Effects of including nitrogen emissions from soil in environmental systems analysis of waste management strategies

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Abstract

The environmental impacts of nitrogen emissions from soil resulting from the use of organic fertilizers, such as manure, are large compared with the corresponding impacts of mineral fertilizers. However, soil emissions are rarely included in systems analysis of waste management strategies. This study examines whether the inclusion of soil emissions can affect the environmental ranking of systems for managing solid biodegradable waste. Waste management scenarios based on incineration, anaerobic digestion and composting, respectively, were compared. The scenarios were analysed using the organic waste research (ORWARE) simulation model. A simplified model for calculating nitrogen availability and emissions was also constructed. Life-cycle analysis methodology was used for choosing system boundaries and evaluating the results. Global warming, acidification and eutrophication were the impact categories considered. The results indicate the vital importance of considering nitrogen emissions from soil when comparing biological waste management systems with other waste management methods, especially with regard to eutrophication effects. Soil emissions are also important when comparing the environmental impacts of anaerobic digestion and composting systems. However, the variation in nitrogen emissions from soil is large and depends on the spreading technique used, climate, drainage and soil texture © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Environmental impact is often an issue when waste management alternatives are discussed in Europe. New waste management systems based on source separation and biological treatments have been introduced to facilitate the recycling of nutrients to farmland. The objectives are to reduce environmental impacts and conserve resources. However, emissions of ammonia (NH₃) and nitrate (NO₃⁻) resulting from the use of organic fertilizers, such as manure, on farmland can contribute substantially to eutrophication problems. Thus, when comparing systems for managing biodegradable waste in terms of their impacts it might be important to consider emissions from soil connected with the use of organic fertilizers, e.g. anaerobic digestion residue and compost.

Several approaches to comparing the environmental impacts of waste management systems have been described in the literature. In general, when biologically treated waste is involved, the amount of organic residues produced is given, but no further data concerning residue-generated emissions from soil are considered [1–4]. However, some studies have considered the environmental impacts of transporting and spreading nutrients on farmland and the degree to which the need for mineral fertilizer can be reduced [5,6]. To our knowledge, no one has yet to assess how the replacement of mineral fertilizers with organic fertilizers affects nitrogen emissions from soil.

The aim of this study was to analyse the importance of including soil emissions when comparing alternative strategies for managing biodegradable wastes. In waste management systems including incineration and landfilling of the ash, no nutrients are recycled to farmland. But, if the waste is source separated and anaerobically digested or composted, the residue can be returned to farmland and used instead of mineral fertilizer. Furthermore, we wanted to determine whether the ranking of waste management systems in terms of their environmental impact would be affected by including emissions from soil in the assessment. An effort was also made to predict differences in emissions from soils supplied with anaerobic digestion residue and soils supplied with compost.

In the present study a systems analysis was conducted that encompassed waste management, waste recycling and increased emissions from soil. Substance flow analysis modelling and life-cycle assessment methodology were used to compare the environmental impacts associated with the different scenarios. A simplified model for describing nitrogen turnover was developed. Furthermore, a case study with three scenarios, i.e. incineration, anaerobic digestion and reactor composting, was performed. A sensitivity analysis was conducted in which the effects of changing parameters concerning climatic region (in Sweden), soil texture and spreading conditions in the nitrogen turnover model were assessed.
2. Method

The organic waste research (ORWARE) simulation model was used to calculate substance flows [7]. A nitrogen turnover model had to be added to calculate the increase in nutrient emissions from farmland resulting from the replacement of mineral fertilizers with organic fertilizers.

2.1. The ORWARE model

ORWARE is a static model for calculating the emissions and flows of energy and nutrients resulting from solid and liquid organic waste management [7,8]. The model considers the collection and transport of waste fractions, treatment of the waste and, finally, the disposal of residues or their use on farmland. Several waste treatment processes are modelled: incineration, landfilling, anaerobic digestion, composting and treatment in a sewage plant. Only direct emissions from the handling of organic waste are included; in other words, emissions resulting from the construction of infrastructure and buildings, for example, are omitted. The entire model is described in Dalemo et al. [7].

Although the model has been used in several case studies [6,9,10], emissions from soil have not been included in any of them. The ORWARE model calculates the reduction in the need for mineral fertilizer resulting from the use of recycled organic residues from waste management. Phosphorus in organic fertilizers was assumed to have the same fertilizing effect and to result in the same emissions as phosphorus in mineral fertilizer, while the fertilizer efficiencies of ammonium (NH$_4^+$) and organically bound nitrogen were assumed to be 80% and 30%, respectively. Most of the nitrogen in the compost and some of the nitrogen in anaerobic digestion residue is organically bound. The remaining 70% of the organically bound nitrogen not previously considered in the model can potentially be emitted and thereby have an important environmental impact. Furthermore, in ORWARE a mass balance approach is used for most substances and processes. Thus, modelling the fate of that part of the nitrogen not available for crop uptake seemed important.

2.2. Modelling of nitrogen turnover

Several advanced models for calculating nitrogen turnover in soil-crop systems were found in the literature. At a workshop at the Soil Fertility Research Institute in the Netherlands 14 different nitrogen turnover models were presented [11]. They are all dynamic models based on a mechanistic approach. Most of the models consider soil water content, water flux, the transport of heat and oxygen in soil, the mineralisation and immobilisation of organic nitrogen, adsorption, the volatilisation and fixation of ammonium, and the uptake of ammonium and nitrate by the crop. These detailed mechanistic models can be applied to a wide range of conditions, but require detailed knowledge concerning the many input parameters. One of the models presented, called SoilN, simulates nitrogen dynamics by dividing the soil profile into layers and modelling the nitrogen processes in each layer and
the transport between layers. Furthermore, the organic nitrogen is divided into three classes depending on its degradability. The model is able to calculate the nitrogen leaching based on weather conditions, soil properties and crop management practices.

Several simplified static models of the nitrogen cycle were also found. Simmelsgaard [12] presented formulas for calculating leaching as a function of the rate of application of mineral nitrogen and manure, respectively. Scholefield et al. [13] presented a model for simulating nitrogen cycling in grassland systems grazed by beef cattle. The data in the model are from long-term measurements of ten different field systems. Sluijsmans and Kolenbrander [14] used an approach in which nitrogen in slurry was divided into three fractions, i.e. ammonium, organically bound nitrogen mineralised in the first year and organically bound nitrogen mineralised later on. The fertilizing effect is compared with that of mineral fertilizer and stated to be 80% for ammonium and 50–90% for the organic fractions depending on the cereal crop and temperature. Beauchamp [15] described a very simple model for predicting nitrogen availability in manure based on contents of ammonia and organically bound nitrogen.

The simplified nitrogen turnover model presented here was designed to compare applications of mineral fertilizer, anaerobic digestion residue and compost in terms of crop nitrogen utilisation and soil emissions. These fertilizers differ in their ratios of organically bound nitrogen, ammonia and nitrate to total nitrogen. None of the simplified nitrogen turnover models for organic fertilizers found in the literature was based on a mass balance approach, where all nitrogen in organic fertilizers ends up either as nitrogen emissions or as crop-available nitrogen. Thus, a new model was needed.

2.2.1. Modeling approach

Nitrogen in organic fertilizers can be divided into three types, i.e. ammonium (\(\text{NH}_4^+\)), nitrate (\(\text{NO}_3^-\)) and organic nitrogen (Fig. 1). It is assumed that the

![Fig. 1. Conceptual model for calculating the reduced need for mineral nitrogen and increased emissions to air and water when using organic fertilizer.](image-url)
Table 1
Emissions of ammonia, as a fraction of the ammonium content, in relation to spreading time, type of manure and application techniques, when spread in cereal crops [16]

<table>
<thead>
<tr>
<th>Time of spreading</th>
<th>Spreading technique</th>
<th>Solid manure</th>
<th>Slurry manure</th>
<th>Urine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>Broad cast spreading + harrowing within 1 h</td>
<td>0.15</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>Spring</td>
<td>Broad cast spreading + harrowing within 12 h</td>
<td>0.50</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>Spring</td>
<td>Band spreading + harrowing within 1 h</td>
<td>0.05</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Spring</td>
<td>Band spreading + harrowing within 12 h</td>
<td>0.20</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Early summer, in growing crop</td>
<td>Band spreading</td>
<td>0.07</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Early autumn</td>
<td>Broad cast spreading + harrowing within 1 h</td>
<td>0.20</td>
<td>0.05</td>
<td>0.15</td>
</tr>
<tr>
<td>Early autumn</td>
<td>Band spreading + harrowing within 1 h</td>
<td>0.03</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Late autumn</td>
<td>Broad cast spreading + harrowing within 1 h</td>
<td>0.10</td>
<td>0.05</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Ammonium and nitrate resemble mineral fertilizer in terms of their availability to crops, except that some ammonium is volatilised as ammonia within the first hours after spreading. Organic nitrogen does not become available to crops until the material has been degraded to mineral nitrogen such as nitrate or ammonium (mineralisation). The modelling approach used for the organically bound nitrogen is to divide the mineralisation of this fraction into two time frames, i.e. the first year and the remaining time. An advantage with this approach is that both the immediate and long-term effects of adding organic fertilizers can be evaluated. In addition, all nitrogen added to the soil can be accounted for in the model output, in the form of emissions and reduction of mineral nitrogen.

2.2.2. Ammonia emissions

Ammonia emissions from manure have been measured for several years in Sweden. These emissions are often related to the ammonia content of the manure. The Swedish Board of Agriculture [16] reported average ammonia emissions associated with different application techniques and spreading times. These are used in the model (Table 1).

2.2.3. Nitrate and nitrogen gas emissions

The spreading of organically bound nitrogen results in increased emissions of nitrate and nitrogen, primarily owing to the nitrogen mineralised during times of the year when there is no crop uptake. These emissions vary between years and areas depending on weather conditions and the type of soil and crop. Heavy rains and a highly permeable soil result in large nitrate emissions. By contrast, nitrogen
Table 2
Proportion of fertilizer nitrogen ending up as NO$_3^-$-N in leachate following a spring application of organic fertilizer to oats or barley (calculated from Johnsson and Hoffman [18])

<table>
<thead>
<tr>
<th>Climatic region</th>
<th>Soil texture</th>
<th>Drainage flow (mm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand</td>
<td>Loam</td>
</tr>
<tr>
<td>Southern part of the southern plains in Götaland (Gss_s)</td>
<td>0.35</td>
<td>0.32</td>
</tr>
<tr>
<td>Northern plains in Götaland (Gns)</td>
<td>0.43</td>
<td>0.39</td>
</tr>
<tr>
<td>Western part of the forest district in northern Gotaland (Gsk_v)</td>
<td>0.60</td>
<td>0.56</td>
</tr>
<tr>
<td>Plains in Svealand (Ss)</td>
<td>0.14</td>
<td>0.10</td>
</tr>
</tbody>
</table>

is more likely to be emitted as nitrogen gas (N$_2$) from a soil with lower permeability, in which anaerobic conditions occur, owing to nitrification and denitrification processes.

Nitrate emission calculations (kg NO$_3^-$-N/ha and year) from the SoilN simulation model [17] were used in our modelling work. These values reflect average emissions for a specific crop grown for 10 years on a specific soil type in a specific region in Sweden. Johnsson and Hoffman [18] calculated nitrate emissions resulting from the use of mineral fertilizer only and the use of a combination of mineral fertilizer and manure. New emission factors that apply to the use of manure instead of mineral fertilizer were established by calculating the ratio between increased emissions of nitrate and the content of organically bound nitrogen in manure. In Table 2, examples of these factors are presented for four regions in Sweden reflecting different drainage flows.

Emissions of nitrogen gas from nitrogen fertilizer are difficult to measure. It is therefore often assumed that they account for a certain proportion of the total nitrogen lost through denitrification and leaching. Scholefield et al. [13] presented corresponding factors for emissions from grassland systems in England based on soil texture and drainage conditions (Table 3). These latter figures were used in the nitrogen turnover model. In Holland, nitrogen gas emissions are assumed to

Table 3
Loss of nitrogen due to denitrification, as a proportion of the loss due to denitrification and leaching, for different soil textures and drainage condition categories [13]

<table>
<thead>
<tr>
<th>Drainage condition</th>
<th>Soil texture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand</td>
</tr>
<tr>
<td>Poor</td>
<td>0.50</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.15</td>
</tr>
<tr>
<td>Good</td>
<td>0.10</td>
</tr>
</tbody>
</table>
account for 80% of the total loss of nitrogen due to denitrification and leaching on clay and 55% on sand [19]. These values correspond well with the figures in Table 3 for poor drainage conditions.

2.2.4. Emissions of nitrous oxide

Soil emissions of nitrous oxide (N\textsubscript{2}O) vary widely depending on the climate, among other factors. According to the IPCC Guidelines for National Greenhouse Gas Inventories [20], research has identified soil texture, water content and the availability of the nitrogen source as having the largest impacts on emissions of N\textsubscript{2}O. However, more data would be needed to make detailed calculations. Therefore, a simplified model for calculating N\textsubscript{2}O from farmland is presently suggested in the IPCC guidelines. The amount of N\textsubscript{2}O emitted is estimated as 1.25% of the total nitrogen added. Moreover, the majority of published field emissions are within the range of 0.25–2.25%. Relating emissions of N\textsubscript{2}O to the total nitrogen added implies that in the present model the increased emission resulting from the use of organic fertilizers, compared with that from mineral fertilizers, is equal to 1.25% of the additional nitrogen losses of nitrate and nitrogen gas. This is because the model describes the additional emissions resulting from the use of organic nitrogen instead of mineral nitrogen.

2.2.5. Plant utilisation and nitrogen pool

The utilisation of nitrogen from organic fertilizers by plants has been of interest in many investigations. In a review of the literature concerning the uptake of manure-nitrogen by plants, Kirchmann [21] found values ranging between 4 and 38% of total nitrogen content. Ammonium and nitrate in organic fertilizers are both available for crop uptake. However, ammonium and nitrate in organic fertilizers can be immobilised in soils with a high C/N ratio. Organically bound nitrogen does not become available for plant uptake until it has been mineralised. However, mineralisation also occurs under conditions where no nitrogen is needed by plants. Therefore, Slujsmans and Kolenbrander [14] suggested that 40% of the organically bound nitrogen becomes available for plant uptake during the first year after application to cereal crops. Beauchamp [15] used a figure of 20% in his model. The proportion of organically bound nitrogen mineralised during the first growing season depends primarily on the degradability of the organic substances and the soil texture. Chae and Tabatabai [22] registered mineralisation rates of 13–67% during the first 26 weeks after applying manure, with the lower figure for cattle manure and the higher one for poultry manure.

In the present model it is assumed that 100% of the nitrate, all of the ammonium left in the soil (after volatilisation) and 30% of the organic nitrogen in waste residues spread on farmland contribute to reducing the need for mineral fertilizer during the first year after application.

The organic nitrogen remaining after the first year is mineralised during the following years. It is assumed that this nitrogen eventually replaces mineral fertilizer or is lost as emissions in the same proportion as the organic nitrogen mineralised during the first year. Thus, the model can mathematically be described in the following way:
Mathematical description of the nitrogen turnover model

\[ N_{NH_4-N} = \text{mass of ammonium spread on farmland as organic fertilizer [ton]} \]

\[ N_{organic} = \text{mass of organically bound nitrogen spread on farmland as organic fertilizer [ton]} \]

\[ N_{pool} = \text{mass of organically bound nitrogen remaining after the first year [ton]} \]

\[ l_{N_2} = \text{increased losses of N}_2\text{ as a fraction of NO}_3^-\text{-N and N}_2\text{ losses (Table 3) [-]} \]

\[ k_{N_2} = \text{increased losses of N}_2\text{ as a fraction of NO}_3^-\text{-N losses with organic fertilizers [-]} \]

\[ k_{NH_4} = \text{increased losses of NH}_4^+\text{-N with organic fertilizers (Table 1) [-]} \]

\[ k_{NO_3} = \text{increased losses of NO}_3^-\text{-N as a fraction of N}_{organic} \text{ with organic fertilizers (Table 2) [-]} \]

\[ k_{N_2O} = \text{increased losses of N}_2O^+\text{-N as a fraction of NO}_3^-\text{-N and N}_2\text{ with organic fertilizers [-]} \]

\[ k_{MF} = \text{fraction of organic nitrogen replacing mineral fertilizer during the first year after application [-]} \]

where: \[ k_{N_2} = l_{N_2}/(1 - l_{N_2}) \]

First-year emissions

Emissions of nitrogen as ammonia: \[ E_{NH_3} = k_{NH_4}\text{*}N_{NH_4-N} \text{ [kg]} \]

Emissions of nitrogen as nitrate: \[ E_{NO_3} = k_{NO_3}\text{*}N_{organic} \text{ [kg]} \]

Emissions of nitrogen gas: \[ E_{N_2} = k_{N_2}\text{*}E_{NO_3} \text{ [kg]} \]

Nitrogen to soil pool: \[ N_{pool} = N_{organic} \text{(1 - k}_{MF}) - E_{NO_3} - E_{N_2} - E_{N_2O} \text{ [kg]} \]

Long-term emissions

Emissions of nitrogen as nitrous oxide \[ E_{PN_2O} = N_{pool} \text{(1 - k}_{MF}) - E_{PN_2} - E_{PN_2O} \text{ [kg]} \]

Reduced need for mineral nitrogen fertilizer: \[ N_{fert} = (1 - k_{NH_4})\text{*}N_{NH_4-N} + N_{NO_3} + k_{MF}\text{*}N_{organic} + k_{MF}\text{*}N_{pool} \text{ [kg]} \]

2.3. Case study

To examine the importance of including nitrogen emissions from soil a case study was performed. The waste fractions included in the simulations were biodegradable waste from households, various trades and restaurants in a municipality of 190000 citizens (Table 4).

Three scenarios were compared. In the incineration scenario, it is assumed that the ashes are landfilled and that the heat produced is used in a district heating system. In the anaerobic digestion scenario we assume that the biogas produced is used in an internal combustion engine for producing heat and electricity and that a digestion residue fraction is spread on farmland. In the reactor composting scenario, it is assumed that the compost is used on farmland. The treatment plants simulated had a high technical standard regarding emission control. In the model, environmental impacts of landfiling are divided into two time frames, a surveyable...
period (within approx. 100 years) and a long-term period corresponding to the time it would take to disperse all of landfilled material. However, only the emissions during the surveyable period were included in the results presented.

Although the same amount of waste was treated in all scenarios, the inputs to farmland and energy conversion differed between them. One way of facilitating the comparison of environmental impacts used in the life-cycle methodology is to expand the system by also considering activities external to the waste management system, so that they can be comparable from an environmental viewpoint [23]. For example, the anaerobic digestion and composting scenarios are complemented with heat production from an external source, i.e. wood chips, so that these scenarios produce the same quantity of net heat to the district heating system as the incineration scenario. Thus, emissions from combustion of wood chips are included in these scenarios [24]. The electricity, nitrogen and phosphorus are handled in a similar way. In scenarios where there are soil deficits of nitrogen and phosphorus with regard to crop production, the production of nitrogen and phosphorus mineral fertilizer was included, using average emissions from the mineral fertilizer used in Germany [25]. For electricity, emissions from external production from oil in an oil condensation plant were used [24].

In addition to the simulation of the three scenarios under normal conditions (reference case), simulations of the anaerobic digestion and composting scenarios were run in which conditions in the nitrogen turnover model were changed (cases 1 and 2). Based on these runs, a sensitivity analysis was carried out to evaluate the impact of the conditions chosen in the nitrogen turnover model on the overall results. In the reference case the parameters were chosen to reflect average nitrogen conditions for Sweden (Table 5). The soil was a loam with good drainage conditions located in the plains district in northern Götaland (Gns) with a drainage period.
Table 6

Weighting factors used for evaluation of environmental impact [23]

<table>
<thead>
<tr>
<th></th>
<th>Eutrophication (O₂-equivalents)</th>
<th>Acidification (SO₂-equivalents)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂-f (100 years horizon; CO₂-equivalents)</td>
<td>1 NOₓ</td>
<td>6 SO₂</td>
</tr>
<tr>
<td>CH₄</td>
<td>24.5 NH₃</td>
<td>16 HCl</td>
</tr>
<tr>
<td>N₂O</td>
<td>320 NH₄⁺</td>
<td>15 NO₃⁻</td>
</tr>
<tr>
<td></td>
<td>NO₃⁻</td>
<td>4.4 NH₃</td>
</tr>
<tr>
<td>P</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>COD</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

flow of 300 mm/year. Furthermore, spreading was carried out with a broadcast spreader in spring, followed by harrowing within 1 h, and the crop was barley. In case 1, conditions were chosen to promote low ammonia emissions and high nitrate emissions, while in case 2, the conditions were conducive to high ammonia emissions and low nitrate emissions. These conditions were chosen in order to determine whether the ranking of scenarios in the impact categories depended on the region and conditions chosen in the nitrogen turnover model. Thus, in case 1 the soil texture was sand with good drainage conditions located in the forest district in Götaland (Gsk) with a drainage flow of 400 mm/year. The anaerobic digestion residue was band spread in the growing crop in summer to reduce ammonia emissions, and the compost was broadcast spread, followed by harrowing within 1 h in spring, with barley as the following crop. In case 2 the soil texture was clay with good drainage conditions located in the plains district in Svealand (Ss) with a drainage flow of 200 mm/year, and the compost was broadcast spread, followed by harrowing within 12 h in spring before sowing barley.

The emissions were weighed in terms of their relative importance in the environmental impacts global warming, acidification and eutrophication. Weighting factors used are presented in Table 6. The maximum potential acidification and eutrophication scenarios were chosen. Therefore, both nitrogen and phosphorus are included in the eutrophication impact category, and gaseous nitrogen compounds were included in the acidification impact category.

3. Results

The nitrogen turnover sub-model described the nitrogen in anaerobic digestion residue and compost in terms of its environmental impact (N₂O, NH₃ and NO₃⁻), its ability to reduce the need for mineral N-fertilizer and its effect on emissions of nitrogen gas. This is presented in Table 7, except the emissions of nitrogen gas which are not causing any environmental impact. Emissions of nitrogen compounds differ significantly between the anaerobic digestion and compost scenarios. The variation of parameters in cases 1 and 2 also influenced the nitrogen emissions considerably. However, the incineration scenario was not influenced since all biodegradable waste was incinerated, and thus no organic fertilizers were used.
Table 7
Soil emissions of $N_2O$, $NH_3$ and $NO_3^-$, and reduced need for mineral N-fertilizer when using waste residues as organic fertilizer on farmland

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$N_2O$-N kg/year</th>
<th>$NH_3$-N kg/year</th>
<th>$NO_3^-$-N kg/year</th>
<th>Mineral N-fertiliser, reduced need, kg/year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First year</td>
<td>Long-term</td>
<td>First year</td>
<td>Long-term</td>
</tr>
<tr>
<td>Reference case</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anaerobic digestion</td>
<td>310</td>
<td>70</td>
<td>5600</td>
<td>18 700</td>
</tr>
<tr>
<td>Reactor composting</td>
<td>600</td>
<td>130</td>
<td>70</td>
<td>36 100</td>
</tr>
<tr>
<td>Case 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anaerobic digestion</td>
<td>80</td>
<td>3</td>
<td>2800</td>
<td>28 700</td>
</tr>
<tr>
<td>Reactor composting</td>
<td>150</td>
<td>5</td>
<td>40</td>
<td>55 500</td>
</tr>
<tr>
<td>Case 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anaerobic digestion</td>
<td>100</td>
<td>160</td>
<td>11 200</td>
<td>2900</td>
</tr>
<tr>
<td>Reactor composting</td>
<td>190</td>
<td>300</td>
<td>140</td>
<td>5600</td>
</tr>
</tbody>
</table>
The environmental impact (i.e. contribution to global warming, acidification and eutrophication) was calculated for each waste management scenario and effect category. Impacts were summed separately for waste transport, waste treatment, soil emissions, energy extraction and mineral fertilizer production. Waste transport included the collection of waste as well as the transport and spread of the residues. Soil emissions are presented separately to show their importance. Furthermore, they are divided into first-year and long-term effects. Based on the simulation results, it is also possible to assess the importance of including the production of heat, electricity, nitrogen and phosphorus.

Soil contributed to the global warming effect through emissions of N₂O in both the first year and the long-term (Fig. 2). Other greenhouse emissions in the scenarios were carbon dioxide (CO₂) from fossil fuels consumed in waste transport and in the production of electricity from oil. The contribution of mineral fertilizer production was in the form of CO₂ (15%) and N₂O (85%) generated in connection with nitrogen extraction. The emission sources and substances emitted in connection with waste management differed between the scenarios: in the incineration scenario, N₂O was emitted during the incineration process; in the anaerobic digestion scenario methane was generated from landfills; and in the composting scenario methane was generated from landfills, while methane and N₂O were produced in the composting process. In the anaerobic digestion and composting scenarios only waste rejected for digestion/composting in connection with mechanical sorting at the plants was landfilled.

Soil contributed significantly to the acidification effect only in the anaerobic digestion scenario, through emissions of ammonia (Fig. 3). In the incineration and anaerobic digestion scenario, emissions of nitric oxide (NOₓ) and sulphur oxide (SOₓ) in connection with waste transport, energy conversion and waste treatment contributed to acidification. In the composting scenario ammonia from the composting process and ammonia together with NOₓ and SOₓ, generated when producing mineral fertilizer had acidifying effects.

![Fig. 2. Total contribution of waste management to the global warming potential for each of the studied scenarios in the reference case.](image-url)
Fig. 3. Potential contribution of activities related to waste management to acidification for each of the studied scenarios in the reference case.

The large eutrophication effect of soil emissions was primarily in the form of nitrate leaching to water both during the first year and in the long-term (Fig. 4). However, in the anaerobic digestion scenario ammonia accounted for 23% of the eutrophication impact in the first year. Waste transport, energy extraction and mineral fertilizer production all resulted in small emissions of NOx. Emissions from waste treatment differed between scenarios: emissions in the incineration scenario were primarily in the form of P effluent from water used in the gas purification process in the incineration plant. In the anaerobic digestion scenario NOx formed when combusting biogas for heat and electricity generation accounted for most of the eutrophication impact. In the reactor composting scenario, ammonia from the composting process was the main contributor to eutrophication.

In cases 1 and 2 other parameters for the nitrogen turnover model were chosen. These resulted in changed impacts for all categories, but the ranking of scenarios was only influenced for the eutrophication category (Table 8).

Fig. 4. Total potential contribution of activities related to waste management to eutrophication for each of the studied scenarios in the reference case.
Table 8
Simulation results from the three scenarios including long-term emissions of nitrogen in three cases reflecting different conditions in the nitrogen turnover model

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Global warming</th>
<th>Acidification</th>
<th>Eutrophication</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ton CO₂-eq. /year</td>
<td>%</td>
<td>Ton SO₂-eq. /year</td>
</tr>
<tr>
<td>Reference case</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incineration</td>
<td>2730</td>
<td>100</td>
<td>12</td>
</tr>
<tr>
<td>Anaerobic digestion</td>
<td>654</td>
<td>24</td>
<td>43</td>
</tr>
<tr>
<td>Reactor composting</td>
<td>2618</td>
<td>96</td>
<td>20</td>
</tr>
<tr>
<td>Case 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anaerobic digestion</td>
<td>507</td>
<td>19</td>
<td>38</td>
</tr>
<tr>
<td>Reactor composting</td>
<td>2404</td>
<td>89</td>
<td>20</td>
</tr>
<tr>
<td>Case 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anaerobic digestion</td>
<td>731</td>
<td>23</td>
<td>53</td>
</tr>
<tr>
<td>Reactor composting</td>
<td>2245</td>
<td>71</td>
<td>18</td>
</tr>
</tbody>
</table>

Soil emissions have no influence in the incineration scenario since no residues are spread on farmland. Both the absolute and relative values are presented.

4. Discussion

In the present study, taking into account the increased emissions from soil resulting from the replacement of mineral fertilizers with organic fertilizers had a significant influence on the outcome of the calculations used to compare systems for managing biodegradable municipal waste in terms of their environmental impacts. However, as can be seen in Figs. 2–4, although the soil emissions influenced the results significantly, the ranking of scenarios in terms of impacts on global warming and acidification was the same regardless of whether or not nitrogen emissions were included. By contrast, the inclusion of nitrogen emissions did affect the ranking with regards to eutrophication: when soil emissions were excluded the largest impact was registered in the incineration scenario (reference and case 1 scenarios), whereas when they were included the composting system had the largest impact. In addition, the influence of soil emissions on total emissions was also greatest in the eutrophication category. Long-term emissions from soil had only a minor influence on the results, except in case 2 where more than 50% of the emissions of both N₂O and nitrate were long-term emissions (Table 7).

Global warming potential was significantly influenced by emissions of N₂O from soil. Emissions of N₂O were higher from soils receiving organic fertilizers than from those receiving mineral fertilizer since N₂O emissions are positively related to the total dosage of nitrogen, and this dosage had to be higher for organic fertilizers to compensate for larger nitrogen losses (NO₃⁻ and N₂). However, the modelling of emissions of N₂O is based on a general assumption related to the total nitrogen dose and would need to be studied further. Of the scenarios compared, the
composting scenario, in which the proportion of organic nitrogen was the largest, was influenced most by the changes in the parameters in the nitrogen turnover model. In cases 1 and 2 a lower and an upper interval value were chosen for N\textsubscript{2}O emissions because clay soils often emit more N\textsubscript{2}O than sandy soils. But since emissions are related to nitrogen losses (NO\textsubscript{3}\textsuperscript{-} and N\textsubscript{2}) and these were small in case 1 and large in case 2, both cases resulted in emissions of the same magnitude which were lower compared with the reference case. Other combinations of parameters in the nitrogen turnover model could have resulted in considerably larger emissions of N\textsubscript{2}O, if, for example, case 2 had been located in the western part of the forest district in Götaland where there is more drainage flow, and thus losses of nitrate and nitrogen gas are larger.

The acidifying effect of soil was due to ammonia emissions and thus related to the content of ammonium in organic fertilizers. The emissions depended heavily on the type of spreader and time of spreading. In all situations the low content of ammonium in compost resulted in low emissions of ammonia. In the anaerobic digestion treatment organic nitrogen was mineralised, and the emission of ammonia from the residue was large. Although the variation in emissions was large, the anaerobic digestion scenario contributed most to acidification in all cases, since NO\textsubscript{x} emissions resulting from the use of biogas in a stationary engine were large.

Both ammonia and nitrate from soil contributed to eutrophication. In the reference case nitrate dominated, accounting for 80% of the total soil emissions in the anaerobic digestion scenario and 99.8% in the composting scenario. The eutrophication effect in these scenarios was dominated by soil emissions, and a change in nitrate leaching had a large influence on the ranking of these scenarios in terms of their contributions to eutrophication. The proportion of the total nitrogen lost through nitrate leaching as well as the proportion lost through denitrification was related to soil texture and climate region. However, nitrate leaching was influenced more by climate region than by soil texture. Thus, climate region had a large influence on the amount of eutrophication in the composting and anaerobic digestion scenarios. Even though low nitrate leaching was simulated in case 2, the eutrophication effect from these scenarios was considerable owing to long-term leaching from the nitrogen pool.

The reason for focusing on global warming, acidification (max.) and eutrophication (max.) was that they represent three of the important environmental impacts of waste management. Furthermore, there is a scientifically based consensus on the weighting factors for these categories. However, the results would have been different in areas where nitrogen compounds do not contribute to acidification or eutrophication. In areas where nitrogen does not cause acidification, the anaerobic digestion scenario still has the largest acidification impact, primarily owing to SO\textsubscript{x} emissions from biogas utilisation. If nitrogen does not contribute to the eutrophication effect the impact of soil diminishes. In these situations the contribution to eutrophication is, by far, greatest for the incineration scenario owing to emissions of P in water used in the incineration process.

It is important to note that the parameters used in the nitrogen sub-model are for average weather conditions. However, the variation between years due to weather
conditions can be larger than that due to differences between regions, soil textures and spreading techniques. Thus the environmental impacts of soil emissions in cases 1 and 2 are not maximum or minimum values but averages that take into account the conditions most likely to occur in each of the regions.

In Sweden and Denmark, manure, together with biodegradable municipal waste, is often used as substrate in anaerobic digestion plants. If manure had been included in the study, the emissions of nitrogen would have had a larger impact on the overall results.

Several other circumstances could also influence environmental impacts and, hence, the relative importance of including soil emissions. For example, electricity production from oil and heat production from wood chips had large and small impacts, respectively, on the global warming. But if wood chips also had been used for producing electricity the global warming emissions from this activity would have diminished, and, consequently, the soil emissions would have had a strong effect on the ranking of scenarios in terms of this impact category as well. Furthermore, if biogas were to be used as a substitute for diesel fuel in vehicles, NO\textsubscript{x} emissions would decrease in relation to the other scenarios. As a consequence, nitrogen emissions from soil would become more important in determining the ranking of scenarios in terms of their contribution to acidification. The landfilling of ash increases the long-term potential for emissions (after 100 years) of phosphorus in leachate. If the long-term effect had been included in the case study the contribution of the incineration scenario to eutrophication would have been five times larger, i.e. 4000 metric tonnes O\textsubscript{2}-equivalents per year. In that case the incineration scenario would have had the largest eutrophication effect regardless of the level of soil emissions.

The present study shows that it is of vital importance to include the emissions generated in connection with nitrogen turnover in soil. Since the nitrogen turnover model had such a large impact on the results, it might be worthwhile to increase the level of detail of the model. The present model does not consider the fact that the organic nitrogen in digestion residues is probably mineralised faster in soil, compared with organic nitrogen in compost, since the organic matter in compost is more stable. One way of solving this problem would be to use a dynamic approach to modelling the mineralisation of organic nitrogen during the growing season and winter season. Mineralisation could be related to the degradability of carbon fractions in the organic residues. It would then be possible to calculate the nitrogen mineralisation rate based on the stability of the organic matter in residues. Nitrate leaching from organic residues should also be studied further since it was of vital importance in the comparison of eutrophication impacts. Furthermore, on a clay soil with large drainage flow (Gsk\textsubscript{v}), the model results in a negative mass of nitrogen after the first year. Although this can be interpreted as a net mineralisation of nitrogen from the nitrogen pool, this is probably not the case when organic fertilizers are added. The reason why is that the SoilN model may overestimate the increased nitrate emissions when mineral fertilizers are replaced by organic fertilizers in clay soils with large drainage flow.
There are also several positive effects of using organic fertilizers that were not quantified in this study. In long-term field experiments Cooke [26] showed that the addition of organic residues improves the soil structure, especially in clay soils. In addition, the organic matter enhances the porosity and water-holding capacity. Furthermore, organic fertilizers contain potassium, sulphur and micronutrients essential for plant growth; however, this was not accounted for in the analysis.

5. Conclusions

The aim of this study was to examine the effects of including nitrogen emissions from soil when studying the environmental impacts of activities related to the management of biodegradable municipal waste. A case study was performed using the ORWARE model and a simple nitrogen turnover model. The following major conclusions were obtained.

(1) Nitrogen emissions from soil due to the application of organic residues have a considerable impact on potential global warming (from N₂O), acidification (from NH₃) and eutrophication (from NH₄ and NO₃⁻).

(2) The ranking of waste management alternatives in terms of their potential contribution to eutrophication varies depending on whether soil emissions are included.

(3) In some circumstances nitrogen emissions from soil can also influence the ranking of scenarios with regard to global warming and acidification (max.).

(4) Spreading technique, region and type of soil are of vital importance when comparing the anaerobic digestion and composting waste management systems in terms of their eutrophication impacts.

(5) It is generally more important to include soil emissions than those resulting from the production of mineral fertilizer.

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References


