the focus of the model is describing and exploring the current situation, it can be argued that normative modelling can be used (Buysse *et al.*, 2007). Three, our model focuses only on the manure management problem given the current situation (crop-mix, types of livestock, profitability, etc). Other papers (Becu *et al.*, 2003; Berger, 2001; Schreinemachers *et al.*, 2007) combine the changes in resource use with the possibility of adapting farm activities to economic, ecological or other conditions. Our model is limited in capturing the adaptive capacity of farmers to new changes in

1 Normative mathematical programming models optimize an existing situation while positive programming models calibrate the model to an observed situation and subsequently simulate behavioral changes (see Buysse *et al.*, 2007 for more details on the differences between both approaches)

policies or economic conditions. Fourth, other researchers have used specially-developed software, but we programmed our model using standard optimisation software (GAMS). Berger (2001) and Schreinemachers *et al*.(2007) make use of MP-MAS framework developed at Hohenheim university and Becu *et al.* (2003) uses the Cormas modelling framework (developed at CIRAD). Fifth, our model is comparative static, while other research depends on dynamic simulations of whole farm decisions.

The structure of the model is based on the basic system description of manure production and allocations options (Figure 1).

Figure 1

The model focuses on farmer's manure allocation strategy, which is only a limited part of the decisions at the farm level. Therefore, manure production remains fixed in the model (2.2), and within the manure allocation, every possible decision is taken into account: disposal of manure on own land (2.3), manure processing (2.4) and manure transport (2.5). The final subsection describes the cost calculation of the objective function (2.6).

2.2 Production of manure

Manure production and its nutrient content is very complicated to calculate. These variables not only depend on the number of animals but also on the feeding techniques, the production process, species and the age of the animals. In a policy context, this complexity of nutrient production estimations is reduced by using generally fixed excretion standards for each type of animal[2]. Deviations from these excretion norms are possible when the farmer can prove that he uses feeding techniques that cause his animals to excrete less than average, e.g., nutrient-poor feed. Nutrient production is further corrected for the ammonium losses during storage.

Due to lack of data, this model cannot fully account for farm specific differences in manure volume and quality. However, the model distinguishes the four major types of manure: cattle, pigs, poultry and other. Equation 1 calculates the manure production of farm f for manure type m (P_{mf}).

$$P_{mf} = \sum_{l}\sum_{p} n_{lp} * excr_{lp} \qquad \forall l \in m \qquad (1)$$

with n_{lp} being the number of animals of animal type *l* using feeding technique *p* and $excr_{lp}$ being the corresponding excretion standard per animal.

2.3 Modelling the own-land manure disposal option

A limited amount of the nutrients produced can be spread on the land according to the type of fertilisers, crop category[3] and area[4]. With this disposal constraint, the manure decree actually created a system of tradable emission rights for manure (Lauwers *et al.*, 2003). This viewpoint is justified because manure use, given the imperfect incorporation of nutrient inputs into end products, jointly entails a nutrient emission (Buysse *et al.*, 2008). This system differs from other systems of tradable emission rights, as the right (the land) is linked to a fixed location and the emissions (manure) are tradable. For most other emission rights, the emissions cannot be traded and the rights are not linked to location. In reality, land entails a right to spread manure, and both the land and the manure itself are tradable between farms, but only the manure can be moved.

The exchange of manure happens over short distances is mostly arranged as bilateral agreements between individual farmers. In these cases, the transport is mostly done by the farmers themselves. For longer distances, it are often specialised firms who transport manure and who also offer the service of mediator to the farmers.

Flemish manure legislation constrains the total use of nutrients by four types of fertilisation standards: three for nitrogen and one for phosphorus. The first two are maximum norms for the use of organic nitrogen (N) and inorganic nitrogen per hectare. The third puts limits on the joint use of both nitrogen types per hectare. The fourth emission standard limits the maximum use of phosphorus (P_2O_5) per hectare. We only consider the limits on nitrogen use into because nitrogen is currently the most binding nutrient.

The right to dispose manure on one's own land depends on the number of hectares and the corresponding fertilisation standards. Each combination of crop category and region has a fixed fertilisation standard. The general fertilisation standards are given in Table 1.

Table 1

The farm's assigned emission rights (R_f) are implemented in the model by equation (2)

$$R_f = \sum_c \sum_a norm_{ca} * h_{ca} \qquad (2)$$

where h_{ca} is the number of hectares of the farm per crop category c and area a and $norm_{ca}$ is the fertilisation standard for crop category c in area a. The emission rights are calculated for the three different nitrogen fertilisation standards. R_{of} is the farm emission right for organic nitrogen, R_{if} is the farm emission right for inorganic nitrogen and R_{af} is the farm emission right for total nitrogen.

Equation (2) is expressed as if the available manure disposal space can and will always be precisely used. In reality, emission rights, quota or other constraints are often not exactly binding because of uncertainty about production and the availability of rights, and differences in risk behaviour of farms (Buysse *et al.*, 2008). As it is important to use the actual farmer's fertilising behaviour in simulations, the available emission rights are set equal to the current use of these rights. Two different approaches are used for the cases of over-fertilisation and under-fertilisation.

In 2006, many farms disposed more nutrients on their land than legally allowed by their assigned emission rights because they did not succeed in processing the manure or in exchanging the manure with another farm. Despite the penalties introduced by the manure decree, this over-fertilisation persists because of insufficient manure processing capacity. For the case of over-fertilisation the available emission rights are set equal to the assigned emission rights.

Other farms do not completely use their available quota for organic manure despite the fact the surplus farms are willing to pay to manure deficit farms, in some regions more than 300 euro per ha for manure disposal. One of the reasons for not completely using the organic manure quota is that some farmers prefer inorganic to organic fertiliser for certain crops (Feinerman and Komen, 2005; Van der Straeten et al., 2008). Because we assume that farmers will continue this behaviour and thus use less organic manure than legally allowed, the calibration in the current case sets the available emission rights in the model equal to the current use of the rights. Based on the calibrated emission rights, equations 3-5 describe the legal part of disposing manure on own land.

$$\sum_m U_{mf} \le R_{of} \qquad (3)$$

$$U_{if} \leq R_{if} \quad (4)$$

$$\sum_m U_{mf} + U_{if} \leq R_{af} \quad (5)$$

where U_{mf} is the quantity of manure disposed on the land and U_{if} the quantity of chemical fertilisers used on land. The use of both types of nitrogen is limited to the respective individual emission right and the joint emission right. In the model, the farmer can only optimise his fertilisation behaviour by changing the organic manure allocation. Because of the fixed chemical nitrogen use, only equations (3) and (5) are relevant. As long as the chemical fertiliser use is low enough, equation (3) is the binding constraint. With higher chemical fertiliser doses, the allocation of organic nitrogen will be limited by equation (5) (Van der Straeten *et al.*, 2008).

2.4 Modelling the manure processing

A second manure allocation option is to process the manure. Manure processing or manure treatment has been defined as a comprehensive term for all technologies which remove or recover nutrients out of manure (Flotats et al., 2008) or making manure products that can compete with chemical fertilisers (Melse and Timmerman, 2008). The end products can be used on farmland, home or public gardens, etc. (Melse et al., 2004). The most important technique used in Flanders is a biological nitrification/denitrification system (used in more than 25% of the total processing installations) (VCM, 2007). This technique converts nitrogen into dinitrogen gas (N_2) (Melse and Verdoes, 2005).

Manure processing can be imposed by law (legally obliged processing) or can be the choice of the farmer depending on the market situation (market driven processing).

Obligatory processing is directly imposed by the manure regulation because the policy does not give the farm the option to compete for on-land disposal. Each farm with a production of more than 10,000 kg phosphorus and all farms in a municipality with a production of 100 P_2O_5/ha and a production of more than 7,500 kg phosphorus, are obliged to process a given share of the farm manure surplus. This share depends on the total phosphorus production at the farm. For each farm, the quantity of nitrogen it is obliged to process is known. In the model, obligatory processing is imposed by putting an extra constraint (6):

$$PR_{mf} \geq PR_{obliged} \quad (6)$$

where PR_{mf} is the processed amount of manure and $PR_{obliged}$ the obligatory amount of manure processing.

Farms must process manure as well when they produce manure but are unable to dispose of it within the legal limits on their own land or exchange it with other farms. This market-driven processing is not directly imposed by law but is rather a consequence of the manure disposal limits on land.

The introduction of processing as an alternative to disposal on agricultural land creates a balancing problem in the manure allocation model. Equation (7) imposes that the allocation problem stays balanced during the simulation procedure. The disposal of manure of type m (U_{mf}) is equal to the sum of the production of the manure at the farm (P_{mf}) plus the incoming manure (I_{mf}) minus the outgoing manure (E_{mf}) minus the processed amount of manure (PR_{mf}). The balance between the two variables that depend on the interaction between other farms is described in the next section.

$$U_{mf} = P_{mf} + I_{mf} - E_{mf} - PR_{mf} \quad (7)$$

Manure processing can be conducted in small-scale farm-based installations and in specialised processing firms. However, the model does not distinguish between these, because further simulations only use the total processing capacity in each municipality.

2.5 Modelling the manure transport

All previous policy-driven constraints can be simulated at individual farm level without considering interactions between the farms. However, interactions between farms must be simulated when modelling manure transport. Modelling the manure market differs from other quota markets such as the dairy quota, sugar quota or CO_2-emission rights.

The main difference with the aforementioned quota markets is that, for the manure problem, emissions are tradable and the rights are locally fixed, while in contrast, for the CO_2-emission rights and most other quota markets, emissions are not tradable while the rights are. Manure emissions themselves are tradable, thus manure transport costs become important, as they create a spatial difference in willingness to pay and influence the market price for manure disposal.

Despite the reality of strong rigidities and transaction costs in quota markets, their modelling is often based on a perfect market for quota rights (Alvarez *et al.*, 2006; Brannlund *et al.*, 1998; Bureau *et al.*, 1997; Fraser *et al.*, 1997; Mahler, 1994; Van Passel *et al.*, 2006).

The simulation of each farm in the population and their interactions removes all possible sampling errors. However, it complicates the computation of finding optimal solutions in a large population, as the computer capacity required becomes very large. Our dataset of 38,777 farms and four types of manure would, for instance, result in a transport matrix of 6,014,622,916 cells. We resolved this by introducing a hypothetical transport firm for each municipality. The transport firm acts as an assembly point where each farm of the respective municipality can offer its excess or collect its demand of manure.

Working with municipal transport firms lowers the number of cells in the transport matrix but does not violate the optimisation at farm level. The individual farm still decides whether transport of manure is desirable or not. Once these optimal levels are determined at farm level, the optimisation of the exchange of manure between the different municipalities occurs at transport firm level. The transport firm itself is only a tool for allowing optimal exchange over the whole Flemish region and results have proven that the outcome is identical to a simulation where all farms interact directly with each other while the transport matrix contains only 1232*1232 cells. Theoretically both should be equal since the transportation costs between farms are identical to those between the municipalities they are located in and the constraints of demand and supply of manure on municipality level are added up out of these farms.

Figure 2

Figure 2 shows the example for the transport firm of municipality 1. This municipality has *n* farms. Instead of allowing interaction between these *n* farms with the whole population, only interaction with the municipal transport firm is taken into account. The interactions with farms of other municipalities are lifted to the higher level where only the interactions between the municipality transport firms are simulated. The model optimises both the transports within the municipality and the transports between the municipalities.

The transport behaviour of the farms is integrated into the equations (8) to (10).

$$E_{mft} \leq P_{mf} \quad (8)$$

$$\sum_{t2} T_{mt_1t_2} = \sum_{f} E_{mft_1} \quad (9)$$

$$\sum_{t_1} T_{mt_1t_2} = \sum_{f} I_{mft_2} \quad (10)$$

with E_{mft} being the amount of exported manure of manure type *m* from the farm to transport firm *t*, I_{mft} the amount of incoming manure of manure type *m* at the farm from transport firm *t* and T_{mt1t2} the amount of manure of manure type *m* transported from transport firm t_1 to transport firm t_2. Constraint (8) prevents the amount of exported manure from exceeding the produced manure of each manure type. Equation (9) imposes that all the exported manure of the individual farms to their respective transport firms is also exported out of these firms to other transport firms (or the transport firm itself). Equation (10) does the same but on the incoming side. It imposes that the transport firm distributes its total received amount of manure to the respective individual farms.

The equations (9) and (10) introduce the manure market in the model because they link the manure transports of all farms to each other. The supply and demand of manure is balanced when a market equilibrium is reached. The two equations are defined at the level of a municipality resulting in equal transport shadow prices for all farms in a municipality. The differences in shadow prices between municipalities are driven by the transport costs. This type of simulation behaviour of markets is similar to a Spatial Price Equilibrium Model (Takayama and Judge, 1971).

2.6 Cost calculation

The final step in the model description is defining the objective function. According to Aubry *et al.* (2006) manure management in the Reunion Island (France) is not fully controlled and planned as is the case with other farm activities. Manure management choices depend on time rather than on economic or ecological principals. The author argues that similar behaviour in other locations can be found. However, in Flanders, because of the strict legal prescriptions, this is not the case. Local experts believe that manure management takes a leading place in farm management. In the region with the highest cost for manure allocation, the allocation costs run up to 2 euro per kg nitrogen, resulting into a cost of 19 euro per finishing pig place. This is more than 8% of the total turnover and almost 30% of gross margin (based on average Flemish FADN data of 1989-2003). Therefore it is very unlikely that economic principles do not play a role. Moreover, in practice it is seen that livestock farmers do minimise their costs. The model thus assumes cost minimising behaviour.

As we have limit the use of manure to the actual use of manure in 2006, we fixed the possible profits from manure use. The farmer remains free to choose among the three aforementioned allocation options. All three options involve costs (Table 2).

Table 2

Expressed to the volume, the costs are all assumed equal for each manure type. There is, however, a large difference in nitrogen content between the four types of manure. As the model is driven by the nutrient rights, the costs per kg of nutrient need to be taken into account (Table 3).

Table 3

The allocation results result from the differences in costs between the three allocation options and the differences in nitrogen content between the four types of manure. The distribution option (i.e., disposing the manure on own farm's land) is the least expensive option. When all the available emission rights are used, the farmer will search for available emission rights on other farms. The final option is to process the manure. Manure from poultry has the highest nitrogen content, followed by pig manure. Consequently, transport costs and processing costs expressed per kg N will be the lowest for poultry. As a result the farmer will choose to process manure in the following order of manure type: poultry, pigs, other and cattle.

Equations (11) to (13) calculate the costs of the different manure allocation options.

$$C_{uf} = \sum_{m} U_{mf} * \cos t_{um} / N\_content_{m} \qquad (11)$$

$$C_{PRf} = \sum_{m} PR_{mf} * \cos t_{PRm} / N\_content_{m} \qquad (12)$$

$$C_{t_1} = \sum_{t_2} \sum_{m} T_{mt_1t_2} * \cos t_{em} * dis\tan ce_{t_1t_2} / N\_content_{m} \qquad (13)$$

with $cost_{um}$ being the costs to dispose of 1 m³ manure of type *m* on the farmer's own land, $cost_{PRm}$ the costs to process 1 m³ manure of type *m*, $cost_{em}$ the costs to transport 1 m³ manure of type *m* over 1 km, $distance_{t1t2}$ is the distance between farm t_1 en farm t_2 and $N\_content_m$ the N content per m³ of manure of type *m*. C_{uf} and C_{PRf} are the total disposal and processing costs of the farm, respectively, while C_t is the total cost of the transport firm t.

The final phase in constructing the model is to define the objective function (equation 14).

$$\underset{U_{mf},V_{mf},E_{mf}}{Min} \cos ts = \sum_f (C_{uf} + C_{PRf}) + \sum_t C_t \qquad (14)$$

3 Data

The Flemish Land Agency (FLA)'s database was used for our model. It contains all variables related to manure production, transactions, acquisitions and use of nutrients, for each Flemish farm. The total dataset consists of 60,577 farms over a period of seven years (2000-2006) with a total of 311,430 unbalanced panel observations. The current paper only takes farms with more than 2 hectares or a nutrient production of more than 300 kg phosphorus in the year 2006 into account. The sample used consists of 38,777 farms. Table 4 shows the aggregated figures of the total emission rights and the nutrient excretion in the sample.

Table 4

In 2006, 102 million emission rights for organic nitrogen (kg N) were used in practice, a total of 72.5% of the available emission rights for organic nitrogen. In practice, Flanders is not able to dispose about 26.4 million kg out of the 102 million kg of nitrogen produced on the available farmland. As only 16.3 million kg is processed, an over-fertilisation of 10.1 million kg nitrogen remains.

4 Model results

The proposed model and the dataset can be used for different applications in manure management choices, policy evaluations and investment decision support analysis.

All results focus on macro (regional) impact but they are driven by the decisions at the micro (farm) level. First, the model can be used to evaluate policy alternatives and their impact on costs of manure allocation. Second, the model supports investment decisions by advising on location and type of manure processing. The simulations compare the existing manure processing capacity with the optimal demand. The model results indicate whether the manure processing capacity developed so far is efficiently located. Taking the already existing capacity into account, new simulations show where more investments in processing capacity are needed. Finally, the model produces results for an indicator that creates transparency in the manure transport and processing market.

To validate the model results with actual figures the Pearson's correlation coefficient (r) is used (Nolte, 2008). The coefficient for net transport flows between municipalities (R: 0.809; P:0.000) and the process behaviour (R: 0.786, P: 0.000) are rather high. This indicates that our model is capable of reproducing actual farmers' behaviour rather well.

4.1 Policy analysis

First, the model is applied for straightforward calculations of the impact of policy choices on sector parameters. The effect of the legally obliged manure processing on the total manure allocation costs is taken here as an example. The manure policy tries to cool down the manure market by imposing a processing obligation on the farms with the largest manure surplus. Moreover, this enables policymakers to steer the development of manure processing. The model is used to investigate the cost-effectiveness of the attempt. The total cost for manure allocation with the obliged manure processing is compared to the situation where only market-driven processing is simulated (Table 5 and Table 6).

Table 5 & Table 6

In the case of market-driven processing, the individual decision makers in the model will optimise the location and the type of manure processing to meet the nitrogen fertilisation restrictions. This increased freedom for the individual decision makers lowers the total cost of manure allocation by 2,399,330 euro while keeping the amount of nitrogen used on the land according to the fertilisation standards. The model shows that the policy indicator for steering manure processing is not very efficient.

More than 20% of the nitrogen from manure has to be processed, which also creates a high cost for the farms with a manure surplus. Therefore, it is important to search for the most cost-efficient policy and investments for optimal manure allocation. We show here how the policy could be improved, while the following subsection shows how the use of MP-MAS as a planning instrument can help investors to obtain more benefits from manure processing by the development of the best type of plant on the optimal location.

4.2 Investment decision support analysis

In 2006, the total demand for manure processing was 26.40 million kg nitrogen (Table 5: sum of simulated obligatory and market-driven processed N) while only 16.3 million kg nitrogen was effectively processed. This gap implies that there is an extra demand for manure processing of 10.1 million kg nitrogen. The model enables investors to determine where extra processing capacity is most desirable according to the stated objective.

The lowest possible costs for the farmer (cost-efficient) and the highest benefit from the manure processor is reached by optimising the location of the processing systems and the type of manure that can be processed. Building capacity close to the farms demanding extra processing capacity lowers the transport distance to the processing system. The choice of type of manure is also very important because processing costs differ significantly among manure types.

The results of model simulations of the optimal manure processing locations given the current policy are shown in Figure 3, including the municipal manure surplus[5] and thus the processing demand. In total, 26.40 million kg must be processed in Flanders including both legally obliged and market-driven manure processing. The location of the obliged processing is driven by the policy criteria and is spread quite evenly in Flanders. The market-driven processing is only driven by the maximum fertilisation limits on the land, production and economic motivations for minimising transport and processing costs.

Figure 3

Figure 3 gives only a purely normative outcome of where the optimal location of processing capacity should be planned. For the implementation of extra processing capacity, it is important to know where the current operational processing capacity is located. This is illustrated in Figure 4. As already indicated, the current operational processing capacity is almost 16.4 million kg N in Flanders.

Figure 4

Given the current situation, the new optimal location pattern must be updated. The operational capacity now available (Figure 4) is introduced in the model and a new simulation procedure is performed. Figure 5 illustrates the result of the second simulation: the most cost-effective investment would be a pig manure processing plant in the centre of West-Flanders.

Figure 5

4.3 Regional manure pressure indicator

The legally-imposed processing has allocation costs of + 2%. This is far from optimal, and is caused by the criteria on which obligatory manure processing is based. The current policy, i.e., steering the obligatory manure processing, uses an indicator that is based on a simple comparison of animal production and the number of hectares. This indicator is not very precise because it ignores the possibility of transport to neighbouring regions and disregards the fertilisation behaviour of the farms.

The needed processing capacity (Figure 5) is already a much better indicator because it takes transport, type of manure and actual fertilising behaviour into account. However, Figure 5 does not tell the decision maker how much the investment in processing capacity may cost and how much an individual farm may pay for manure disposal on land. Therefore, the decision maker needs an economic estimate linked to the disposal constraint. This can be found in the dual outcome of the mathematical programme.

A regional manure pressure indicator (RMPI) is defined from the dual value of the manure allocation equation (3) of the MP-MAS manure allocation model presented in this paper. This dual value gives the marginal cost of disposing 1 kg nitrogen, or the shadow price of the disposal constraint. For simplicity, we opted for one RPMI per municipality. This aggregates the farms within a municipality into a single farm. The model is then run for the remaining 308 farms (equal to the 308 existing municipalities in Flanders). In regions with highly concentrated animal production and a relatively low number of emission rights nearby, this cost (dual value or regional manure pressure) is high. When competition for free emission rights is rather low, the regional manure pressure will also be low. Figure 6 gives the regional manure pressure.

Figure 6

The RMPI is expressed in monetary terms, which makes it very relevant additional information for policy makers and manure processing investors. The RPMI shows the spatial distribution of the willingness to pay for manure processing. While Figure 5 indicates the quantity of the manure processing demand , the RMPI also indicates the regional impact of the demand in monetary terms. This may lead investors to develop a larger capacity in a certain municipality than needed with the aim of serving neighbouring municipalities with a high RPMI.

The RPMI can therefore also provide market information on transport of manure between farms. Better market information can make the transport market more transparent because it clearly shows the maximum cost of disposing manure in each region.

5 Discussion

Nitrate pollution is a typical example of emission where the spatial aspect is important, in particular because of emissions in water or soil often disperse slowly. As a consequence, emission thresholds to soil and water need to be expressed as amount of pollution per area, or per volume of water or soil, and per time. This also means that the standards of the European Nitrates Directive (91/676/EEC)1, which has also been enacted in Flanders, can be seen as emission rights that are tradable but bound in space and time. Current paper focuses mainly on the spatial aspect. To make abstraction of the time component, which is theoretically important, the time unit of one simulation run in the presented model equals one year. Within-year time factors, such as the period of emission of manure within the year, and its environmental impact are out of the scope of the present article.

The MP-MAS methodology presented here has three important strengths. First, the model can simulate the interplay between micro (farm) and macro (regional) level. Second, the spatial pattern of emission and emissions rights can be taken into account. Third, the heterogeneity between firms and emission abatement technology can be simulated. Compared to existing MP-MAS applications, the current paper has the advantage of working with the entire population, which eliminates all possible sampling errors. The application illustrates that with modern IT software and hardware MP-MAS applications can be developed for national or international samples of agents.

One disadvantage of the present model is that it focuses on only one part of the decision making process of the agents (manure management) and ignores possible interactions with other management decisions at farm level, such as crop choice. Further research efforts will focus on building in this feature into the model. Another disadvantage compared to other MP-MAS applications is that the current application is normative, while other models such as the one used by Berger (2001) and Schreinemachers et al. (2007) are positive, although this is justified given the research questions. A future line of study could be to create a positive version of the model for other applications (e.g., to model farmers' reactions in case of policy changes).

The method in this paper introduces and quantifies the spatial economic impact of the emission rights policy, and goes beyond traditional manure allocation simulation, because it also takes agents' behaviour (farmers and processing investors) into account. As such, the model has a decision support value for both policy makers and private actors. Towards the private actors, optimal processing capacity and location in accordance to the transportation flows is at stake. Because the large spatial differences in manure production and manure disposal space and individual behaviour, the model provides the necessary insights for the transportation-processing choice problem. The results show that the demand for extra manure processing capacity is heterogeneously spread over the whole Flemish regions, confirming that it would be hard to define those places in advance without having a total view on the market. The same can be said about the regional manure pressure indicator which uses available information in an integrative way to indicate the economic cost of allocating one extra kg of nitrogen in a given location. These integrative understandings help to make better decisions in the future, both at private (farmers and processing investors) and policy level. It may avoid that processing capacity is built in regions where there may be a lack of 'cheap' manure.

Mandatory manure processing is used as a case for policy analysis. Mandatory manure processing can be seen as a policy intervention in a quota market. The results show that the total cost of such policy amounts to 2.4 million euro compared with the present situation without a processing obligation. This is in accordance with other studies: additional interventions in an existing quota system increase the costs for private actors in the system without enhancing the effectiveness of the quota system (Tietenberg, 2003; Van der Straeten et al., 2009). A comparable study (Helming and Reinhard, 2009) in the Netherlands, also a country with huge nutrient emissions, quantified the costs of different measures to reduce nitrate leaching. Their model simulates, next to the manure transport, also production decisions for the livestock and crop activities. From modeling perspective, Helming and Reinhard (2009) confirm the assumption in the current paper that transport and processing (they call this export) are the main options to deal with manure surplus. The more aggregated approach of Helming and Reinhard (2009), however, underestimates the transport costs compared with the firm level approach as applied in this paper.

Despite this similarity, the results of the policy simulations of Helming and Reinhard (2009) are not comparable because of the differences in cases and the focus of the cost calculation. Helming and Reinhard (2009) found a total cost of €81.5 million per year for the additional measures of the water framework directive while our paper focused on more specific policy interventions such as a manure processing obligation.

6 Conclusions

The model presented in this paper simulates spatially heterogeneous environmental pollution and is applied to the case of manure surplus in Flanders. In this way, the possibilities of a MP-MAS based model as decision support tool for policymakers and for private investors is illustrated. The model results for the concrete case have shown that the current manure processing capacity is already located close to regions where the emission abatement is the most profitable, but also that further investments in manure processing capacity remain necessary.

The model has two types of results that are interesting for decision makers. First, the model can compare different policy alternatives and calculate the differences in costs for the farmers. As an example, we have shown here that the current manure processing obligation introduces an extra cost of almost 2.4 million euro that could be saved if a more market-based approach was used. Second, the model provides a spatial indicator of the intensity of the economic consequences of the policy. The newly proposed measure is based on location-specific marginal costs of pollution abatement, and improves the current policy indicator which is only based on a simple ration of manure production and area. The new measure benefits both the policymaker and the farmer. The regional manure pressure indicator in our model measures the impact of the policy more precisely, because it takes regional interactions into account. A better policy indicator also allows the policymaker to better target the policy in question. The regional manure pressure indicator is also relevant for farmers because it increases market transparency.

Given the method's strengths and despite some disadvantages discussed in previous section, the proposed way of analyzing tradable emissions rights fixed in time and space has many other possible applications. Environmental management of undesirable outputs, such as heavy metal emission, soil pollution, or noise pollution, has the similar property of being expressed as acceptable threshold per unit of space and time. The management of spatially limited resources such as water is also similar. Berger (2001) and Becu et al. (2003) have already applied a MP-MAS model on the water management for a small basin. It shows that further development of this kind of models gives clear perspectives certainly when the availability of stronger calculation capacities make also application on larger cases possible.

Acknowledgements

This research was funded by the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT-Vlaanderen).

[1]The main purpose of the directive was to protect the waters against pollution caused by nitrates from agricultural sources

[2]Animal type: combination of species and age

[3]The manure regulation has subdivided crops into four different categories (grassland, maize, low nitrogen crops and other crops)

[4]In the manure regulations distinction is made between general areas and several vulnerable areas (e.g. water, nature, phosphorus saturated areas)

[5]Surplus manure : manure which can not be disposed on own land or transported to other farms

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Table 1. Fertilisation standards in kg N /ha (*) (period 1/1/2003 until 31/12/2006) (Vlaamse regering, 2006)

Crop category	P_2O_5	Total N	Organic N	Inorganic N
Grassland	130	500	250	350
Maize	100	275	250	150
Low N crops (**)	100	125	125	100
Other crops (***)	110	275	200	200

*** Only the fertilization norms for the general areas are given. More stringent norms are imposed for vulnerable areas**

****Crops with a low N demand, e.g. onions, chicory, clovers, fruit plantations, flowers,…**

*****All crops not belonging to one of the 3 other categories, e.g. potatoes, sugar beets, cereals, legumes, …**

Table 2. The costs for each allocation option (VCM STIM, 2004)

Allocation options	Used value
Distribution costs (€/m³)	2.5
Transport costs (€/km/m³)	0.18
Processing costs (€/m³)	22.5

Table 3. Average nitrogen content per m³ (kg N/ m³)

Manure type	Used value (*)
Cattle	4.95
Pigs	6.91
Poultry	15.89
Other	4.14

*** within the 4 types of manure the N-content varies among the different animal types. Therefore, the used value is the weighted average N-content of all produced manure in Flanders (source: own calculations)**

Table 4. Aggregated figures regarding the production and use of organic nitrogen in Flanders in 2006 (source: own calculations)

variable	Value
Total used emission right for organic nitrogen (million kg N)	102.09
Actual production of organic nitrogen (million kg N)	128.50
Production surplus of organic nitrogen (million kg N)	26.40

Table 5. the simulated allocation choices compared between market driven manure processing and legally obliged processing (in million kg)

	cattle	pig	poultry	other
Nitrogen production	67.69	45.66	12.71	2,44
Market driven processing option				
Simulated total disposed N	67.70	31.31	0.66	2.44
Simulated transported N	10.53	26.34	1.05	0.32
Simulated (market driven) processed N	0	14.35	12.05	0
Legally obliged processing option				
Simulated total disposed N	67.16	31.31	1.19	2.43
Simulated transported N	7.48	18.99	1.16	0.58
Obligatory processed N	0.53	7.14	4.93	0.007
Simulated (market driven) processed N	0	7.21	6.59	

Table 6. total costs per allocation option compared between market driven manure processing and legally obliged processing (million euro)

	No legally obliged processing	Legally obliged processing
Disposal costs	47.09	46.90
Transport costs	8.97	9.87
Processing costs	63.80	65.48
Total costs	119.86	122.26

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