Micro-simulation as a tool to assess policy concerning non-point source pollution: the case of ammonia in Dutch agriculture

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Abstract

Non-point source pollution is notoriously difficult to asses. A relevant example is ammonia emissions in the Netherlands. Since the mid 1980s the Dutch government has sought to reduce emissions through a wide variety of measures, the effect of which in turn is monitored using modeling techniques.
This paper presents the current generation of mineral emission models from agriculture based on micro-simulation of farms in combination with a spatial equilibrium model for the dispersion of manure from excess regions with high livestock intensities within the country to areas with low livestock intensities. The micro-simulation approach retains the richness in the heterogeneity of farm household decision making that are the core cause of the difficulty of assessing non-point source pollution, while using the best available data to track corresponding pollution.
Examples are provided that illustrate the strengths of the modeling framework for both pollution monitoring and environmental policy scenario analyses.

Key words: micro-simulation, spatial equilibrium model, non-point source pollution

1. Introduction

Non-point source pollution is notoriously difficult to asses, precisely because it is diffuse, usually with many sources that are often difficult to monitor. At best aggregate figures can be provided based selected measurements which tends to be unsatisfactory for policy assessment purposes where the precise effects of policy interventions is desired. Relevant examples are ammonia emissions and nitrate and phosphate leaching from agriculture to ground and surface water in the Netherlands.
One of the ways of addressing the issue of non-point source pollution is to use models to estimate emissions of pollutants into the environment. In this paper we discuss combined micro-simulation models with a spatial equilibrium model to deal with the fore mentioned pollution issues from agriculture. We believe that micro-simulation is a powerful tool to address the issue of non-point source pollution because it deals with the processes that cause the pollution. In this paper we present MAMBO a micro-simulation model of livestock and agriculture that looks at the mineral flows within the sector and the resulting emissions.
The structure of the paper is as follows. In the next section we discuss the issue of ammonia emissions from agriculture and the issue of excess application of minerals in agriculture. In the section following that one we briefly discuss some issues in micro-simulation in relation to work done in other fields. Next we present the model itself and its mathematical equations. Next we discuss the data that enters into the model. This is crucial because micro-simulation models are highly data intensive. We then go on to discuss the two cases to which the model is applied, namely monitoring of emissions from agriculture and livestock and the effect of environmental policies on economic performance. We wrap up our paper with a brief discussion of the results and model.

2. Emissions from livestock and agriculture

In the past decades point-source pollution to air and water have been lowered dramatically. Effective legislation with both command and control measures and economic instruments have reduced emissions of many pollutants to a bare minimum.
Identification and quantification of non-point source pollutants have proven difficult and have thus limited the implementation of appropriate and effective solutions. Currently, most strategies that address non-point source pollution are driven by dissociated economic, political and ecological

interests that are difficult to reconcile. As a result non-point source pollution is typically not well regulated.

Atmospheric Ammonia in the Netherlands is amongst the highest in the world, partly because of natural circumstances (peat bogs) but importantly due to the high population density of farm animals (dairy and beef cattle, poultry, pigs, sheep, goats, horses and fur animals). The high animal density also threatens water quality through the leaching of nitrate and more importantly phosphate to groundwater. The role of livestock and agriculture in emissions can be represented graphically in Figure 1. The flags represent points within the system where ammonia emissions occur. At flag number 6 we also find the emission of nitrate and phosphate to ground water.

The ability to monitor the effects of policies that influence the processes in this system allow legislators to construct meaningful policy frameworks that address both ecological and economic indicators. In the Netherlands we have a long history of addressing the emissions from agriculture and livestock, both analytically and in terms of legislation.

3. Micro-simulation

The notion of micro-simulation to study economic phenomena dates from the pioneering work of G.H. Orcutt from the late 1950s onwards (Orcutt et al. 1976; Orcutt, 1990; Merz 1991). By micro-simulation, we mean a model in which economic decision-makers are individually modelled, and then policy relevant quantities are generated via the aggregation of the agents' 'microeconomic' actions. Although micro-simulation has been around for half a century, its applications have been sparse and concentrated in a few special areas: demographics and income distribution (*e.g.* Orcutt, 1976; Galler and Wagner, 1986, tax policy(Sadowsky 1977), social security and employment (Brennecke, 1981; Devine and wertheimer II, 1981). There have been a few examples from the US Bergmann and Bennett 1986; Basu et al 1998). Linked micro-macro simulation models are very rare (Basu et al 1998) Potentially it affords several advantages over more 'traditional' techniques (i.e., macro-econometric or computable general equilibrium (CGE) models) of modelling the economy or a part thereof.

(a) We have more freedom when modelling the behaviour of individual agents because there are less limitations on functional forms of equations, and can model them in great detail. In addition, one can explicitly model the effect of certain 'nonlinear' legal, regulatory, and/or policy changes, such as in environmental regulations.

(b) Since the procedure is individual agent-based, one can utilize existing rich sources of micro-level data, and expand to macro-level where relevant.

(c) It is possible to include stochastic elements in the models using a simple random number generator.

On the other hand, we feel there have been a number of major *disadvantages* to the use of microeconomic simulation up to now. First, because the technique is rather novel, not all modelling kinks have been worked out, including the estimation of accepted parameter values, the way there has been for other types of models, which requires the modellers to be very explicit about what the model does, as there are no accepted standards as in the case of macro-economic CGE models for instance. Secondly, it is clear that keeping track of numerous agents, especially if they are modelled in great detail, can take up enormous computing capacity. It is only with recent increases in computational capacity that micro-simulation is becoming an acceptable alternative to more traditional forms of policy modelling.

Micro-simulation can also be viewed as a multi-agent system. Multi-agent systems, a term from the field of artificial intelligence, may have many different definitions, following Tweedale et al (2007) we provide two. The first defines the term 'agent' as having ability to provide simple autonomy, sociability, reactivity or pro-activeness (Castelfranchi, 1995; Genesereth and Ketchpel, 1994).

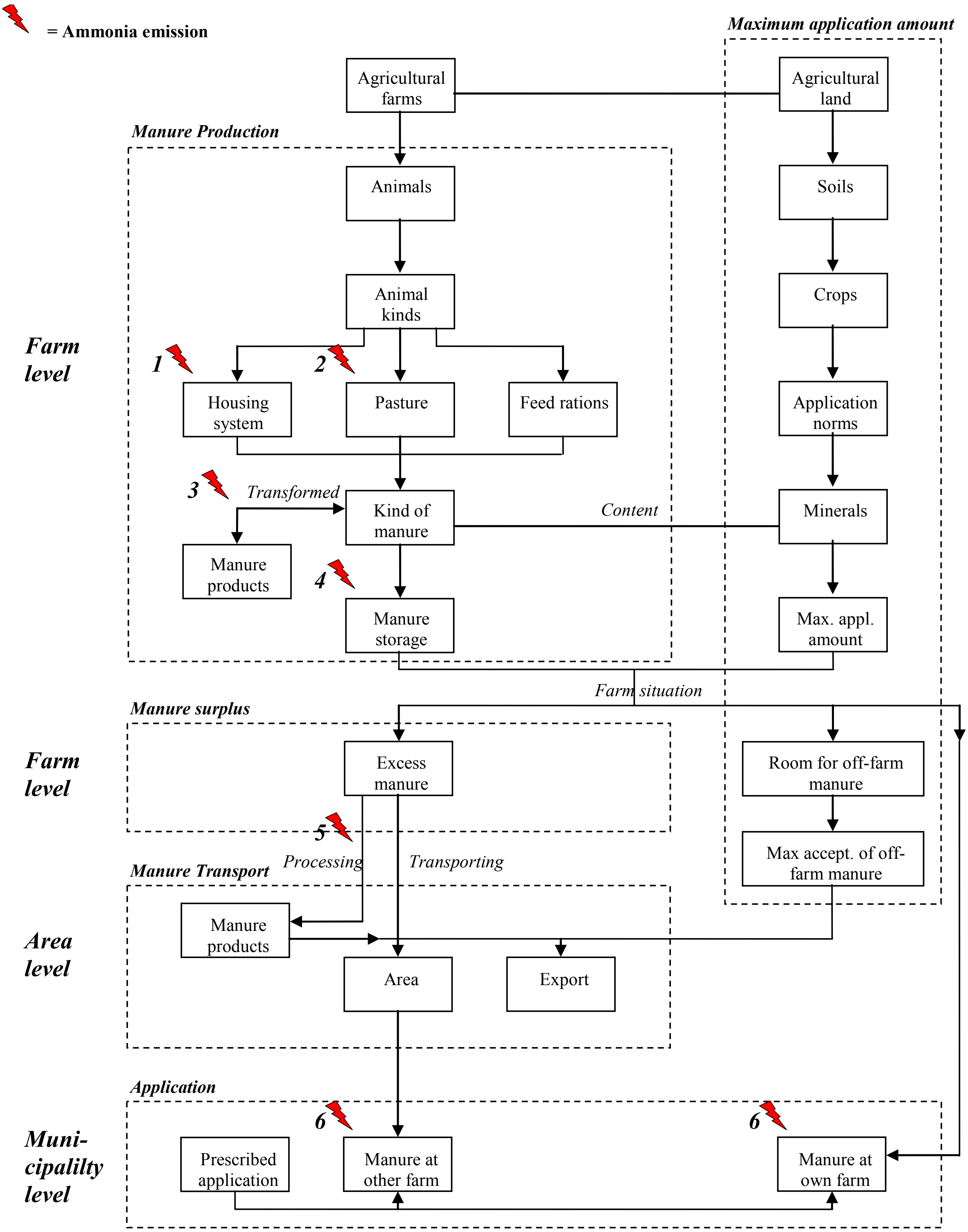

Figure 1. The manure and ammonia emission model structure

Multi-agent systems, using concepts that are more usually applied to humans, especially heuristics, learning, teaming, and coordination, tend to be more stylized and not developed for direct policy analysis. In the field of environmental economics micro-simulation it is still a relatively new approach. Multi-agent systems have been applied to model interactions between agents especially in relation to dynamic decisions, related to for instance land use (Montecino, 2007), but also to the dynamics of water quality in a relatively small setting by combining a simple septic tank and leaching system modelled in stella (Brown Gaddis et al, 2007) with spatially explicit Landscape Modeling Framework (LMF) which can be used to estimate the relative impact of different nutrient sources on waters throughout a watershed (Costanza and Voinov, 2004). This type of model is used primarily for stakeholder discussions by showing possible effects of alternative technology options through the simulation of human behaviour to those technology changes. Alternative approaches concentrate on optimizing the technically best options (Koo and Connell, 2006).

There is always a trade-off between how detailed a model represents the reality that is being analysed and the complexity of the model. This holds true for the use of representative data or a full data set. It holds true for the processes that are taken into account, both the biophysical processes as well as the behavioural processes related to decisions made by economic actors. Another important issue is calibration and validation. With micro-simulation models calibration can be tricky. Very often the underlying micro-simulation models are not accurate for a single actor but the aggregate results are quite adequate and less biased. This phenomenon is often denoted as aggregation gains. Calibration of the micro-simulation model then becomes difficult and calibration is done on aggregate indicators. Validation with micro-simulation models is even more difficult, because very often the necessary independent data set needed for validation is lacking. Especially when census data are used this is inherently so.

4. MAMBO model

Following the structure of mineral flows in agriculture highlighted in figure 1 we develop a model MAMBO is a suite of modules written in GAMS (General algebraic modelling system (McCarl, 2006)). MAMBO follows a modular approach and allows for calculations at varying levels of aggregation depending on the availability of data and the requirements of a specific application of the model. The logic of MAMBO is based on the validated and calibrated MAM model (Groenwold et al., 2001).

In the first calculation modules of interest in this context, animal numbers are converted into manure quantities by taking into account the housing situation of the animals and whether or not they are grazing in the grazing season. The basic outputs we want to generate here are manure production per animal category on firm (B^{manure}), Mineral production through manure per animal category on firm (M^{manure}), and the Ammonia emissions that can be attributed to animals and their location (E^{Stable}, $E^{Pasture}$).

This is done in the following manner at the level of animal categories (not individual animals) on establishments of firms located in specific municipalities (for expositional purposes we will suppress the indices related to level of aggregation, namely firms identifier, establishment number and municipality code). The manure production depends on the number of animals ($N^{animals}$), the ration (ρ) the animals are fed, the excretion volume (v) of the animal and the time spent in various departments (stable and pasture) in which the animal is located. Rations are independent of whether an animal is housed indoors or outdoors. The department is in general an animal housing structure (interchangeably called stable throughout this chapter). Time fraction (τ) is used to assign more than one department (pasture in summer and stable in winter) to animals during a year, where relevant. The dimension is kg manure per animal category (subscript a) per department (subscript d) per farm establishment and per ration type (subscript ρ).

$$B_{\rho da}^{manure} = N_{da}^{animals} * \rho_{\rho a} * v_{\rho a} * \tau_{\rho da} \qquad (1)$$

Within MAMBO, manure categories (subscript f) are defined in terms of the animals that produce the manure, the departments where the manure is produced, and the type of rations that the animals are fed.

$$B_{\rho daf}^{manure} \Leftrightarrow B_{\rho da}^{manure} \qquad (2)$$

Mineral (subscript m) production (M^{animal}) of an animal in a department for a manure category depends on the mineral content of the manure excreted (μ). The dimension is kg mineral in manure per animal category per department (hence per mineral category) per farm. There is a further difference in definition of the mineral content. The scientific manure mineral content is the content prior to emissions, while the fixed manure mineral content is net of emissions.

$$M_{mdaf}^{manure} = \sum_{\rho} \left(B_{\rho daf}^{manure} \right) * \mu_{mf} \qquad (3)$$

The mineral content of manure warrants a little extra explanation. In principle depending on the specific circumstances on the farm the mineral content of manure will differ. In MAMBO certain standardized procedures are used. This is the basis of the multiple mineral accounting framework used in the modelling procedures. The procedures are mentioned here in random order. In the first place we have the legal mineral content of manure (this is a relevant concept in Dutch agriculture). These are the mineral contents used for evaluating if firms comply with the manuring standards for the cropped area. In the second place MAMBO also uses the best scientific knowledge concerning mineral content of manure in order to provide as accurate calculations as possible concerning emissions of minerals into the environment. In the third place for the specific case of dairy cattle (in the Dutch case), there is an alternative method for determining mineral contents of manure based on milk urea content and average milk production per cow. This milk urea procedure is valid only for the legal mineral accounting framework and not for the scientific accounting framework. In the current version of MAMBO, manure mineral contents related to milk urea and milk production are discrete amounts based on tables. Equation 3 therefore can be rewritten for dairy (subscript a^d) and non-dairy (subscript a^{nd}).

$$M_{mda^{nd}f}^{manure,fixed} = \sum_{\rho} \left(B_{\rho da^{nd}f}^{manure} \right) * \mu_{mf}^{fixed} \qquad (3a)$$

$$M_{m^N da^d f}^{manure,urea-based} = \sum_{\rho} \left(B_{\rho da^d f}^{manure} \right) * \sum_{uq^{milk}} \left(\mu_{m^N uq^{milk}}^{milk\,urea-based} * D_u * D_{q^{milk}} \right) \qquad (3b)$$

$$M_{mdaf}^{manure,scientific} = \sum_{\rho} \left(B_{\rho daf}^{manure} \right) * \mu_{mf} \qquad (3c)$$

$$D_u^{lb} < u^{milk} < D_u^{ub} \qquad (4)$$

$$D_{q^{milk}}^{lb} < Q^{milk} < D_{q^{milk}}^{ub} \qquad (5)$$

where D are dummy variables denoting the linkage of the firm level production of milk(Q^{milk}) and the firm level average urea content (u^{milk}) to the discrete steps.

The emission factors (subscript φ: NH3, NO, N2, N2O in the case of nitrogen and ammonia monitoring in the Netherlands) for grazing ($\varepsilon^{pasture}$) is different from that of the animal housing (ε^{stable}). Hence, the mineral emissions (E) from the animal manure inside the animal house and from grazing are expressed separately in equations 6 and 7. The emission is expressed as kg mineral emitted per animal category per department (hence per mineral category) per farm and emission kind (one of them is ammonia).

$$E^{stable}_{\varphi md^s af} = M^{manure,scientific}_{md^s af} * \varepsilon^{stable}_{\varphi md^s f} \qquad \text{(6, flag 1 in Figure 1)}$$

$$E^{pasture}_{\varphi md^p af} = M^{manure,scientific}_{md^p af} * \varepsilon^{pasture}_{\varphi md^p f} \qquad \text{(7, flag 2 in Figure 1)}$$

The mineral production per animal after stable and pasture emission is calculated by adding up the two emission sources. The mineral production (M) after emissions of minerals at animal level is given in equation 6.

$$M^{manure,scientific,after\,emissions}_{mdaf} = M^{manure,scientific}_{mdaf} - \sum_{\varphi}\left(E^{pasture}_{\varphi mdaf} + E^{stable}_{\varphi mdaf}\right) \qquad (8)$$

Manure processing on a farm level is not yet implemented in MAMBO.

Emissions from manure storage at farm level are calculated at the level of stables in the Aggregate Manure Production Calculations module. The rationale is that storage systems are often linked to stable categories. However there is often more than one storage system available per stable type. Information on the storage distribution (s_{do}, where subscript o denotes storage types) is used to distinguish what storage systems are applicable on average for each firm.

$$E^{storage}_{mdfo} = s_{do} * \varepsilon^{storage}_{\varphi do} * \sum_{a} M^{manure,scientific,after\,emissions}_{mdaf} \qquad \text{(9, flag 4 in Figure 1)}$$

Surplus manure can be processed on farm prior to transportation. Although on-farm processing is not yet implemented in MAMBO the principal is highlighted anyway.

As presented in equation 10, the emissions from processing depend on the amount of manure processed, the mineral content of that manure and the way of processing.

$$E^{process}_{\varphi\rightarrow\phi,M\varepsilon} = \varepsilon^{process}_{\varphi\rightarrow\phi,M\varepsilon} * \sum_{Rrm}\left(\mu_{M\varphi} * \sum_{FE}\left(Q^{process}_{FERrm,\varphi}\right) * R^{average}_{Rrm,\varphi,M}\right) \qquad \text{(10, flag 5 in Figure 1)}$$

Firms with both animals and crops and or pastures will apply their manure to their own fields to the extent legislation permits. Farm firms with pastures and crops (A) are faced with legal standards regarding the amounts of minerals from manure and other fertilizers they can apply on their land. With respect to own manure applied to crops, firms have to take into account the maximum amount of minerals from manure that may be applied to crops. This amount depends on the legal manure standard (l^m) that is defined for different crops (subscript c) and whether or not the firm is eligible for derogation. In addition in 2006 in the Netherlands, government provided firms with the possibility of applying an additional 5% manure to ease the overheated manure market, by not fining the first 5% excess manure placement over and beyond what is permitted by law. This extra allowance ($l^{allowance}$) can take on the value zero if such an allowance is not in place in a specific year. This is summarized in equation 11a.

Furthermore the maximum allowable manure deposition can also be limited by another set of legislation covering all minerals from all fertilizer sources. Here we deal with legal fertilizer standard (l^f) which is soil specific and can be at any level of aggregation. We also need to take into account the fact that there are certain minimum levels of artificial fertilizer applications based on information from manuring experts (e). The degree to which the minerals count towards the maximum application constraint depends on the minimum effect coefficient. This coefficient is 1 for phosphate but unequal to 1 for nitrogen from manure (organic fertilizer). The value of this coefficient depends on where the manure comes from (own farm or from outside the farm), soil type, crop, and fertilizer or manure category ($\gamma^{Min\ effect\ coef}$), which is also regionally specific. This is summarized in equation 12a.

$$M_m^{Max\ allowable,crops} \leq \sum_{sc}\left(\sum_{\delta}\left(D_\delta^{derogation} * l_{m\delta c}^m\right) * A_{sc}^{crops} * \left(1 + l^{allowance}\right)\right) \tag{11a}$$

$$M_{mf}^{Max\ allowable,crops} \leq \sum_{sc}\left(\sum_{\delta\sigma^{own}}\left(D_\delta^{derogation} * \left[\frac{\left(l_{m\delta sc|r}^f - e_{mc}^{Min\ application}\right)}{\gamma_{m\sigma^{own}scf|n}^{Min\ effect\ coef}}\right]\right) * A_{sc}^{crops} * \left(1 + l^{allowance}\right)\right) \tag{12a}$$

The actual amount of minerals from manure applied on crops depends on fertilizer categories that capture feeding strategies pursued by the farmers. The amount of minerals the firm has to take into account are based on the fixed mineral contents (equation 13a)[1].

$$M_m^{Actual,crops} = \sum_{ad^s f}\left(M_{md^s af}^{manure,\ fixed}\right) \tag{13a}$$

Alternatively it can be calculated over the scientific knowledge-based mineral production of stable manure (equation 13b)[2].

$$M_m^{Actual,crops} = \sum_{ad^s f}\left(M_{md^s af}^{manure,scientific}\right) \tag{13b}$$

The farm household is faced with an optimization problem, what manure to apply to which crops in order to minimize the surplus manure that has to be disposed of. Trading manure is costly. Farmers are faced with transaction costs related to finding a destination for their manure, transportation costs for getting the manure to the destination. This firm can be another farmer with more crop area than own manure or a manure processing plant. [3]

The minimization problem faced by the farmer is twofold. In the first place the farmer will minimize the surplus manure. If there is no surplus manure, the farmer will optimize manure application by directing the manure to those crops that are best served with manure from an agronomic perspective.

$$\min B_{daf}^{manure,surplus} = B_{daf}^{manure} - B_{daf}^{manure,applied\ own\ farm} \tag{14}$$

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[1] In the current situation (*post* 2005 legislation) the amount of minerals the firm has to take into account are based on the legally fixed mineral contents after emissions

[2] This was the case up till 2005 where scientifically based firm level mineral accounts were used to determine allowable application.

[3] In the Netherlands farmers with surplus manure currently pay to have the manure removed in terms payments to the firm at the destination. In other countries and in the Netherlands in the past farmers have to pay to get manure if the do not have sufficient amounts. In both cases trading is costly and include the opportunity costs of not applying the manure on the own farm.

In order to abide by the constraint presented in equation 12a and 12b the following equation can be derived:

$$\sum_{\delta}\left(D_{\delta}^{derogation} * l_{m\delta c}^{m}\right) * A_{scdf}^{crops\ \ own\ manure} * \left(1 + l^{allowance}\right) \geq I_{dfsc}^{own\ manure,appl.own\ crops} * \left[\frac{\sum_{a} M_{mdaf}^{manure,\ fixed}}{\sum_{a} B_{daf}^{manure}}\right] \quad (15)$$

where

$$\sum_{sc} I_{dfsc}^{own\ manure,applied\ own\ crops} = \sum_{a} B_{daf}^{manure,applied\ own\ farm} \quad (16)$$

This equation is defined over the domains of minerals, soil type, crops, department category and fertilizer category. The two choice variables involved are cropped areas with own manure and manure volume applied to crops. These choice variables are defined over the four domains of the equation: soil type, crops, department category and fertilizer category.

In a similar way we derive an equation to capture the constraint related to the legal fertilizer standards:

$$\sum_{\delta\sigma^{own}}\left(D_{\delta}^{derogation} * \left[\frac{\left(l_{m\delta sc|r}^{f} - e_{mc}^{Min\ application}\right)}{\gamma_{m\sigma^{own}scf|n}^{Min\ effect\ coef}}\right]\right) * A_{scdf}^{crops\ with\ own\ manure} * \left(1 + l^{allowance}\right) \geq$$

$$B_{dfsc}^{own\ manure,applied\ own\ crops} * \left[\frac{\sum_{a} M_{mdaf}^{manure,\ fixed}}{\sum_{a} B_{daf}^{manure}}\right] \quad (17)$$

We also define a manure volume balance (equation 19) and a cropped area balance (equation 18):

$$A_{sc}^{crops} \geq \sum_{df}\left(A_{scdf}^{crops\ with\ own\ manure}\right) \quad (18)$$

$$\sum_{a} B_{d^{p}af}^{manure} = \sum_{sc}\left(B_{d^{p}fsc}^{own\ manure,applied\ own\ crops}\right) \quad (19a)$$

$$\sum_{a} B_{d^{s}af}^{manure} \geq \sum_{sc}\left(B_{d^{s}fsc}^{own\ manure,applied\ own\ crops}\right) \quad (19b)$$

Note the difference between pasture and stable manure. Pasture manure is manure deposited by grazing animals on pastures during grazing and constitutes a volume that cannot enter into the surplus of the farm, while for stable manure this surplus can exist.

The second optimization is a stepwise process for those cases where:

$$B_{daf}^{manure,surplus} = 0 \quad (20)$$

and

$$A_{sc}^{crops} - \sum_{df}\left(A_{scdf}^{crops\ with\ own\ manure}\right) \neq 0 \quad (21)$$

The objective function becomes:

$$\max A_{scdf}^{crops\ with\ own\ manure} \quad (22)$$

for the crop with first preference for manure, given constraint equations 15-19, and abiding by non-negativity constraints and rules regarding allowed crop fertilizer combinations. If equation 20 holds we repeat the process for the crop with second preference for manure holding $B_{daf}^{manure,applied\ own\ farm}$ for the crop with first preference fixed at the optimal level. We repeat the process until all manure has been applied to crops and are held fixed. This implies that there are no degrees of freedom left and optimization is complete.

After the manure has been placed on the own firm to the extent that rules and regulations allow, some firms are confronted with surplus manure they need to dispose of. Some firms with little or no livestock will still have fields that can be manured. The surplus manure distribution module of MAMBO has been developed with the explicit purpose of determining the spatial equilibrium in the manure market.

It is important to note an important difference between the calculations at this level and the calculations with respect to the optimal allocation of own manure on own fields. In the previous calculations it was the fixed manure mineral content as described in legislation in combination with the legal norms with respect to manure and fertilizer application that determined the equilibrium. In the following equations it is the actual mineral content that is important. A second important difference is that the scale at which we calculate the spatial equilibrium is different. In the previous sections the scale was the firm and everything on it. Now the scale is a regional area. These regional areas are the manure regions defined at the national level and used in spatial disaggregation of policy instruments. These manure regions (subscripts *r* and *R*) represent areas with different types of livestock management systems. Surplus manure that cannot be applied on own fields can be disposed of in several ways. It can be transported to other firms, exported from the agricultural sector, processed or stored. In the case of storage one should also take into consideration the amount of manure in store from the previous period.

$$B_{df|r}^{manure,surplus} + B_{df|r,t-1}^{Storage} = \sum_{R} B_{df|r\rightarrow R}^{manure,transported} + \sum_{\omega} B_{df\omega|r}^{manure,processed} + B_{df|r}^{manure,Exported} + B_{df|r}^{Storage} \tag{23}$$

where the total amount of exported manure and processed manure are limited by demand constraints that are given exogenously. Whether or not storage is taken into account is a matter of user defined choice. The processed manure has its own dynamics. Processed manure is processed in manure products based on fractions that the of the manure that go into each of the (by) products. One of these by products is waste-water from dehydration processes which contains insignificant amounts of minerals and can be dumped on the surface water. As with the case of unprocessed manure there are exogenous demand constraints related to export.

$$\sum_{\omega}\left(\varphi_{dfDF\omega}^{proceesed\ manure\ fraction} * B_{df\omega|r}^{manure,processed}\right) = QB_{DF|r}^{manure\ product,Exported} + B_{DF|r}^{manure\ product,Dumped} + \sum_{R} Q_{DF|r\rightarrow R}^{manure\ product,Transported} \tag{24}$$

The transported manure and manure products can be applied to fields of farmers willing to accept the manure and/or products. Acceptation of manure depends on the potential application area comparable to what happened to own manure applied to own fields, which depends on legislation and an acceptation degree factor (α_c) which is crop and regional area specific. The acceptation degree factor depends on perceived risk of using off-farm manure and is based on empirical information from the Dutch Farm Accountancy Network. Note that normally the acceptation degree factor is less or equal to 1 if farmers are to abide by the rules and regulation. However the fact that we use most limiting minerals to define allocation according to the existing methodology, some farmers will have additional space left for application within the bounds of the law. This can lead to acceptation degrees in excess of 1.

$$\sum_{\delta\sigma^{offfarm}} \left(\left[\frac{\left(l^{f}_{m\delta sc|R} - e^{Min\,application}_{mc} \right)}{\gamma^{Min\,effect\,coef}_{m\sigma^{offfarm}scf|N}} \right] \right) * \left(D^{derogation}_{\delta} * \left[A^{crops}_{\delta sc|R} - \sum_{DF} A^{crops\,with\,own\,manure}_{scDF|R} \right] \right) *$$

$$\left(1 + l^{allowance} \right) * (\alpha_{c|R}) \geq$$

$$Q^{manure\,product,transported}_{df|r\rightarrow R} * \left[\frac{M^{manure\,product,scientific}_{mdf|r}}{\left(Q^{manure\,product,Exported}_{df|r} + Q^{manure\,product,Dumped}_{df|r} + Q^{manure\,product,Transported}_{df|r\rightarrow R} \right)} \right]$$

$$+ B^{manure,transported}_{df|r\rightarrow R} * \left[\frac{\sum_{a} M^{manure,scientific}_{mdaf|r}}{\sum_{a} B^{manure}_{daf|r}} \right] \qquad (25)$$

Where the mineral content of manure products is defined as follows:

$$M^{manure\,product,scientific}_{mdf|r} = \sum_{DF\omega} \varphi^{Mineral\,distribution\,fraction}_{mDFdf\omega} * B^{manure,processed}_{DF\omega|r} * \frac{\sum_{a} M^{manure,scientific}_{mDaF|r}}{\sum_{a} B^{manure}_{DaF|r}} \qquad (26)$$

The left-hand side of equation 25 signifies potential demand. The right-hand side is supply. In equilibrium there is a quantity of manure and manure products that are applied to crops on soils . In order to determine how the surplus manure is distributed we apply a spatial equilibrium model based on linear programming techniques. In order to determine the optimal allocation minimization of distribution costs is used as main concept. Distribution costs entail all costs necessary to dispose of surplus manure and encompass physical distribution costs (loading and unloading manure, storage and transport), manure processing costs and export costs..

The objective function becomes:

$$\min C^{AggregateCost} - \Pi^{Aggregate\,revenues} \qquad (27)$$

Where CAggregate Cost are the aggregate costs, and ΠAggregate revenue are aggregate revenues from manure distribution:

$$
C^{Aggregate\,Costs} = \sum_{df} \left(\begin{array}{l}
\displaystyle\sum_{r\to R|r=R} \left(\sum_{\mu\in M\mu f} \left(\begin{array}{l} \left(c_{\mu}^{fixed,in\,r} + c_{\mu}^{storage,in\,r} + \displaystyle\sum_{\sigma^{offfarm}} c_{\sigma^{offfarm}f}^{application} \right) * \\ \left(B_{df|r\to R}^{manure,transported} + Q_{df|r\to R}^{manure\,product,transported} \right) \end{array} \right) \right) + \\
\displaystyle\sum_{r\to R|r\neq R} \left(\sum_{\mu\in M\mu f} \left(\begin{array}{l} \left(\begin{array}{l} c_{\mu}^{transport} * d_{r\to R} + \\ c_{\mu}^{fixed,out\,r} + c_{\mu}^{storage,out\,r} + \displaystyle\sum_{\sigma^{offfarm}} c_{\sigma^{offfarm}f}^{application} \end{array} \right) * \\ \left(B_{df|r\to R}^{manure,transported} + Q_{df|r\to R}^{manure\,product,transported} \right) \end{array} \right) \right) + \\
\displaystyle\sum_{\omega|r} \left(\begin{array}{l} \left(\displaystyle\sum_{\mu\in M\mu f} \left(c_{\mu}^{storage,\,processed\,manure} + c_{\mu}^{fixed,\,Sector} \right) + c_{\omega f}^{process} \right) * \\ B_{df\omega|r}^{manure,\,processed} \end{array} \right) \\
\displaystyle\sum_{r} \left(\sum_{\mu\in M\mu f} \left(\begin{array}{l} c_{\mu}^{fixed,\,Export} * \\ \left(B_{df|r}^{manure,\,Exported} + Q_{df|r}^{manure\,product,\,Exported} \right) \end{array} \right) \right) + \\
\displaystyle\sum_{sc} \left(c_{scdf}^{risk\,penalty} * I_{scdf|R}^{crops\,with\,offfarm\,manure} \right)
\end{array} \right) \quad (28)
$$

and

$$
\Pi^{Aggregate\,revenues} = \sum_{r\to R,r=R} \left(\pi_{fR}^{manure\,revenue} \left[B_{df|r\to R}^{manure,transported} + Q_{df|r\to R}^{manure\,product,transported} \right] \right) \quad (29)
$$

For surplus manure in a specific region the following possibilities exist: supply within the region; supply to other regions; export.

We can calculate the area available for fertilization with inorganic fertilizers based on the initial area and subtracting the areas with full fertilization based on placement of own manure (from equation 14-22) and placement of off-farm manure and manure products (from equation 23-29).

$$
A_{\delta sc|m}^{crops,not\,fertilized} = A_{\delta sc|m}^{crops} - \sum_{df} \left(A_{scdf|m}^{crops\,with\,own\,manure} + A_{scdf|m}^{crops\,with\,offfarm\,manure} + A_{scdf|m}^{crops\,with\,manure\,products} \right) \quad (30)
$$

$$
\sum_{\delta\sigma^{offfarm}} \left(\left[\frac{\left(l_{m\delta sc|R}^{f} \right)}{\gamma_{m\sigma^{offfarm}scf|m}^{Min\,effect\,coef}} \right] \right) * \left(\left[A_{\delta sc|m}^{crops,not\,fertilized} \right] \right) * \left(1 + l^{allowance} \right) \geq I_{\delta fsc|m}^{artificial\,fertilizer} * \mu_{mf} \quad (31)
$$

with

$$
e_{mc}^{Min\,application} \leq \frac{\displaystyle\sum_{f\in m} \left(I_{\delta fsc|m}^{artificial\,fertilizer} * \mu_{mf} \right)}{\displaystyle\sum_{f\in m} \left(A_{\delta fsc|m}^{artificial\,fertilizer} \right)} \quad (32)
$$

Holding for each soil type with crops. We now have all the organic and inorganic fertilizer applications and can calculate application emissions:

$$E_{\varphi mscf|s}^{Organic\,application} = \left(\sum_{\kappa\delta\sigma\eta\mu} \left(\begin{array}{l} M_{m\delta\sigma fsc}^{Organic\,Minerals\,applied\,to\,crops} * \eta_{\eta\mu sc}^{application\,utilization} * \\ \varepsilon_{\varphi m\kappa\eta\mu}^{application} * \varphi_{m\kappa f}^{Mineral\,fraction} \end{array} \right) \right)$$

$$* \gamma_{mcf|s}^{Mineral\,effect} * \varphi_{sc|s}^{season\,application} \qquad \mu \in \Phi_{\mu f}, f \in \{f^{m}, f^{mp}\} \quad \text{(33, flag 6 in Figure 1)}$$

For artificial (inorganic) fertilizers a different equation is used

$$E_{mscf^{a}|s}^{Inorganic\,application} = I_{\delta scf^{a}}^{Artificial\,\,fertilizer} * \mu_{mf^{a}} * \varepsilon_{mf^{a}}^{Artificial\,\,fertilizer} \qquad \text{(34, flag 6 in Figure 1)}$$

5. Data

Data is crucial in micro-simulation models because individual actors and their characteristics are taken into account. In this section we discuss the data that is used in the model, and their principal sources. The lowest level of detail possible in MAMBO is each individual animal and fields as starting point for calculations. However for most calculations there is no information available for individual animals or fields, so the starting point will be at firm level. Although, this information can be obtained from any available source, we use the data from the agricultural census, implying that we model every single Dutch livestock enterprise. Some information such as inventories of housing systems and outside storage facilities, application techniques of manure (Hoogeveen et al., 2006) are only conducted every four, ten or five years, respectively.

Within the Dutch farm accountancy data network (a sample of about 1500 agriculture and horticulture farms), every year an inventory is made of many relevant parameters such as: grazing systems available, grazing period, artificial fertilizer applied, acceptation degree of off-farm manure.

Excretion of manure and minerals can vary because of grazing system and ration. These factors are different for each firm and for each year. Therefore the WUM (state committee for determining consensus technical coefficients) estimates each year the manure excretion of animal categories that are relevant for the manure policy and the CBS determines the mineral content (Cor van Bruggen, 2007). The agricultural mineral effect coefficient is a fraction per mineral, crop and fertilizer category, based on scientific research or expert judgment and is provided by PPO.

For legal standards the data is taken from legislation. The fixed mineral effect coefficient is provided by LNV. The principle of the fixed mineral effect coefficient is similar to the agricultural mineral effect coefficient, but their values have political intentions as to discourage farmers to apply manure in autumn and winter. Other data is obtained from The Regulatory Agency of the Ministry of Agriculture, Nature, and Fisheries (LNV-DR). For soil distribution we rely on Farm Plots Registration (BRP, LNV-DR) as a result of which each firm receives it's specific soil distribution. They also provide data on manure trade (exports, processing) based on transport registration forms of transport companies. For monitoring the manure market LNV-DR provides the registrated transported manure and minerals. This information is first verified and aggregated by the CBS.

6. Results

6.1 Monitoring pollution

Monitoring pollution is one of the primary goals of MAMBO. The results of the ammonia emission inventory are published regularly (MNP, 2005, 2006a, 2006b; Brouwer et al., 2002; Hoogeveen et al., 2007; Luesink, 2004; Starmans et al, 2007).

Table 1 presents the Dutch ammonia emission from different sources over time. The data presented in this table are the official ammonia emissions of the Netherlands as reported to the European Union. The emission of housing and storage is combined because manure is mainly stored indoors in the Netherlands and the emission factors of housing include indoor storage of manure. Only part of the manure is stored outside the animal houses, in the 80's this part was very small (almost no slurry and about 50% of the solid manure). At the end of the 90's about 50% of cattle manure, 20% of pig manure and almost all solid poultry manure were stored outside the animal house. Due to legislation, all these outside storages had to be covered, and this leads to an emission of 4 million kg of ammonia from outside storage, about 2.5% of the total ammonia emission in the Netherlands at that time.

Table 1. Ammonia emission from Dutch agriculture 1980 - 2004 (million kg of ammonia)

	1980	1985	1990	1995	2000	2004
Animal manure	204	227	210	166	128	111
Housing & storage	77	86	89	89	73	60
Grazing	14	16	16	14	10	9
Application	114	125	119	63	45	43
Fertilizer	15	12	13	13	11	9
Total agriculture	220	239	237	179	139	120
Emission per ha Agriculture area (kg NH_3)	107	118	110	90	71	62
Index (1980 =100)	100	110	108	81	63	55

Source: (Luesink, 2004 and Hoogeveen et al, 2007)

Currently the national ammonia emission is half of the maximum value calculated in 1985. There are a couple of reasons why the ammonia emissions declined:

- Introduction and reduction of the milk quota caused a reduction in the number of dairy cattle from 4.2 million heads in 1985 to 2.6 million heads in 2004;
- Laws prescribing manure application techniques with low emission factors were implemented in 1988 at arable land and in 1991 at grassland. In 1995 they were fully implemented for all areas in the Netherlands.
- Buying of animal production rights by the government in 2001 and 2002 caused a decrease in the amount of pigs and poultry of about 15%.

The last few years the trend of a declining ammonia emission from agriculture has stabilized at around 120 million kg ammonia per year. The ammonia emission from non-agricultural sources in the Netherlands is about 13 million kg. Thus, the total ammonia emission in the Netherlands ranges from about 130 to 135 million kg in the last few years. This is almost the NEC target of 128 million kg in 2010 (MNP, 2006b).

As seen in table 2, the ammonia emission from grazing animals slowly declines over the last few years. Besides the structural decline in the number of grazing animals it also originates from changes in the amount of nitrogen in fed roughage. Due to the Dutch manure laws (MINAS-system) the use of nitrogen fertilizer on grassland declined from more than 250 kg per hectare in 1998 to about 170 kg in 2002 and 2003, which led to a lower nitrogen content in on-farm produced roughage (Luesink and Wisman, 2005). The decline of ammonia emission would be even more when the grazing systems in the same period did not change from day and night grazing, to more limited grazing and summer feeding.

6.2 *ex-ante* evaluation of tightening legislation

In 2006, new manure laws were introduced in the Netherlands. Application norms are an essential element of these new laws. From 2006 till 2015 the application norms will get more tight. In 2015, the application of phosphate in animal manure and artificial fertilizer should be in balance with the use of the crops it is applied on. The study described in this section was conducted on behalf of the ministry of agriculture in order to establish the expected impact of these norms on the Dutch manure market in 2009, 2012 and 2015. The MAMBO model was used to calculate the impact. In this section some of the results are shortly presented.

Figure 2 displays the predictions of the production of phosphate for four different years. Figure 3 displays the total application of phosphate (from animal manure) for four different years. The results for nitrogen are in line with these results except for a level difference (application of nitrogen is a factor 2.3 higher). Figure 4 is based on the results of scenario 1.

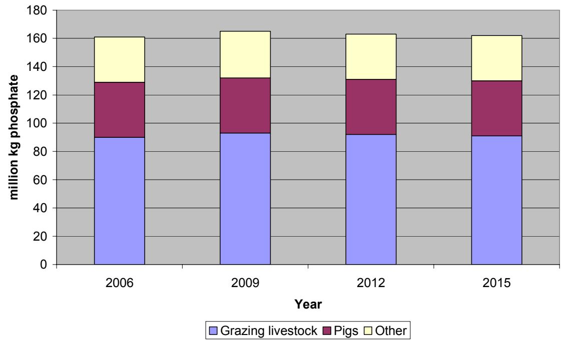

Figure 2 Estimated production of phosphate in 4 different years

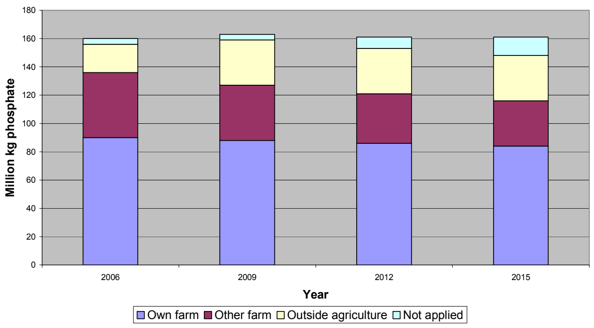

Figure 3 Estimated application of phosphate (for the year 2006, 2009, 2012, 2015)

The estimated phosphate production for 2009 is slightly higher than for 2006 (see figure 3). This is due to the fact that the calculation for dairy and calving cows for 2009 is based on the firm specific values based on the milk productivity and the ureum content of milk, and the calculation for 2006 is based on the excretion values according to the WUM (base year 2004). The firm specific values result in a 5% higher value than the WUM values. In 2015, the phosphate production is more than 1% lower due to a decrease in the number of poultry and dairy animals.

Due to the tightening of the application norms the amount of applied phosphate from manure decreases between 2006 and 2015 from 90 million kg till 84 million kg (see figure 3). Due to the lower acceptance of manure produced at other farms and the more tight application norms the application of manure from other farms is 7 million kg lower in 2009 then in 2006 (15% reduction).

The further tightening of the phosphate application norms after 2009 will result in a further decrease of 7 million kg of the application of manure produced on other farms. An increase in export (5 million kg) and the introduction of the manure incineration facility in Moerdijk will result in an increase of 12 million kg phosphate that is applied outside of Dutch agriculture. Figure 2 also displayes the amount of produced manure that cannot be applied. In 2006 as well as 2009, 2,5% of the production cannot be applied (4 million kg phosphate). This amount increases till 8% of the production for the year 2015 (13 million kg phosphate).

7. Discussion and Conclusions

In the paper we presented MAMBO a combined micro-simulation model and a spatial equilibrium model for simulating relevant actors behaviour with regard to manure and artificial fertilizer in order to get a handle on emissions of pollutants (nitrate, phosphate and ammonia) from livestock and agricultural activities. The models were calibrated with empirical data from regulatory agencies. Validation of model components has been conducted on a number of occasions. The results from the modeling framework are robust and form the basic input into policy discussions in the Netherlands on non-point source pollution from agriculture. The results are being used to evaluate policies both ex-post to see the impact the policies have had on both emissions and on economic indicators related to the manure market.

We feel that micro-simulation for addressing policy issues related to non-point source pollution is the way forward. The modeling framework MAMBO we use is flexible enough to take into account changing policies while still capturing the behavior of economic actors. Our choice of model has been a combination of micro-simulation and a spatial equilibrium model for the manure market. Obviously there is still a lot of work that can be done to improve the performance of the model, especially where it concerns explorations of the future. This is primarily due to the fact that the current applications of the model concentrate on monitoring current levels of pollution where a lot of variables are known (prices, investment decisions, production structure). By linking the model to investment modules we will be able to simulate possible changes in the structure of agriculture.

At present it suffices to say that MAMBO is able to deal with the complex issues of non-point source pollution in a way that offers scope for the future.

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