The impact of concentrated pig production in Flanders: a spatial analysis

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Abstract

Historically concentrated livestock production and, consequently, manure production and management in Belgium have resulted in severe environmental impacts. One major impact, nitrate leaching from soil to surface water, is being tackled through the European Nitrates Directive by imposing strict fertilization standards. However, another significant impact of manure management is the emission of greenhouse gasses (GHG - CO_2, CH_4, NH_3 and N_2O) into the air, thereby contributing to global warming. Calls have been made to reduce the high manure pressure and related environmental effects in Belgium by relocating and more evenly spreading livestock production.

This paper explores the spatial spreading of CO_2-equivalent emissions from livestock production in Belgium and attempt to answer the following question: 'Can spatial reallocation of livestock production in Belgium reduce the impact of GHG emissions?'. This question is translated into several research objectives: 1) conduct an economic (cost minimization) and environmental (GHG minimization) optimization for 3 manure management scenarios, 2) determine the main differences between both approaches, and 3) determine the marginal spatial impact on CO_2 emissions of a decrease in manure pressure (i.e., increased spreading of pig production).

To conduct the analysis, a model was developed that builds on the spatial mathematical programming multi-agent manure allocation model developed by Van der Straeten et al. (2010). Three options for manure management are inserted: transport of raw manure from nutrient excess to nutrient deficit areas, biological treatment of manure (manure processing) and manure separation. The model optimizes, at municipal level, either the cost-efficiency, either the environmental effect of the manure market in Belgium based on Belgian fertilization standards. While cost-efficiency is calculated based on transport distances and cost of manure separation and processing, GHG emissions, and hence, carbon footprint, are determined based on a life cycle analysis type calculation.

The results of the model simulations show that, while the economic optimum is reached by maximizing the transport of raw manure until fertilization standards are fulfilled and subsequently separating and processing the excess manure, the environmental optimum, from a carbon footprint point of view, is reached by separating all manure as this option has the lowest CO_2 emissions, mainly due to the limited manure storage time. Moreover, the analyses indicate that rearrangement of the spatial spreading of livestock production in Belgium will not substantially decrease CO_2 emissions. As manure storage is the main contributor to the carbon footprint, solutions should rather lie in changing these storage systems.

1. Introduction

During the last decades, European regions with intensive livestock production, such as Belgium (Flanders), are facing a big challenge to cope with manure surpluses. Manure management causes a big environmental problem, since it is associated with nutrient leaching to ground and surface water, threatening the ecological stability in those regions (Lopez-Ridaura et al., 2009). Moreover, large amounts of greenhouse gas (GHG) emissions, such as methane and nitrous oxide, related to manure storage and its application on crop land cause a large environmental burden associated with intensive livestock production (Loyon et al. 2007; Lopez-Ridaura et al. 2009; Rigolot et al. 2010; De Vries et al. 2012).

Up to now, the European Nitrates Directive (91/676/EEC) has shown the largest impact on the GHG emissions related to intensive livestock production by strictly regulating manure application, reducing the manure surplus and obliging manure processing (European Environment Agency, 2014). Manure processing by means of the biological processes of nitrification and denitrification not only reduces the nutrient pressure on agricultural soils, but also decreases the ammonia and greenhouse gas emissions originating from raw manure significantly (Lemmens et al., 2007).

However, the main bottleneck of manure management in Flanders is the strongly concentrated production of livestock and manure in the West of Flanders and Northern part of Antwerp (Van der Straeten and Buysse, 2013). Hence it is assumed that the transport distance will be an important parameter in the determination of the total carbon footprint. At this moment, manure export mainly occurs to Northern France and Zeelandic Flanders in the south-western Netherlands to limit transport distances. Though, calls have been made to reduce the high manure pressure and related environmental effects in Belgium by relocating and more evenly spreading livestock production. Furthermore, manure transport from Flanders to Wallonia, which is not allowed yet, could possibly result in important CO_2 emission savings.

To quantify the environmental impact of manure management, the amount of manure production and the available crop land have to be taken into account. As a consequence, changes in both nutrient production and nutrient allocation will affect the greenhouse gas emissions coming from manure management.

In this paper the effect of a reduced manure pressure will be investigated and to verify the impact on the carbon footprint, a consequential life cycle approach is selected above an attributional approach as the most appropriate approach. The attributional approach to environmental impact calculation, also called accounting or descriptive approach, attempts to provide information on the share of global burdens that can be associated with a product and its life cycle, while the consequential approach estimates how flows to and from the environment will change as a result of different potential decisions (Curran et al., 2005; Sonnemann and Vigon, 2011), such as in this case spatial reallocation of livestock production.

The paper is organized as follows: after a short introduction, the methodology is explained, followed by a presentation and discussion of the results and finally a conclusion will be drawn. Due to the extensive methodology involved, what follows is a summary of the methodology. Further explanation can be found in annex.

2. Methodology

2.1. Functional unit and system boundaries

The functional unit is the total amount of piggery manure produced on yearly basis in each municipality in Belgium. System boundaries are set starting from manure production to the arrival of the (processed) manure at its final destination, thus from cradle to grave. The system boundaries exclude the production of capital goods, such as machines and equipment, similar to most international studies. The CO_2 emissions from manure storage and treatment are not taken into account because those emissions are considered part of the short carbon cycle, i.e. resulting from recent CO_2 uptake by crops. On the other hand, the emission of CO_2 originating from fossil energy use is taken into account.

2.2. Data sources

Greenhouse gas emissions within the system boundaries of the three scenarios are determined for each municipality in Belgium. The emissions of each livestock category are calculated using the '2006 Intergovernmental Panel on Climate Change (IPCC) guidelines for national greenhouse gas inventories' (IPCC, 2006a; IPCC, 2006b), reports on emissions and energy use and available country specific data from the norms and guidelines of VLM (VLM, 2014), the Belgian National Inventory System (NIS) database and the National Inventory Report of Belgium (VMM et al., 2014). The data and equations are then implemented in the standard optimization software GAMS (General Algebraic Modelling System).

2.3. Description of the manure management scenarios

In the transport scenario, excess raw manure is transported outside the pressure region within Flanders and applied to crop land, substituting mineral fertilizers. In the treatment scenario, excess manure is separated and the liquid fraction is treated in a biological treatment plant, while the second fraction is composted and exported. The separation scenario considers the separation of excess manure after which the liquid fraction is applied as mineral N-fertilizer replacement and the solid fraction is composted and exported. The following subsections provide, together with Table 1, a summary of the actions and emissions that take place in the different scenarios. More information about the assumptions is provided in Annex 1.

Table 1 provides a schematic overview of the different types of emissions that arise in the different stages of manure management. This table serves as a guide for interpretation of the different scenarios.

2.3.1.Raw manure transport scenario

The manure transport scenario includes on-farm storage, its transport to the spreading area and its application on the crop land. Piggery manure is stored as slurry in a pit under the stable and causes methane and nitrous oxide emissions (VMM et al., 2013; Jacobsen et al., 2014; IPCC, 2006a). The use of non-renewable energy in this scenario includes the energy use for transport of the manure slurry to the spreading area and for its injection. In regard to soil management and fertilizer application, direct and indirect nitrous oxide emissions from managed soils can be derived using the IPCC equations (Equation 6 and 8, Annex 1b). Finally, the manure slurry can be applied on crop land and substituting synthetic fertilizers. For the calculation of the carbon footprint, it is necessary to include (subtract) the impact related to the production, transport and application of these replaced fertilizers.

2.3.2.Separation scenario

The separation scenario includes storage, its transport to a manure treatment plant where it is separated, intermediate storage of the separated fractions, transport and application of the liquid fraction to crop land, and composting and export of the solid fraction. Good practice dictates that manure is delivered to the treatment plant as fresh as possible, but in reality the slurry is stored on-farm before treated. The unloading of the liquid manure takes place in-house or emission-poor seals are used for pumping the slurry from the truck to the buffer tank through a manure hose. The slurry is blown into the storage tank by which the displaced air is emitted. After unloading, all the air from the hose is blown out before the seals are closed (Lemmens et al., 2007). Leakage is assumed to be negligible. It is assumed that a centrifuge is used for the mechanical separation of the slurry since it is the most common technique used in Flanders. Separation occurs most of the time in a closed instrument or in the stable, therefore emissions are expected to be very little and the amount of nutrients that enter the system should be the same as the amount that leave the system (Lemmens et al. 2007; Melse et al. 2004). In most cases, the solid fraction is composted and the liquid fraction is biologically treated. The purpose of manure composting (biothermal drying) is germ elimination by increasing the temperature, volume and weight reduction by evaporation of the moisture, and the stabilisation of the organic material. Manure separation doesn't have an influence on the emission of ammonia from the liquid fraction or the solid fraction when applied to grassland and cropland respectively, in comparison to raw manure. This was also the case for nitrous oxide emissions from the liquid fraction when applied to grassland (Mosquera et al., 2010). Consequently, the same emission factors are used as for the application of raw manure.

2.3.3. Treatment scenario

In Flanders, manure processing consists of three important phases: (i) physical separation in a liquid (85%) and a solid (15%) fraction; (ii) composting of the solid fraction to an exportable product and (iii) reduction of the nutrient content in the liquid fraction through biological treatment (Meers et al., 2008). Hence, the manure treatment scenario includes storage, its transport to the treatment plant, mechanical separation, biological treatment of the liquid fraction, transport and composting of the solid fraction, and transport and application of the effluent and the compost to crop land. It is assumed that the manure slurry is stored on- farm in a similar way as in the separation scenario. The separation of the slurry at the biological treatment plant also occurs in the same manner. Afterwards, the liquid fraction is almost immediately biologically treated in the nitrification/denitrification reactor(s). The solid fraction is transported to a composting installation as is the case for the separation scenario. In a biological treatment plant where nitrogen is biologically removed from the liquid fraction by nitrification and subsequent denitrification, electrical energy is necessary for aeration, pumping and power. The high residual content of N, P and K in the effluent of the biological treatment plant is still too high to allow discharge in Flanders; however, the effluent can be applied to crop land as potassium fertilizer since the amount of potassium is more or less equal to the amount in raw slurry.

2.4. Manure Allocation Model

2.4.1. Model build-up

To conduct the analysis, a model was developed that builds on the spatial mathematical programming multi-agent manure allocation model (MAM) developed by Van der Straeten et al. (2010). The three options for manure management are the ones mentioned above: transport of raw manure from nutrient excess to nutrient deficit areas, biological treatment of manure (manure treatment) and manure separation. The model optimizes, at municipal level, either the cost-efficiency, either the environmental effect of the manure market in Belgium based on Belgian fertilization standards. While cost-efficiency is calculated based on transport distances and cost of manure separation and treatment, GHG emissions, and hence, carbon footprint, are determined based on a consequential life cycle approach.

Figure 1 shows a schematic representation of the MAM. Different types of livestock produce manure with a different nutrient content, i.e. a specific amount (in kg) of nitrogen and phosphorus each year (left on the figure). The manure is applied on the field, where different crops have different fertilization standards, meaning that, per crop type, a specific amount (in kg) of nitrogen and phosphorus can be applied per hectare per year on the land (right on the figure). Because, in the case of Flanders, a manure surplus exists, not all raw manure can be applied on the field. Therefore, the manure has to be processed, altering the nutrient content of the different manure streams. This is the middle step in the figure, representing the different manure treatment scenarios mentioned before. The cylinder represents raw manure, the square represents biological treatment, and the trapezium represents manure separation. By adjusting the nutrient content of the different types of manure through treatment, more (treated) manure can be applied on the field.

Of course this manure allocation comes at a cost. Firstly, there is the cost of manure transport C_{TR}(raw and processed) from storage to field (equation 1),

$$C_{TR} = \left(\sum_{m1,m2,A} M_{m1,m2,A}^{RAW,TR} + \sum_{m1,m2,A,T} M_{m1,m2,T,A}^{THIN,TR}\right) * c_{trans} * d_{m1,m2} \quad (1)$$

where m1 and m2 refer to the municipality of origin of manure and the receiving municipality respectively. A refers to all the different types of animals from which the manure originates, i.e, pig, chicken, cattle, etc. while T refers to the type of processing technology used, i.e., separation or biological treatment. $M_{m1,m2,A}^{RAW,TR}$ and $M_{m1,m2,T,A}^{THIN,TR}$ refer to the quantity of raw manure and thin fraction from separation and biological treatment respectively that are transported from m1 to m2, while c_{trans} refers to the unit transport cost per m^3 manure and per km, and $d_{m1,m2}$ the distance between municipalities m1 and m2.

Secondly, there is the cost of spreading the manure on the field C_{SPR} (equation 2),

$$C_{SPR} = c_{spread} * \left(\sum_{m1,A} M_{m1,A}^{RAW} + \sum_{m1,m2,A} M_{m2,m1,A}^{RAW,TR} - \sum_{m1,m2,A} M_{m1,m2,A}^{RAW,TR} + \sum_{m1,m2,T,A} M_{m2,m1,T,A}^{THIN,TR} - \sum_{m1,m2,T,A} M_{m1,m2,T,A}^{THIN,TR}\right) \quad (2)$$

where c_{spread} is the unit cost per m^3 of manure spread. $M_{m1,A}^{RAW}$ is the total quantity of raw manure produced in m1, $M_{m2,m1,A}^{RAW,TR}$ and $M_{m2,m1,T,A}^{THIN,TR}$ the respective quantity of raw manure and thin fraction from processed manure (separated and treated) imported from m2 to m1, and $M_{m1,m2,A}^{RAW,TR}$ and $M_{m1,m2,T,A}^{THIN,TR}$ the respective quantity of raw manure and thin fraction from processed manure (separated and treated) exported from m1 to m2.

Thirdly, the cost of manure processing C_{PR} must be included (equation 3),

$$C_{PR} = \sum_{m1,T,A} M_{m1,T,A}^{PROC} * \ c_{T,A}^{proc} \quad (3)$$

where $M_{m1,T,A}^{PROC}$ is the total quantity of raw manure (all animal types) to be processed in m1, and $c_{T,A}^{proc}$ the processing cost per ton manure, per animal type.

Finally, we subtract the avoided costs C_{AV} that would have been incurred had mineral fertilizer be used instead of (processed) pig manure (equation 4)

$$C_{AV} = \left(\sum_{m1,pig} M_{m1,pig}^{RAW,N} + M_{m1,pig}^{THIN,N}\right) * \ MFE_N * \ c_N + \left(\sum_{m1,pig} M_{m1,pig}^{RAW,P} + M_{m1,pig}^{THIN,P}\right) * MFE_P * \ c_P + \left(\sum_{m1,pig} M_{m1,pig}^{RAW,K} + M_{m1,pig}^{THIN,K}\right) * \ MFE_K * \ c_K \quad (4)$$

where $M_{m1,pig}^{RAW,N}$, $M_{m1,pig}^{RAW,P}$, and $M_{m1,pig}^{RAW,K}$ refer to the respective amount of nitrogen, phosphorus and potassium present in the raw pig manure, while $M_{m1,pig}^{THIN,N}$, $M_{m1,pig}^{THIN,P}$, and $M_{m1,pig}^{THIN,K}$ refer to the respective amount of nitrogen, phosphorus and potassium present in the thin fraction pig manure (from separation as well as treatment). Moreover, $MFE_{N,P,K,} \, c_{N,P,K}$ refer to the mineral fertilizer equivalent and cost of nitrogen, phosphorus and potassium respectively.

When looking at economic optimization of manure allocation, we will ask the model to minimize the total cost (equation 5)

$$Min. C_{TOT} = \ C_{TR} + \ C_{SPR} + \ C_{PR} - \ C_{AV} \quad (5)$$

On the other hand, when we look at ecologic optimization of manure allocation, we ask the model the minimize the total emission $CO_{2,TOT}$. The total emission is composed of the emissions during the different stages of manure management, described in section 2.3 and Table 1. The objective function takes the form of (equation 6)

$$Min. CO_{2,TOT} = \ \sum_{SC} CO_{2,SC}^{STORE,CH4} + CO_{2,SC}^{STORE,N2O_D} + \ CO_{2,SC}^{STORE,N2O_{ID}} + \ CO_{2,SC}^{TR} + \ CO_{2,SC}^{APPL_D} + CO_{2,SC}^{APPL_{ID}} + \ CO_{2,SC}^{APPL,FUEL} + \ CO_{2,SC}^{PROC} - (CO_{2,SC}^{AV,MF} + \ CO_{2,SC}^{AV,MF\ APPL} + \ CO_{2,SC}^{AV,MF\ APPL\ FUEL})$$

(6)

where $CO_{2,TOT}$ is the sum, over the 3 management scenarios SC of raw manure transport, biological treatment and separation, of emissions from storage, more specifically methane $CO_{2,SC}^{STORE,CH4}$, direct nitrous oxide $CO_{2,SC}^{STORE,N2O_D}$ and indirect nitrous oxide $CO_{2,SC}^{STORE,N2O_{ID}}$, emissions from transport $CO_{2,SC}^{TR}$, emissions from manure application/soil management, direct, $CO_{2,SC}^{APPL_D}$, as well as indirect, $CO_{2,SC}^{APPL_{ID}}$ and from fuel consumption $CO_{2,SC}^{APPL,FUEL}$, emissions from manure processing $CO_{2,SC}^{PROC}$, and subtracting avoided emissions from the production of mineral fertilizer MF $CO_{2,SC}^{AV,MF}$, avoided emissions from mineral fertilizer application $CO_{2,SC}^{AV,MF\ APPL}$, and avoided emissions from fuel use during mineral fertilizer application $CO_{2,SC}^{AV,MF\ APPL\ FUEL}$.

A number of other conditions have to be fulfilled as well to be able to conduct this optimization. First of all, we have to make sure that the 'manure balance' is in order (equation 7)

$$\sum_{m1} M_{m1,m2,A}^{RAW,TR} + \sum_{m1,T} M_{m1,m2,T,A}^{PROC,TR} \leq M_{m1,A}^{RAW} \qquad (7)$$

This means that, per municipality and type of animal present there, the amount of raw manure $M_{m1,m2,A}^{RAW,TR}$ and processed manure $M_{m1,m2,T,A}^{PROC,TR}$ that is transported out of each municipality has to be smaller than the total amount produced in that municipality. It has to be smaller and not equal to because raw manure can also be applied on fields in the same municipality, and this is not accounted for under 'transport'.

Secondly, the 'nutrient balance' has to be correct (equation 8)

$$\sum_{A} M_{m1,A,NUT}^{RAW,NUT} + \sum_{m2,A} M_{m2,m1,A,NUT}^{RAW,TR,NUT} - \sum_{m2,A} M_{m1,m2,A,NUT}^{RAW,TR,NUT} + \sum_{m2,T,A} M_{m2,m1,T,A,NUT}^{THIN,TR,NUT} - \sum_{m2,T,A} M_{m1,m2,T,A,NUT}^{THIN,TR,NUT} - \sum_{m2,T,A} M_{m1,m2,T,A,NUT}^{THICK,TR,NUT} \leq 0.95 * \sum_{CR} ha_{m1,CR}^{NUT} * NR_{CR}^{NUT} \qquad (8)$$

Here, we impose that, for each municipality, the sum of the amount of each nutrient NUT (N and P) produced (through all types of manure) $M_{m1,A,NUT}^{RAW,NUT}$, transported in $M_{m2,m1,A,NUT}^{RAW,TR,NUT}$ and out $M_{m1,m2,A,NUT}^{RAW,TR,NUT}$, processed and thin faction transported in $M_{m2,m1,T,A,NUT}^{THIN,TR,NUT}$ or out $M_{m1,m2,T,A,NUT}^{THIN,TR,NUT}$, or thick fraction transported out $M_{m1,m2,T,A,NUT}^{THICK,TR,NUT}$ of the municipality has to be less than 95% of the total nutrient requirement from crops in that municipality. The total nutrient requirement for one municipality is determined by multiplying the nutrient requirement of each crop type NR_{CR}^{NUT}, where CR stands for crop type, with the surface of each crop in a specific municipality $ha_{m1,CR}^{NUT}$, and making the sum over all crop types present in that municipality. We opt for 95 instead of 100% because we assume the farmers will only accept 95% of the total allowed nutrient quantity because of the variability of nutrient content in manure and the uncertainty related to it. Variability in nutrient content in manure can be caused by a number reasons such as the type of stables, stable management, manure storage, livestock feed etc. If farmers accept the full amount allowed and the actual nutrient content applied on their fields is higher than the theoretical one, they might face fines due to increased nitrate leaching in surface waters.

Apart from these essential conditions, a number of other equations were added to the model, having to do with the calculation and minimization of the carbon footprint to be able to solve equation 6. These equations are not written out in this section as they are merely based on IPCC calculations and described in Annex 1to Annex 5. While equations 7 and 8 are applied to all livestock present in the data, the carbon footprint related equations only apply to pigs in this study as we only look at the carbon footprint of pig production. Of course, the model can be extended to include all livestock types present in the data.

2.4.2.Model scenarios

After developing the model, a number of scenarios were chosen to be analysed with a focus on Belgium. Currently, the regional border between Flanders and Wallonia equally acts as a 'manure border', meaning that no transport of manure is allowed between both regions. This action looks at the carbon footprint and cost of manure allocation when the manure border remains closed and in case it would be opened. For both open and closed border, analyses were conducted with either minimization of carbon footprint, either minimization of cost as model objective function. This approach resulted in a total of 4 scenarios to be analysed (see Table 2).

For each scenario the model was run and results were attained relating to the cost and carbon footprint. Moreover, as the main focus of the model lies on the carbon footprint, more detailed outputs were generated on the different carbon footprint for (i) each type of manure management - raw, processed or separated manure, and (ii) each group of emissions - emissions from storage, transport, treatment, application and avoided emissions. The results of these analyses are presented in the following section.

3. Results and discussion

In this section, a summary of the outcome of the model simulations is presented. For a detailed overview of the cost and carbon footprint per scenario, please refer to Table 4 in Annex 6.

It must be emphasized that the results presented here only apply to pig manure and not to other types of manure. Hence, when we, for instance, state that no manure processing takes place, we imply that no pig manure processing takes place. This does however not mean that there is no processing of other types of manure. Moreover, to avoid confusion, when we talk about manure processing, we mean both treatment and separation. When we mention manure treatment, we mean separation of manure, followed by biological treatment.

3.1. Overall overview of the model objective outcome

Figure 2 gives an overview of the main outcomes of the different scenarios. The figure clearly shows the difference in cost and carbon footprint when either is being minimized or not. Moreover, it seems a lower cost coincides with a higher carbon footprint and vice versa.

Indeed, transport of raw manure is the cheapest way to get rid of excess manure. Hence, during cost minimization, the model will choose the transport as much raw manure as is possible, and excess manure will be separated or processed. The difference between closed and open border is that, when the border is closed, Flanders – with a manure surplus – will have to process much more manure because the supply of nutrients is much higher than the demand for them. When the border is open, on the other hand, excess raw manure can be transported to Wallonia, where the demand can certainly take in all the supply. The cost of manure management under an open border is also significantly lower as compared to closed border as much more transport of raw manure becomes possible.

Even though transport of raw manure is the cheapest way to deal with manure allocation, it is also the most polluting way, when it comes to CO_2 emissions mainly due to CH_4 emissions from storage. Raw manure is stored a lot longer than manure that is to be processed and CH_4 emissions are 25 times more powerful as a greenhouse gas than CO_2. This explains why the carbon footprint in scenarios 1 and 3 is much higher than the one in scenarios 2 and 4. Moreover, the carbon footprint in scenario 3 is even higher than that in scenario 1 as more raw manure is transported over the border from Flanders to Wallonia. The carbon footprint (and cost) of scenarios 2 and 4 is identical as manure separation has the lowest carbon footprint of all three scenarios and, in a scenario with carbon footprint minimization, the model opts to separate all manure.

3.2. Detailed overview of the model objective outcome

Figure 3 provides an overview of the carbon footprint, per model scenario. The difference with the previous figure is that, in this case, the carbon footprint is presented for each of the three manure management options, taking into account the amount of manure that is allocated per option.

Figure 3 confirms the conclusions drawn from Figure 2. Transport of raw manure dominates scenarios with cost minimization, hence, the majority of carbon emissions originates from raw manure management. In the two CO2 minimizing scenarios, emissions only originate from manure separation, as this management technique offers the lowest level of carbon emissions.

Figure 4 presents an overview, per scenario, of the shares of each type of emission calculated in the model. In general, when looking at all four figures together, they present a similar image in regard to specific shares of the different types of emission sources. As expected, in scenarios where cost was minimized, almost half of the emissions are due to methane emissions from storage. In the other 2 scenarios, this emission source dominates as well, even though less than in the previous two scenarios. Another large source of emissions in all scenarios is the direct N_2O emission from the soil after manure application.

Emissions from nitrification/denitrification only are present in cost minimizing scenarios as these are the only ones where manure processing, i.e. biological treatment, takes place. Another important observation is that manure transport as such only contributes a small part to the overall emissions.

In regard to avoided emissions, the figure indicates that avoided emissions from use (production) of mineral fertilizer and avoided emissions from the use of manure instead of mineral fertilizer are similar in size. Avoided emissions from fuel use are negligible.

3.3. Spatial analysis

The last part of the modelling exercise is a spatial analysis. As can be seen from the maps in Figure 5, livestock production in Belgium, and hence, carbon footprint, are concentrated in the North and North-Western part of the country. It has been suggested that a more equal spreading of livestock production might reduce the carbon footprint.

In this section of the paper, we calculate and visualise the carbon footprint at municipality level, simulate a more spatially equalized production and compare both scenarios in regard to CO_2-equivalent emissions.

3.3.1. Spatial representation of the modelling outcome

Figure 5 gives a spatial overview of the carbon footprint for each Belgian municipality for each of the 4 analysed scenarios. At a first glance, all maps look similar. Indeed, the hotspots for carbon emissions remain, in all 4 scenarios, the North and North-Western part of the country, namely, the Antwerp region and West-Flanders. The main difference between the figures is the scale of emissions, where those in scenarios 3 and 4 are the lowest, followed by scenario 1 and finally scenario 2. As we already discovered before, scenarios 3 and 4 display the same results as manure separation emits the lowest amount of CO_2 and, therefore, CO_2 minimizing scenarios tend to choose this manure processing technique for all manure management. The scale of emissions for scenario 1 and 3 is higher, since here the model chooses to transport as much raw manure as possible, this being the most cost-efficient option. When comparing both cost-minimizing scenarios, the open border scenario (scenario 3) displays the highest carbon emissions as due to the open border, more raw manure can be transported from the Flemish to the Walloon region.

3.3.2. Impact of spreading of livestock production

After conducting the carbon footprint calculation and analysis of the results, we will now look into the question of spreading of livestock production to decrease the carbon footprint. To translate the spreading of livestock production to the model, we assume that the effect of spreading of livestock production equals the effect of relaxing fertilisation standards, i.e., allowing more nutrients from manure to be put on the field. More specifically, in the model, we will increase the nitrogen standard by 1 kg per municipality and let the model calculate the marginal CO_2 impact of this increase, i.e., how much more or less CO_2 is emitted per kg N.

To be able to put the outcome of the analysis into perspective, we made a rough calculation on how to interpret the results. Every ton of manure that is transported over the distance of 1 km emits about 100 g of CO_2. On average, for pigs, 125 kg of manure contains 1 kg N. That means, that, in the case of pigs, for every kg N that is transported over 1 km, 12.5 g of CO_2 is emitted.

The marginal CO_2 impact of an increase in N fertilization standards is conducted for the 2 emission minimizing scenarios (i.e., open and close manure border). However, since these two scenarios yield identical results, we will discuss them as one.

Figure 6 provides an overview of the marginal CO_2 impact of a 1 kg increase in the fertilisation standards per municipality. From the scale of the legend we can already suspect that the impact will be small. The greatest reductions in carbon footprint are attained in areas with high livestock densities and carbon emissions. To make the results more concrete we focus on one specific municipality. This municipality is encircled in red and called Hoogstraten, in the North of the country and Antwerp province. When we look at the previous Figure 5, we can see that Hoogstraten is one of the municipalities with a high carbon footprint, namely around 2300 ton CO_2 when emissions are minimized and 2900 and 4400 ton for cost minimization under closed and open border respectively. When we allow for an extra kg of N to be disposed of in the municipality, the carbon footprint decreases by 250 g CO_2. This decrease cannot be caused by additional manure processing as in this scenario all manure is separated as it is. This means that the only possibility lies in a decrease in transport of treated manure. Indeed, more nitrogen allowed on the field means that more manure is allowed on the field and that less manure has to be transported to other regions. More specifically, according to the calculation made above, 250 g CO_2 corresponds to 125 kg of manure being transported over a distance of 20 km. The maximum reduction that can be reached in this analysis is around 0.5 kg CO_2, for the municipality of Hooglede (blue circle), located in West-Flanders.

From the spatial analysis we can conclude that a spatial rearrangement of pig production in Belgium will not substantially decrease the carbon footprint of this agricultural activity as the emissions from transport are small compared to those from manure storage. Indeed, as most emissions occur during storage of manure, the solution for reducing the carbon footprint lies in changing the manure storage systems.

3.3.3. Carbon footprint reduction during manure storage

A number of ways to reduce carbon footprint during manure storage have been described in literature. For instance, (Clemens et al., 2006) found that biogas production is a very efficient way to reduce the GHG emissions both through production of renewable energy and through avoidance of uncontrolled GHG emissions into the atmosphere during manure management. More specifically for pig manure slurry, (Haeussermann et al., 2006) made a summary of research results related to methane emission from slurry.

4. Conclusions

In European regions with intensive livestock production, manure management causes big environmental problems. In the past, transport distance was assumed an important parameter in the determination of the total carbon footprint. In this paper, the effect of a reduced manure pressure through spatial spreading of CO_2-equivalent emissions was investigated and the impact on the carbon footprint verified through a consequential life cycle approach. An economic and environmental optimization was conducted through mathematical linear programming and the main differences between both approaches determined Also, the marginal spatial impact on CO_2 emissions of a decrease in manure pressure was investigated. The results of the model simulations show that, while the economic optimum is reached by maximizing the transport of raw manure until fertilization standards are fulfilled and subsequently separating and processing the excess manure, the environmental optimum, from a carbon footprint point of view, is reached by separating all manure as this option has the lowest CO_2 emissions, mainly due to the limited manure storage time. Moreover, the analyses indicate that rearrangement of the spatial spreading of livestock production in Belgium will not substantially decrease CO_2 emissions. As manure storage is the main contributor to the carbon footprint, solutions should rather lie in changing these storage systems.

Overview of Figures

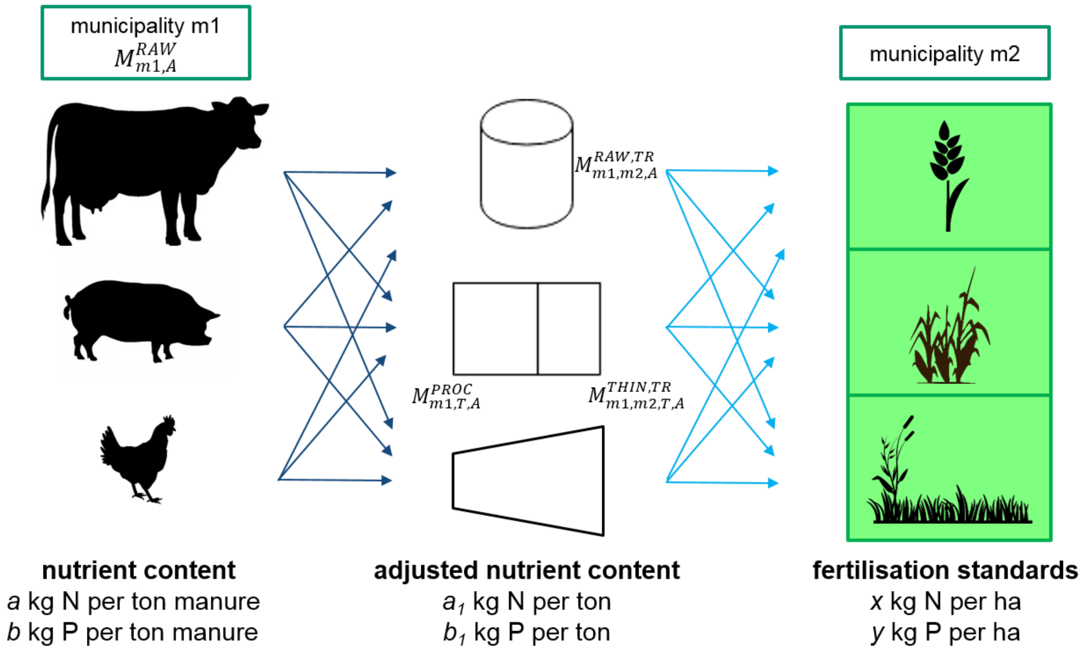

Figure 1: Schematic representation of the adapted Manure Allocation Model

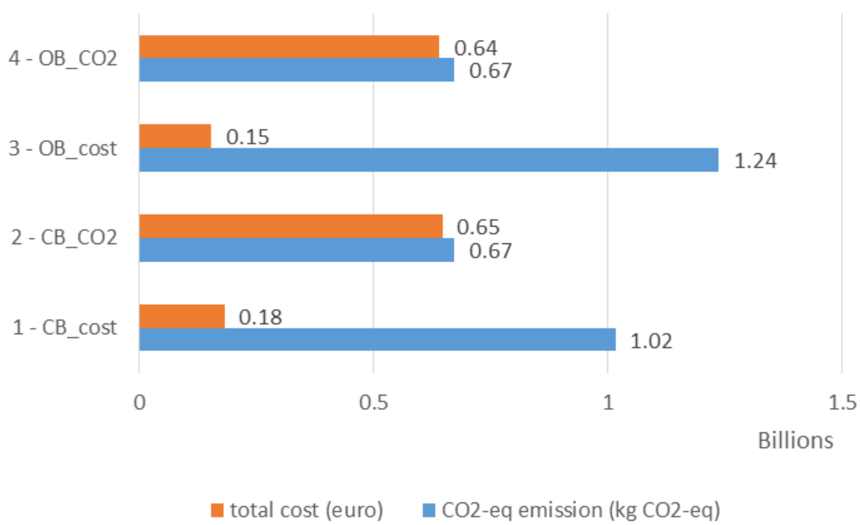

Figure 2: Overview of the general outcome of the 4 model scenarios. Scenarios 1 and 2 assume a closed border (CB), while scenarios 3 and 4 assume an open border (OB). Moreover, scenarios 1 and 3 minimized cost, while scenarios 2 and 4 minimized carbon footprint (CO_2).

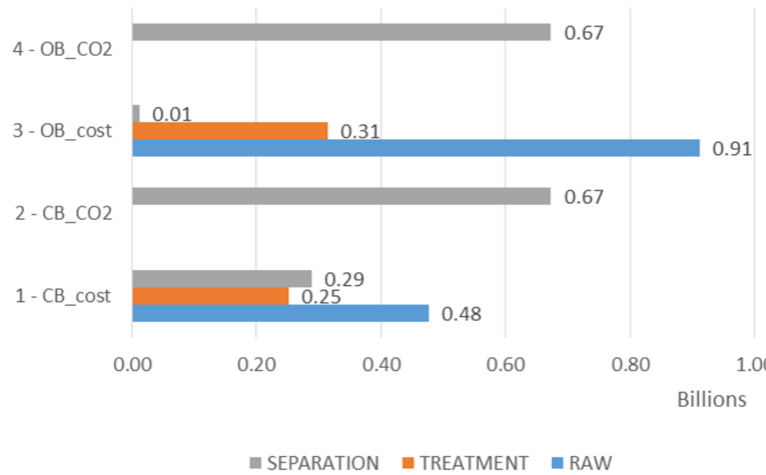

Figure 3: Overview, per scenario, of carbon footprint, shown per manure management option

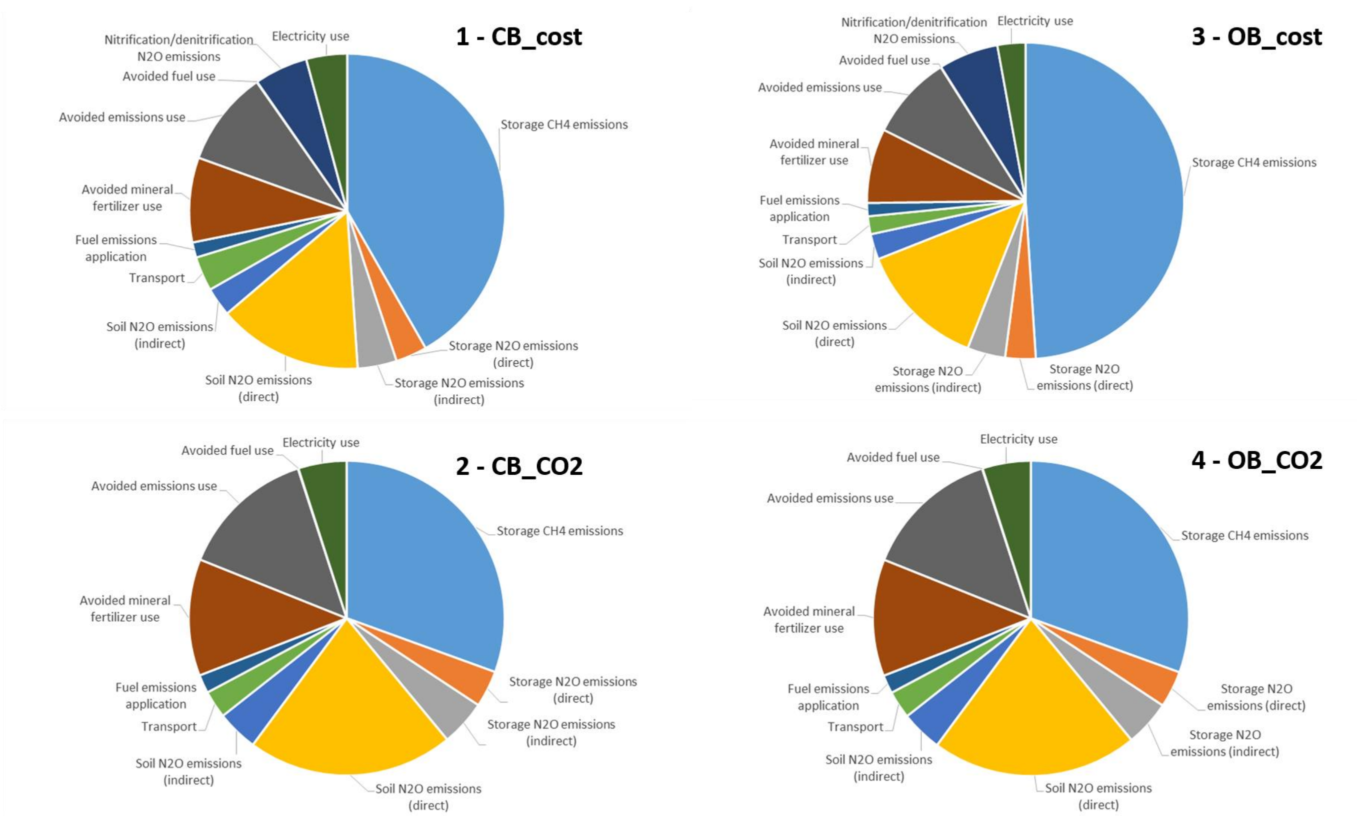

Figure 4: Pie diagram for the 4 scenarios depicting share of each type of emission

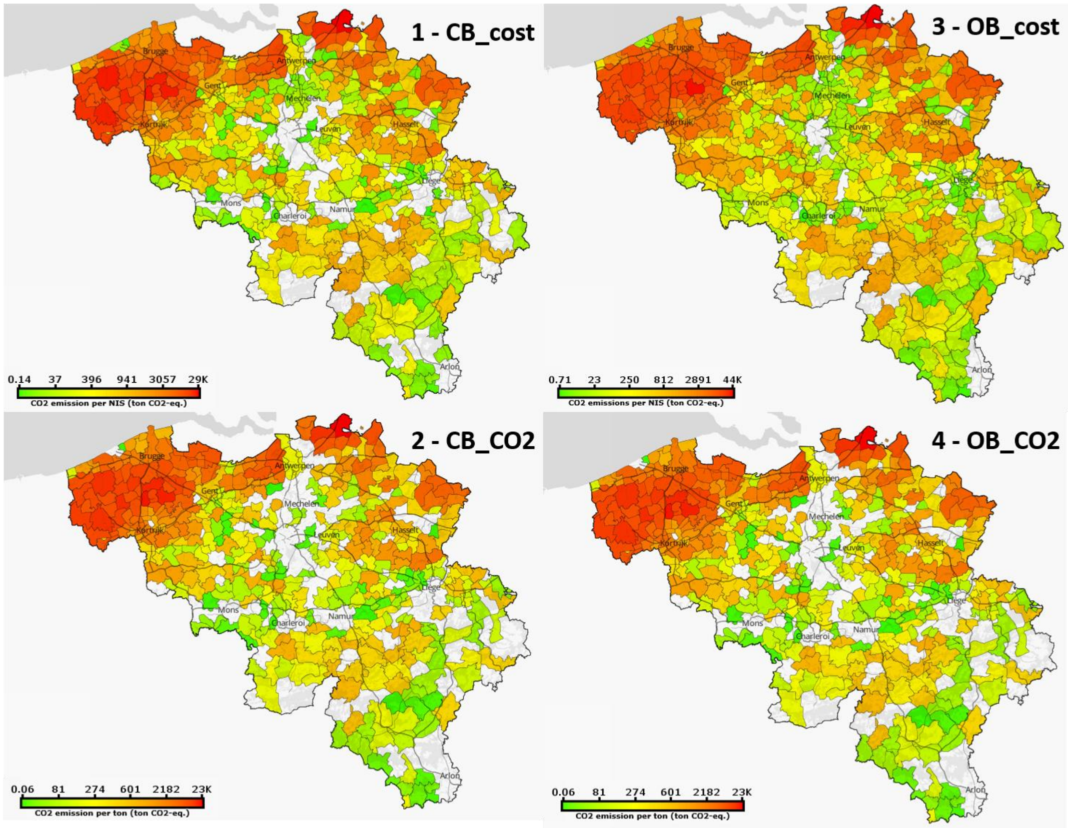

Figure 5: Spatial overview of total CO2 emissions per municipality in Belgium

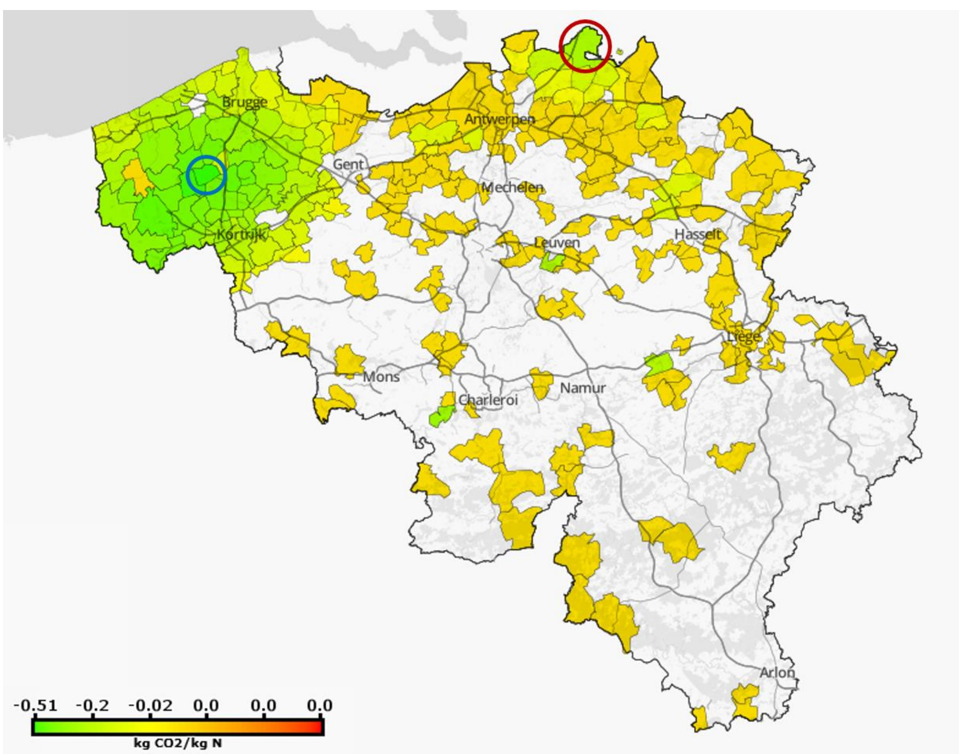

Figure 6: Marginal CO_2 impact of 1 kg N increase in fertilization standards per municipality for closed and open manure border when minimizing the carbon footprint.

Overview of Tables

Table 1: Overview of emissions in the different stages of manure management

Overview of emissions	assumptions	emissions
storage	in pit under stables intermediate storage of manure for processing/separation storage of thin fraction after separation	CH_4 direct N_2O indirect N_2O from NH_3 and NO_x
transport	non-renewable energy use from transport and injection of slurry	CO_2
application	emissions from managed soils emissions from machinery use	direct N_2O indirect N_2O from NH_3 and NO_x CO_2
processing	energy use centrifuge, biological treatment and composting process manure separation in closed vessel, no other emissions emissions biological treatment transport to composting plant and France	CO_2 from energy use direct N_2O indirect N_2O from NH_3 and NO_x (negligible)
avoided emissions	emissions from production and transport NPK application of replaced mineral fertilizers	CO_2 direct N_2O indirect N_2O from NH_3 and NO_x

Table 2: Overview of the different scenarios

Scenario	**Border**	**Minimize**
1 – CB_cost	Closed	Cost
2 – CB_CO2	Closed	CO_2
3 – OB_cost	Open	Cost
4 – OB_CO2	Open	CO_2

Acknowledgements

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Annexes

Annex 1. The different manure management scenarios described in detail

1. Raw manure transport scenario

- **Slurry storage**

Piggery manure is stored as slurry in a pit under the stable and causes methane and nitrous oxide emissions (VMM et al., 2013; Jacobsen et al., 2014; IPCC, 2006a). Direct nitrous oxide emissions are small in comparison to the large amount of methane emissions from pig slurry storage (Montes et al., 2013). Based on the IPCC (Forster et al., 2007), the global warming potential for 1 kg of nitrous oxide gas and 1 kg of methane for a time horizon of 100 years equals 298 kg and 25 kg of CO_2 equivalents respectively. The calculations are based on 6 months of storage before spreading, since the total storage capacity has to be sufficient to store at least the quantity of manure produced by the animals in the stable during a period of 6 months (Lemmens et al., 2007; Vlaamse Regering, 2014). This capacity is necessary, since the time period in which manure can be applied is limited, according to the crop cycles and nutrient requirements. In Flanders, manure and other fertilizers can only be applied from mid-February until the end of August (VLM, 2010).

❖ Methane

Methane is produced during manure decomposition under anaerobic conditions (Jacobsen et al., 2014; IPCC, 2006a). This is the case when large numbers of animals are kept in a confined area, such as a swine farm, and when manure is disposed in liquid-based systems (IPCC, 2006a). The temperature and the storage time largely affect the amount of methane emitted (Lemmens et al., 2007; IPCC, 2006a). The IPCC Tier 2 method is used to calculate the methane output which depends on the amount of excreted volatile solids excreted by the animals (VS) along with the maximum methane producing capacity for the manure (B_0) (Equation 2, Annex 1a) (VMM et al., 2014; IPCC, 2006a).

❖ Nitrous oxide

Nitrous oxide emissions of stored manure are a consequence of nitrification and denitrification processes. The amount of nitrous oxide that is emitted depends on the storage type. Additionally, indirect nitrous oxide emissions from manure are caused by volatilized ammonia and NO_x which may deposit at sites downwind from manure handling areas and contribute to indirect N_2O emissions.

- **Non-renewable energy use**

The use of non-renewable energy in this scenario includes the energy use for transport of the manure slurry to the spreading area and for its injection. It is assumed that transport occurs by truck with a load over 20 ton with an emission of 110 g CO_2 equivalents per ton km (Skao et al., 2011). For slurry injection, a fuel use of 0.8 L of diesel per m³ is assumed (Lopez-Ridaura et al., 2009). According to Defra (2012), well-to-wheel greenhouse gas emissions for the combustion of 1 L of diesel equals 3.18 kg CO_2-equivalents. Manure transported outside the Flemish borders, has to be disinfected (hygienized). Disinfection of manure by heating it to 70°C during 1 hour consumes approximately 24 kWh electricity per ton of manure (De Vries et al., 2012). Nitrogen emissions during the hygienization process are not taken into account as it is assumed the process occurs in a closed vessel (Melse et al., 2004).

- **Soil management**

Direct nitrous oxide emissions from managed soils can be derived using the IPCC equation (Equation 6, Annex 1b) with the default emission factor (EF_1) for N addition from mineral fertilizers and organic amendments, which has been set at 1% of the N applied to soils. The method for estimating indirect N_2O emissions takes into account the fraction from organic N fertilizers that volatilizes and re-deposits as NH_3 and NO_x ($Frac_{GASM}$) with a default value of 20% and an emission factor (EF_4) related to volatilised nitrogen of which 1% volatilizes as N_2O (Equation 8, Annex 1b) (IPCC, 2006b).

- **Mineral fertilizer replacement**

The manure slurry can be applied on crop land and substituting synthetic fertilizers. For the calculation of the carbon footprint, it is necessary to include (subtract) the impact related to the production, transport and application of these replaced fertilizers. The production of fertilizers has a large energy demand, and consequently accounts for a large carbon footprint. According to (Yara, 2010), the production of 1 kg N with the Best Available Techniques (BAT) emits 2.2 kg CO_2 equivalents taking into account the energy use for ammonia production by the Haber-Bosch process, i.e. 31.8 GJ per ton ammonia which is lower than the European average consumption of 35.2 GJ per ton (Fertilizers Europe 2014; Yara 2010). Next to that, the energy use for solidification and the nitrous oxide emissions from nitric acid production cause an emission of 1.3 and 0.1 kg CO_2 equivalents respectively. Transport by ship, truck or railway accounts for 0.1 kg CO_2 equivalents, which adds up to a total carbon footprint of 3.7 kg CO_2 equivalents per kg N. The average cradle-to-gate carbon footprint for the production of 1 kg phosphorus fertilizer (triple super phosphate) and 1 kg potassium fertilizer (potassium sulphate) in Western Europe equals 0.46 kg CO_2-equivalents (kg P_2O_5)$^{-1}$ and 0.29 kg CO_2 equivalents (kg K_2O)$^{-1}$ respectively (Kool et al., 2012). For transport an emission factor of 0.1 kg CO_2 equivalents is assumed. The Mineral Fertilizer Equivalent (MFE) of nitrogen is based on the system of effective nitrogen and equals 60% for slurry (VLM, 2014). For P_2O_5 and K_2O, the MFE is assumed to be 90% (Coppens, 2008). Fuel use for the application of the mineral fertilizers is estimated by the average diesel consumption for the injection of 1 ton of product (0.8 L) and the average nutrient content per product (25% N for ammonia based fertilizers, 45% P for triple super phosphate and 50% K for potassium sulfate). The use of synthetic fertilizers also results in direct and indirect N_2O emissions through volatilisation of ammonia and nitrogen oxides. The avoided emissions can be derived from Equation 6 and 8 (Annex 1b), similarly to the emissions related to the application of organic fertilizers. The fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x ($Frac_{GASF}$) equals 10%.

2. Separation scenario

The separation scenario includes storage, its transport to a manure treatment plant where it is separated, intermediate storage of the separated fractions, transport and application of the liquid fraction to crop land, and composting and export of the solid fraction.

- **Slurry storage**

In practice, the manure is delivered to the treatment plant as fresh as possible, but in reality, the slurry is stored on-farm before treated. It is assumed that the excess manure is delivered to the collective treatment plant at 25% of the storage capacity (6 months), so that the **average storage time equals 1.5 months**. Transport of manure from the farm to the central manure treatment plant occurs most of the time by truck (Lemmens et al., 2007) and the average distance is assumed to be 20 km.

- **Intermediate storage of the slurry**

The unloading of the liquid manure takes place in-house or emission-poor seals are used for pumping the slurry from the truck to the buffer tank through a manure hose. The slurry is blown into the storage tank by which the displaced air is emitted. After unloading, all the air from the hose is blown out before the seals are closed (Lemmens et al., 2007). Leakage is assumed to be negligible. The collected manure is stored for a short period of time (10 days on average) in a buffer tank with a storage capacity of 200 – 1000m³, depending on the scale of the treatment plant (Lemmens et al. 2007; BioArmor, personal communication). In Flanders, manure slurry stored outside the stable has to be shut off from the air, except for air drain pipes (Vlaamse Regering, 2014). The buffer tank can be sealed with a firm, flexible or floating cover (Lemmens et al., 2007) to keep rainwater out and to reduce odour and emissions, such as ammonia emissions from the manure slurry. Gases from the slurry storage can still be emitted into the atmosphere through vents that are applied to release the gases that build up under the cover. The effect of coverage on the emissions is not clear, but coverage could reduce the ammonia emissions up to 90 - 98%, depending on the cover type (European Commission, 2006). For this reason, ammonia emissions are assumed to be 0. On the other hand, covering pig manure slurry creates an anaerobic condition and a small temperature raise of about 2°C, which leads to more rapid formation of methane. Mixing also increases the emissions of methane. Furthermore, the lack of oxygen reduces the aerobic process of nitrification, and consequently denitrification is reduced. Hence, nitrous oxide emissions could be reduced significantly (European Commission, 2006). According to the IPCC (IPCC, 2006a), the N_2O emissions of slurry in tanks (without natural crust cover) are indeed negligible based on the absence of oxidized forms of nitrogen in combination with almost no nitrification/denitrification processes in the tank. There are no experimental data about the methane emissions from covered slurry storage, but it is assumed that the rate is similar to on-farm storage (BioArmor, personal communication). To estimate the CH_4 emissions, the methane conversion factor (MCF) for slurry (without natural crust cover) during manure storage in a cool climate (11°C) is used in Equation 2 (Annex 1a). This conversion factor (19%) is the same as for pit storage below animal confinements (IPCC, 2006a). Before separation, the slurry is mixed. The average energy consumption for 1 m³ of manure slurry equals 1 kWh (BioArmor, personal communication).

- **Mechanical separation of the slurry**

It was assumed that a centrifuge was used for the mechanical separation of the slurry since it is the most common technique used in Flanders. According to Lemmens et al. (2007) the energy consumption of a centrifuge is 2 kWh per m³ of slurry. Separation occurs most of the time in a closed instrument or in the stable, therefore emissions are expected to be very little and the amount of nutrients that enter the system should be the same as the amount that leave the system (Lemmens et al. 2007; Melse et al. 2004). The emission factor for electricity in Belgium is 400 kg CO_2 MWh^{-1} (Commissie Benchmarking, 2009). After separation, 15% of the mass, 45-50% of the dry matter, 20% of the nitrogen and 70-75% of the phosphorus ends up in the solid (thick) fraction (Table 1) (Lemmens et al. 2007; Melse et al. 2004). In most cases, the solid fraction is composted and the liquid fraction is biologically treated.

Table 3. Composition of the slurry input, liquid and the solid fraction after mechanical separation, the composted solid fraction and the effluent after biological treatment of the liquid (Lemmens et al., 2007)

	Input	Solid	Composted solid	Liquid	Effluent
Mass (kg)	1000	150	58	850	750
Dry Matter	90	50	35	40	17.1
N total (kg)	8.1	1.62	1.13	6.48	0.65
P_2O_5 (kg)	4.0	3.0	3.0	1.0	0.40
K_2O (kg)	7.2	0.72	0.72	6.48	6.48

- **Storage of the liquid and solid fraction**

It is assumed that the liquid fraction is stored 4 months on average before application to crop land, while the solid fraction is almost immediately transferred to the composting installation.

❖ *Methane*

From experiments and literature reviews, it can be derived that methane emissions during storage of the separated fractions are a lot lower in comparison to the methane emissions from raw slurry (Mosquera et al. 2010; Petersen et al. 2013) This can be explained by the fact that methane is formed during the storage of fluid slurry in an anaerobic environment in the presence of a vast amount of degradable organic matter which is fermented in those circumstances. It is assumed that the methane emissions from the liquid fraction are 12 times lower in comparison to raw slurry for the same storage period, while the methane emissions from the solid fraction are assumed to be negligible (Mosquera et al., 2010).

❖ *Nitrous oxide*

Nitrous oxide emissions from the liquid fraction are assumed to be negligible due to the anaerobic circumstances which prevent nitrification, almost no nitrous oxide is formed (Mosquera et al. 2010; Petersen et al. 2013). The solid fraction on the other hand causes higher nitrous oxide emissions, since there are more mineralisation and nitrification processes due to the more aerobic environment, leading to more nitrous oxide emission. Due to the short storage period, the nitrous oxide emissions from the solid fraction are assumed to be 0. Ammonia emissions are the highest in fluid slurry (liquid fraction and raw slurry) in comparison to the stackable solid fraction, since ammonia is emitted through diffusion from the liquid phase to the air. Next to the physical differences, the higher C/N ratio in the solid fraction leads to lower ammonia emissions (Mosquera et al., 2010). Ammonia emissions are assumed to be inhibited by coverage of the storage tanks.

- **Composting of the solid fraction**

The purpose of manure composting (biothermal drying) is germ elimination by increasing the temperature, volume and weight reduction by evaporation of the moisture, and the stabilisation of the organic material. It is assumed that the solid fraction is transported over an average distance of 50 km to a composting plant. The energy use of composting on a large scale is assumed to be 50 kWh/ton, including pre- and post-treatment, conversion, aeration (Lemmens et al. 2007; Melse et al. 2004). During composting, 28% of the nitrogen of the solid manure is emitted as NH_3-N, 1% as N_2O-N and 1% as N_2, which adds up to a total N-loss of 30% (Basset-Mens et al., 2007). Similarly, (Lemmens et al. 2007; Melse et al. 2004) mention an N reduction of 30% and 15 to 50% during the composting process respectively. However, manure composting occurs in closed systems (hall or tunnel composting) where the gases are captured and treated, and thus the emissions considered to be 0. Through composting, 30% of the dry matter is broken down (Table 1). To calculate the mass balance, only pig manure is taken into account, while in practice the solid fraction of manure is co-composted with chicken manure. By adding dry organic material such as chicken manure, the C/N ratio is increased, necessary for the composting process. The composted solid fraction is transported to the North of France (average distance 200km) where it can be applied on crop land and substituting synthetic fertilizers.

- **Soil management**

Separation doesn't have an influence on the emission of ammonia from the liquid fraction or the solid fraction when applied to grassland and cropland respectively, in comparison to raw manure. This was also the case for nitrous oxide emissions from the liquid fraction when applied to grassland (Mosquera et al., 2010). Consequently, the same emission factors are used as for the application of raw manure.

3. Treatment scenario

In Flanders, manure processing consists of three important phases: (i) physical separation in a liquid (85%) and a solid (15%) fraction; (ii) composting of the solid fraction to an exportable product and (iii) reduction of the nutrient content in the liquid fraction through biological treatment (Meers et al., 2008). Hence, the manure treatment scenario includes storage, its transport to the treatment plant, mechanical separation, biological treatment of the liquid fraction, transport and composting of the solid fraction, and transport and application of the effluent and the compost to crop land.

- **Slurry storage and mechanical separation**

It is assumed that the manure slurry is stored on- farm in a similar way as in the separation scenario. The separation of the slurry at the biological treatment plant also occurs in the same manner. Afterwards, the liquid fraction is almost immediately biologically treated in the nitrification/denitrification reactor(s). The solid fraction is transported to a composting installation as is the case for the separation scenario.

- **Biological treatment of the liquid fraction**

In a biological treatment plant where nitrogen is biologically removed from the liquid fraction by nitrification and subsequent denitrification, electrical energy is necessary for aeration, pumping and power. Aeration consumes the biggest part of the energy. Registered uses for the two systems used in Flanders are 16 kWh/m^3 manure (BioArmor system) or 17 kWh/m^3 (Trevi system). In the BioArmor manure is biologically treated in a sequential batch reactor (SBR) and sedimentation occurs in the SBR or in a regular sedimentation tank. The average storage capacity per year ranges from 5,000 to 35,000 m³ manure. The Trevi biological treatment system is characterized by a separate nitrification and denitrification basin. There is a big uncertainty about the nitrous oxide emissions caused by nitrification and denitrification. Under well-controlled conditions, emissions of up to 0.5% of N_2O and 0.01% of NH_3 were measured at a full scale installation of Trevi (Lemmens et al. 2007; Smet and Deboosere 2007). The low ammonia emissions are a result of the natural acidification of the activated sludge and the low concentration of ammonia during the nitrification/denitrification process (Lemmens et al., 2007). The nitrous oxide emissions are even lower than the emissions from raw manure applied to soil (Smet and Deboosere, 2007). Analogously, Loyon et al. (2007) found that less than 1% of the total nitrogen entering the treatment plant was emitted as N_2O, and this result is in accordance with other findings in literature. Methane emissions are assumed to be negligible

(BioArmor, personal communication). The high residual content of N, P and K in the effluent of the biological treatment plant is still too high to allow discharge in Flanders; however, the effluent can be applied to crop land. The effluent is assumed to be applied in a region close to plant, with an average distance of 5 km. In practice, the effluent is applied on pasture and cropland as potassium fertilizer since the amount of potassium is more or less equal to the amount in raw slurry.

Annex 2. IPCC equations for the calculation of methane and nitrous oxide emissions from manure management (IPCC, 2006a)

Equation 9 shows how to calculate methane emissions (Gg CH_4 yr^{-1}) from manure management.

$$CH_{4_{Manure}} = \sum_{(T)} \left(\frac{EF_{(T)} * N_{(T)}}{10^6}\right) \qquad (9)$$

with $N_{(T)}$ the number of head of livestock species per category T and $EF_{(T)}$ the annual CH_4 emission factor for livestock category T (kg CH_4 $animal^{-1}$ yr^{-1}), calculated according to Equation 10.

$$EF_{(T)} = VS_{(T)} * 365 * \ B_{O(T)*} 0.67 * \ \sum_{S,k} \frac{MCF_{(S,k)}}{100} * MS_{(T,S,k)} \qquad (10)$$

with $MCF_{(S,k)}$ the methane conversion factor for manure management system S in climate region k (%), $MS_{(T,S,k)}$ the fraction of livestock the $B_{0(T)}$ the maximum methane producing capacity for manure produced by livestock category T (m^3 CH_4 kg^{-1} of volatile solids (VS) excreted), 0.67 the conversion factor of m^3 CH_4 to kg CH_4, 365 the basis for calculating annual VS production and $VS_{(T)}$ the daily volatile solids excreted by livestock category T (kg VS $animal^{-1}$ day^{-1}). For pit storage below animal confinements, the methane conversion factor (MCF) corresponding to the average temperature of 11°C and more than 1 month storage is 19% (VMM et al., 2014; IPCC, 2006a).The default value for the maximum methane production in Western Europe is 0.45 m^3 CH_4 $(kg\ VS)^{-1}$ (IPCC, 2006a). The VS content of manure equals the fraction of the consumed diet that is not digested and thus excreted as fecal material. Volatile solids excreted by pigs are region specific, using the average manure production in m^3, its density and its dry matter content. Region-specific values for the VS content were found in the National Inventory Report (VMM et al., 2014).

Equation 11 shows the calculation of direct N_2O emissions (kg N_2O yr^{-1}) from manure management (mm).

$$N_2O_{D(mm)} = 44/28 \sum_S \left[EF_{3(S)} \sum_T \left(N_{(T)} * N_{ex(T)} * MS_{(T,S)}\right)\right] \qquad (11)$$

where $N_{(T)}$ is the number of head of livestock species per category T, $N_{ex(T)}$ the annual average N excretion per head of species per category T(kg N $animal^{-1}$ yr^{-1}), $MS_{(T,S)}$ the fraction of total annual nitrogen excretion for each livestock species per category T that is managed in manure management system S, $EF_{3(S)}$ the emission factor for direct N_2O emissions from manure management system S (kg N_2O-N/kg N) and 44/28 the conversion of (N_2O-N)(mm) to N_2O(mm) emissions. To quantify the nitrous oxide emissions from pig slurry stored underneath the stable, 0.2% ($EF_{3(S)}$) of the total nitrogen is lost as nitrous oxide, according to the default value of IPCC (2006a) (VMM et al., 2014).

There may also be nitrogen losses in other forms (f.e. ammonia and nitrous oxides) during manure management. Nitrogen volatilized as ammonia may be deposited at sites downwind from manure handling areas and contribute to indirect N_2O emissions. The calculation of N volatilization in forms of NH_3 and NO_x is based on Equation 12.

$$N_2O_{volatilization-MMS} = \sum_S \left[\sum_T \left[\left(N_{(T)} * N_{ex(T)} * MS_{(T,S)}\right)\left(\frac{Frac_{GasMS}}{100}\right)_{(T,S)}\right]\ \right] \qquad (12)$$

where $N_2O_{volatilization\text{-}MMS}$ is the amount of manure nitrogen that is lost due to volatilization of NH_3 and NO_x (kg N yr^{-1}), $N_{(T)}$ is the number of head of livestock species per category T, $N_{ex(T)}$ the annual average N excretion per head of species per category T (kg N $animal^{-1}$ yr^{-1}), MS(T,S) the fraction of total annual nitrogen excretion for each livestock species per category T that is managed in manure management system S, $Frac_{GasMS}$ the percent of managed manure nitrogen for livestock category T that volatilizes as NH_3 and NO_x in manure management system S. It is assumed that 25% ($Frac_{GasMS}$) of the total nitrogen emission from pig manure stored underneath the stables is converted to ammonia or NO_x (IPCC, 2006a).

The indirect N_2O emissions from volatilization of N as NH_3 and NO_x are estimated using Equation 13.

$$N_2O_{G(mm)} = (N_{volatilization-MMS} * EF_4) * 44/28 \quad (13)$$

with $N_2O_{G(mm)}$ indirect N_2O emissions due to volatilization of N from manure management (kg N_2O yr^{-1}) and EF_4 emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces (kg N_2O-N (kg NH_3-N + NO_x-N volatilized)$^{-1}$). Of the total nitrogen losses, 1% (EF_4) is converted to nitrous oxide (IPCC, 2006a).

Annex 3. IPCC equations for the calculation of nitrous oxide emissions from managed soils (IPCC, 2006b)

The direct N_2O emissions from managed soils can be calculated using Equation 14.

$$N_2O_{Direct} - N = (F_{SN} + F_{ON}) * EF_1 \quad (14)$$

with $N_2O_{Direct-N}$ the annual direct N_2O-N emissions from N inputs, F_{SN} the annual amount of synthetic fertilizer N applied to soils (kg N yr^{-1}), F_{ON} the annual amount of animal manure, compost and other organic N additions applied to soils (kg N yr^{-1}) and EF_1 the emission factor for N_2O emissions from N inputs (kg N_2O-N (kg N input)$^{-1}$).

Conversion of N_2O-N emissions to N_2O emissions is done by the following equation:

$$N_2O = (N_2O - N) * 44/28 \quad (15)$$

The indirect N_2O emissions from atmospheric deposition of N volatilized from managed soils are estimated using Equation 16.

$$N_2O_{(ATD)} - N = [(F_{SN}\, Frac_{GASF}) + (F_{ON}\, Frac_{GASM})] * EF_4 \quad (16)$$

where $N_2O_{(ATD)}$-N is the annual amount of N_2O-N produced from atmospheric deposition of N volatilized from managed soils (kg N_2O-N yr^{-1}), F_{SN} the annual amount of synthetic fertilizer N applied to soils (kg N yr^{-1}), $Frac_{GASF}$ the fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x (kg $N_{volatilized}$ (kg $N_{applied}$)$^{-1}$), F_{ON} the annual amount of managed animal manure, compost and other organic N additions applied to soils (kg N yr^{-1}), $Frac_{GASM}$ the fraction of applied organic N fertilizer that volatilizes as NH_3 and NO_x (kg $N_{volatilized}$ (kg $N_{applied}$)$^{-1}$).

Annex 4. N and P excretion factors per animal type (VLM 2014b)

	kg N animal^{-1} yr^{-1}	***kg P_2O_5 animal^{-1} yr^{-1}***
Piglets (7-20 kg)	*2.18*	*1.53*
Boars	*24*	*14.5*
Sows, including piglets <7kg	*24*	*14.5*
Other pigs (20-110 kg)	*13*	*5.33*
Other pigs (> 110 kg)	*24*	*14.5*

Annex 5. Nutrient composition of manure (VLM, 2014)

	kg N ton^{-1}	*kg P_2O_5 ton^{-1}*
Piglets (7-20 kg)	*6.7*	*4.0*
Sows and piglets	*4.4*	*2.9*
Finishing pigs	*8.1*	*5.0*

Annex 6. Detailed overview of the model outcomes

Table 4: GHG emissions in ton CO2-equivalents per scenario and emission type

GHG emissions (ton CO2-eq.)	CB_minCOST_180815	CB_minCO2_180815	OB_minCOST_180815	OB_minCO2_180815
Storage CH4 emissions	673,552	427,842	897,841	427,842
Storage N2O emissions (direct)	51,714	52,697	56,886	52,697
Storage N2O emissions (indirect)	64,643	65,871	71,107	65,871
Soil N2O emissions (direct)	239,160	295,518	239,160	295,518
Soil N2O emissions (indirect)	47,832	59,104	47,832	59,104
Transport	57,044	39,704	33,546	39,704
Fuel emissions application	25,206	26,547	24,658	26,547
Avoided mineral fertilizer use	- 140,346	-167,933	-139,646	-167,933
Avoided emissions use	-157,845	-195,042	-157,845	-195,042
Avoided fuel use	-671	-748	-664	-748
Nitrification/denitrification N2O emissions	88,362	-	111,668	-
Electricity use	67,517	69,212	52,483	69,212
TOTAL	1,016,167	672,771	1,237,026	672,771