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# Nitrogen Footprint

Vs.

## Life Cycle Impact Assessment methods

- A comparison of the methods in a case  
study

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Master Degree Thesis in  
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30 credits

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## **Abstract**

Nitrogen species have several environmental effects when emitted to water and air, such as eutrophication and acidification but they may also alter the ozone concentration in the troposphere and stratosphere. These effects have not received much attention in the climate and environmental debates, instead the focus has been on carbon emissions. Nitrogen footprint is a newly introduced concept among the environmental footprints, where the carbon footprint is the most known. The nitrogen footprint strives to account for the total nitrogen released during the life cycle of a product or similar. In life cycle impact assessment (LCIA) methods, nitrogen is assessed among other substances for several impact categories. This thesis explores how nitrogen species are evaluated in the nitrogen footprint method and the LCIA methods for global warming, eutrophication, acidification, photochemical ozone formation and stratospheric ozone depletion. Using a case study, of Swedish grown tomatoes, the methods were compared and evaluated. The different approaches yielded different results because the nitrogen footprint method does not distinguish between different nitrogen species and therefore the environmental impacts can currently not be identified with this method. The LCIA methods are more comprehensive as they identify the environmental impacts induced by nitrogen emissions through scientifically derived factors, thereby giving a more comprehensive description of the spectra of impacts. It also became evident during this study that LCIA does not recognise nitrous oxide as an ozone depleting substance and therefore no result for the stratospheric ozone depletion impact category could be derived in the case study. The footprint concept applied in a broader perspective could be used as a tool to communicate and raise awareness of the environmental impacts from nitrogen emissions. Additionally, the nitrogen footprint concept could be valuable in bringing the nitrogen perspective back into the environment and climate debate, as well as in LCAs.

**Keywords:** Nitrogen, footprint, impact assessment, life cycle

## Sammanfattning

Kväveföreningar påverkar miljön på flera sätt när de kommer ut i luft och vatten, bland annat så sker övergödning och försurning men även ozonkoncentrationen kan påverkas i troposfären och stratosfären. Effekterna som kväve ger upphov till har inte fått mycket uppmärksamhet i klimat- och miljödebatter, istället har fokus varit koldioxidutsläppen. Konceptet kvävefotavtryck introducerades nyligen som ett av miljöfotavtrycken. Av de olika fotavtrycken så är kolfotavtrycket mest känt. Kvävefotavtrycket strävar efter att beräkna den totala mängd kväve som förbrukas under en produkts, eller liknande, livscykel. I miljöpåverkansanalysmetoden, som är en del av livscykelanalysen (LCA), värderas kväve bland andra ämnen i flera olika effektkategorier. Det här examensarbetet undersöker hur olika kväveföreningar utvärderas i en kvävefotavtrycksmetod samt i en miljöpåverkansanalysmetod för global uppvärmning, övergödning, försurning, fotokemisk ozonbildning och stratosfärisk ozon nedbrytning. Dessa metoder applicerades i en fallstudie på svenska tomater och de två metoderna jämfördes och utvärderades. De olika tillvägagångssätten gav olika resultat eftersom kvävefotavtrycksmetoden inte skiljer de olika kväveföreningarna åt och därför kan de olika effektkategorierna för närvarande inte identifieras med den här metoden. Miljöpåverkanbedömningsmetoden är således mer omfattande eftersom den kan identifiera de olika effektkategorierna orsakade av kväveutsläppen med hjälp av vetenskapligt erhållna faktorer och på så vis ger en mer rättvis och nyanserad bild av problemet. Det visade sig också att miljöpåverkanbedömningsmetoden inte erkänner lustgas ( $N_2O$ ) som ett ozonnedbrytande ämne vilket bidrog till att inga resultat kunde fås ut av effektkategorin stratosfärisk ozonnedbrytning i den här studien. Konceptet kvävefotavtryck applicerat i ett bredare sammanhang kan användas som ett verktyg till att kommunicera och öka medvetenheten av de olika miljöproblemen som är en konsekvens av kväveutsläpp. Vidare så skulle konceptet kvävefotavtryck kunna vara av värde genom att det skulle kunna bidra till att kväveperspektivet kommer in i miljö- och klimatdebatten samt i livscykelanalyssammanhang.

**Nyckelord:** Kväve, fotavtryck, livscykel, påverkansbedömning

## Contents

1 Introduction .....	1
Objective .....	2
2 Background .....	3
2.1 The nitrogen cycle in short .....	3
2.2 Environmental problems caused by nitrogen .....	3
2.3 The footprint concept and its history in brief .....	5
2.3.1 Short history .....	5
2.3.2 The nitrogen and carbon footprint in foods .....	5
2.3.3 The N-calculator .....	6
2.4 Life Cycle Impact Assessment in short .....	6
2.4.1 Methods of assessing the environmental impacts.....	7
2.4.2 Double counting .....	13
3 Method .....	14
3.1 General method .....	14
3.2 Case study of tomatoes.....	14
3.2.1 Structure of the system model .....	14
3.2.2 Simplifications and excluded parts in the system model.....	17
3.2.3 Calculations made for the life cycle impact assessment.....	18
3.2.4 Calculations of the nitrogen footprint.....	18
4 Results .....	19
4.1 Nitrogen footprint.....	19
4.1.1 Results per activity .....	19
4.1.2 Species distribution .....	20
4.2 Life Cycle Impact Assessment .....	20
4.2.1 Global warming potential .....	20
4.2.2 Eutrophication potential .....	21
4.2.3 Acidification Potential.....	22
4.2.4 Photochemical Ozone Creation Potential (POCP) .....	23
4.2.5. Ozone Depletion Potential (ODP) .....	23
5 Discussion .....	25
5.1 Life cycle impact assessment contra nitrogen footprint .....	25

5.2 Advantageous and disadvantageous of the two methods .....	25
5.3 System model .....	26
5.4 Environmental impact categories .....	26
5.4.1 Photochemical Ozone Creation Potential.....	27
5.4.2 Ozone Depletion Potential.....	27
5.4.3 Warming Potential.....	27
5.5 Nitrous oxide .....	27
6 Conclusion.....	29
Acknowledgement.....	30
References .....	31
Appendix .....	34

## 1 Introduction

The expansion of agriculture made possible by the green revolution has secured the food supply for the Earth's constantly growing population. The increased use of synthesised nitrogen has been one of the solutions to make this food security possible but it has also led to multiple environmental degradations (Tilman et al 2001). The anthropogenic input of reactive nitrogen which is all nitrogen species except for nitrogen gas ( $N_2$ ) has also led to unintentional flows of reactive nitrogen. Ammonia ( $NH_3$ ) from agriculture contributes to amounts of reactive nitrogen to the atmosphere that are in the same size range as nitrogen oxides ( $NO$  and  $NO_2$  collectively known as  $NO_x$ ). Approximately 70% of the nitrous oxide ( $N_2O$ ) emissions in Europe originate from agriculture. Within the food chain there are also leakages of nitrogen species to ground and surface waters, with the dominant species being nitrates ( $NO_3$ ), which originates largely from agriculture and sewage treatment systems (Sutton et al 2011). The impact that the production of different food types have on the environment has gained considerable attention. The carbon footprint has been a popular approach to measure the anthropogenic emissions of greenhouse gases caused by the life cycle of foods with the focus on carbon dioxide ( $CO_2$ ) and methane ( $CH_4$ ) (Wright et al 2011). However, the carbon footprint is still vaguely defined. The nitrogen footprint, measuring the anthropogenic emissions of reactive nitrogen, has not experienced as much attention and few studies have assessed the environmental impacts caused by the excess release of nitrogen from the production of food (Xue & Landis 2010). The only known attempts on calculating a nitrogen footprint has been conducted by Leach et al (2012) and by the Chesapeake Bay foundation (2012), both focusing on the footprint of individuals. The nitrogen footprint calculator by Leach et al (2012) is the most extensive developed nitrogen footprint calculator and was developed to help communicating the extent to which consumption of products and services of an individual contribute to a release of nitrogen. What the nitrogen footprint does not communicate is the specific emissions released as a result of the consumption behaviour and the environmental impacts that the emissions are associated with. A life cycle assessment (LCA) can be used to highlight these environmental impacts for different food types. Life cycle impact assessment (LCIA), which is conducted as a part of an LCA, connects the different emissions to the corresponding environmental impacts.

To the best of my knowledge, no study that compares the footprint approach with an LCIA method from the nitrogen perspective has been conducted before. It was therefore of interest to analyse and compare these two approaches, to highlight differences and similarities, as well as propose options for improvement of the methods.

## **Objective**

The methods of nitrogen footprint and LCIA categories are evaluated in this study from a nitrogen perspective. In a case study the life cycle of one kilogram Swedish tomatoes, grown in a greenhouse, is analysed to compare the two methods. The environmental impact categories analysed through this case study are, according to the CML's impact categories (CML 2001):

- Global warming potential (GWP)
- Eutrophication potential (EP)
- Acidification potential (AP)
- Photochemical ozone creation potential (POCP)
- Ozone depletion potential (ODP)

In order to gain an understanding on how these environmental impacts are measured the methods in which the calculations are conducted needs to be investigated.

The purpose of the thesis is to analyse the nitrogen footprint concept and compare it with how nitrogen is evaluated from an LCA perspective for different LCIA impact categories. The objective is to implement the two approaches in a study of one kilogram of tomatoes and evaluate the differences and similarities in method and outcome and to assess the two methods merits in terms of environmental impacts.

## **2 Background**

### **2.1 The nitrogen cycle in short**

Nitrogen is an abundant element in the atmosphere and 78 % of the earth's atmosphere consists of nitrogen gas ( $N_2$ ). Yet nitrogen is limited in many ecosystems because nitrogen gas is a very persistent molecule due to the triple bonding that binds the two nitrogen atoms together and is therefore highly unreactive. Only a few species of bacteria can convert the molecule into reactive nitrogen (Galloway et al 2004) and this process is called nitrogen fixation. Before it was possible to synthesise nitrogen the natural pathway in which nitrogen reached the terrestrial ecosystems was mainly through nitrogen fixation. The bacteria that can fixate nitrogen are found in soil, sediments and water. The bacteria can also be found within certain parts of vascular plants as well as in lichens in a symbiotic relation with fungi. Plants get access to nitrogen through the decomposition of litter from the nitrogen fixing plants. During the decomposition soil organic matter is broken down and then accessed to microbes which are further degraded into ammonia. This process is called nitrogen mineralization or ammonification since it results in the production of ammonia (Chapin et al 2002). Ammonia can be oxidized to nitrite ( $NO_2^-$ ) and then to nitrate ( $NO_3^-$ ) a process referred to as nitrification. Ammonia and nitrate can be utilized by plants or absorbed by microorganisms, which mean that plants and microorganisms might compete for the nitrate and ammonia available when nitrogen is limited. During nitrification nitrous oxide and nitric oxide (NO) are also produced which both are found in gaseous form. Nitric oxide and nitrous oxide are also produced during denitrification when nitrate is converted through a serial of reactions into nitrogen gas (Sutton et al 2011).

Deposition of nitrogen can occur through wet and dry deposition in particulate, dissolved and gaseous form. Anthropogenic nitrogen has become the most common deposition in many regions. Approximately 80% of all nitrogen oxides are now anthropogenic and originates from fossil fuel combustion and biomass burning etc. Many of the anthropogenic nitrogen species can be transported long distances before being deposited (Sutton et al 2011).

### **2.2 Environmental problems caused by nitrogen**

In the beginning of the 20<sup>th</sup> century the Haber-Bosch process was invented, in which ammonia is synthesised by reacting nitrogen gas with hydrogen with help of an iron catalyst at a high pressure and temperature. In other words, nitrogen gas could now be converted into reactive nitrogen in the form of ammonia which is used in fertilisers. Because of this, agriculture was no longer limited by nitrogen, provided that there the farmer had access to fertilisers. This technique was invented by Fritz Haber and industrialised by Carl Bosch thus the name Haber-Bosch. The Haber-Bosch process made it possible to support a growing population by reducing the shortage of food (Galloway & Cowling 2004). However, this has been made possible in exchange for an environmental cost.

The major consequences seen from the increased nitrogen use as a result of the expansion of agriculture includes eutrophication, acidification, tropospheric ozone formation, stratospheric ozone depletion and global warming.

Emissions of greenhouse gases generate an increase in the long-wave radiation absorption and re-emission in the atmosphere, also referred to as the greenhouse effect. Nitrous oxide is a greenhouse gas which is 298 times stronger than a carbon dioxide molecule, see table 1 (Forster et al 2007). The largest source of anthropogenic nitrous oxide (N<sub>2</sub>O) has its origin from agriculture and in particular from agricultural soils. The concentration of nitrous oxide is increasing due to the growing use of fertiliser in agriculture (Reay et al 2010). The increased concentration of nitrous oxide is of additional concern because nitrous oxide is also a substance that depletes stratospheric ozone.

Ground-level ozone, or tropospheric ozone as it is also called, has a complex chemistry where nitric oxide is one of the reactants. Elevated concentrations of tropospheric ozone can, for example, have damaging effects on vegetation. Ozone enters the plant via stomata and kills the plant cells, which lead to reduced capacity of photosynthesis, early leaf loss and a decline in productivity among other problems. In addition ozone also affects the human health and can cause breathing problems, lung diseases and trigger asthma (Sutton et al 2011).

In Sweden, the nitrogen oxides pollutants mainly originate from petrol and diesel combustion. Acidification is a result of when these nitrogen oxides and ammonia emissions are directly or indirectly transferred to water bodies, soil and vegetation (Petersson 2006).

The intensive farming has led to degradation of the water quality due to nutrients leakage that occurs to the aquatic ecosystem where it causes eutrophication and hypoxia (Xue & Landis 2010). Nutrients of anthropogenic origin increase the productivity in the aquatic ecosystem which increases algal biomass. The algal bloom in turn causes a decrease in the water transparency and thus decreases the depth of the water body that is exposed to enough sunlight for photosynthesis to occur. This also affects the concentration of oxygen (Chapin et al 2002). Hypoxia is a phenomenon that occurs when the oxygen concentration reaches critically low levels in the bottom waters. The phenomena occur in coastal marine waters and have increased exponentially around the world since the 1960s. Hypoxia has serious consequences for the benthic flora and fauna, as it alters the biogeochemical cycles of nutrients. The Baltic Sea surrounding Sweden is affected by hypoxia and the problem is growing as the anthropogenic input of nutrients from the agriculture is increasing (Conley et al 2009). Hypoxia is reported to cover an area of more than 245 000 square kilometres (Diaz & Rosenberg 2008) which is approximately the same size as New Zealand. Eutrophication is considered a far larger problem than acidification in Europe (Sutton et al 2011).

The excess release of reactive nitrogen has also led to losses in native ecosystems and biodiversity, which changes the composition of species. Both aquatic and terrestrial ecosystems are affected by the increased use of nitrogen and since agriculture is projected to continue to expand the coming decades as a result of a growing and wealthier population, it can be assumed that the impacts caused by nitrogen fertilisation will not be resolved within the near future (Tilman et al 2001).

## **2.3 The footprint concept and its history in brief**

### **2.3.1 Short history**

The nitrogen footprint concept was developed to communicate how individuals and collective actions contribute to the loss of reactive nitrogen to the environment. The nitrogen footprint is defined by Leach et al (2012) as the accumulated amount of anthropogenic reactive nitrogen released to the environment during an entity's life cycle. However, the concept of nitrogen footprint is very new and not many studies applying this method can be found in the literature.

There are several types of footprints that take different environmental aspects into consideration. The general aim of a footprint is to quantify the person's or populations' demand on an ecosystem and evaluate the exceedance of the ecosystem's capacity to regenerate the resources it consumes and absorbs (Global Footprint Network 2012). The *carbon footprint* investigates those greenhouse gases that are a by-product of a product or service and converts the numbers into carbon dioxide equivalents using a 100-year GWP (Pihkola et al 2010). The *ecological footprint* focuses on the biologically productive area of sea and land that, for example a human or a region needs in order to produce the resources it needs and the area needed to absorb the carbon dioxide emitted compared to how much land and sea area that exist. The biologically productive area is the area that can be used to produce food and different resources for humans such as forest, crop land, fishing grounds and cities but excludes areas like glaciers, open oceans and deserts (Global Footprint Network 2012). The *water footprint* analyses the total volume of fresh water used for an individual or a service (Hoekstra 2011). These three footprints – carbon, ecological and water - together comprise the footprint family according to the definition by Galli et al (2011). The footprint family concept was developed in order to shed light on the fact that one indicator cannot accurately reflect the complexity of the human impact on the environment but that several indicators are needed. The nitrogen footprint is not included in the footprint family as the methodology is not yet standardised and developed to the same extent as for the other three footprints. The nitrogen footprint has to be developed and researched further before it can be included in the footprint family (Galli et al 2011).

Various methods can be used when a footprint model is performed which can lead to confusion and inconsistency in the analysis when different footprint models are compared with each other. Since a growing number of organisations and communities etc. use these footprints as indicators of what is sustainable or not the importance of well-defined standards and guidelines increases. The ecological footprint is in the process of developing standards and guidelines (Global Footprint Network 2009). Guidelines and standards for the carbon footprint method are in the process of development and have partially been inspired by the ISO 14040 series developed for LCAs (Pihkola et al 2010).

### **2.3.2 The nitrogen and carbon footprint in foods**

When assessing the impacts of different food types with a footprint approach it is important to remember that the environmental impacts can vary depending on the footprint evaluated. The carbon footprint of foods and the various impacts on the environment have received considerable more attention than the impacts caused by the corresponding nitrogen footprint.

Xue and Landis (2010) looked at eight different food types and calculated the carbon and nitrogen footprint for the respective food types. The result showed that the carbon footprint of a food group was not always consistent with its nitrogen footprint. The nitrogen footprint is higher for dairy products, fish, chicken and eggs compared to the carbon footprint. Conversely, sweets, oil, fruits and vegetables have a lower nitrogen footprint but a higher carbon footprint. However, the only food group with both a low carbon and nitrogen footprint is cereals/carbohydrates while red meat has both a high carbon and nitrogen footprint and is the least environmentally friendly option from both a nitrogen and carbon perspective (Xue and Landis 2010).

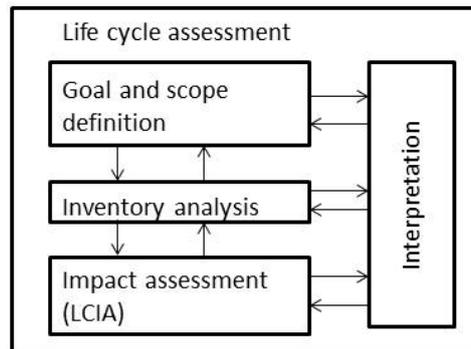
### **2.3.3 The N-calculator**

Few nitrogen footprint models have been developed. Chesapeake Bay foundation (2012) has developed a nitrogen footprint for people living in the Chesapeake Bay region. The aim is to communicate how the impact on the bay can be reduced but it does not include the dietary choices or the food production process. The most extensively developed and known nitrogen footprint model is developed by Leach et al (2012), also known as the N-calculator. The N-calculator was developed to help communicating the amount of nitrogen that an individual gives rise to. This nitrogen footprint aims to increase the awareness of the effects of nitrogen to the public and policymakers. Since food and energy consumption contributes most to the production of reactive nitrogen the N-calculator emphasises on these two categories. When using the N-calculator the user has to answer questions about his/her food consumption and energy use. The average usage of anthropogenic nitrogen per capita for respective country is used and scaled depending on the user's answer to the questions. The user will be informed what gives rise to a high production of reactive nitrogen and consequently how to reduce his or her nitrogen footprint. The nitrogen footprint is presented in kilograms of elementary nitrogen per person and year for four different categories namely food consumption, housing, transportation and consumptions on goods and services. Thus the different nitrogen species are not distinguished and therefore it is not possible to connect the nitrogen footprint with environmental impacts. However, the N-calculator will no-doubt undergo further developments, and it is planned that the environmental effects will be included in the model in the future (Leach et al 2012).

### **2.4 Life Cycle Impact Assessment in short**

Life Cycle Assessment (LCA) was developed as a response to the increased awareness of the environmental impacts associated with production and consumption of products and services. The objective of an LCA is to assess the environmental aspects and potential environmental impacts. This technique can be used as a tool to detect stages of a product or service's life cycle where improvements of the environmental performance can be made. It can also serve as a support for policymakers at different levels (i.e. in industries, government and non-government organizations) which benefit the environmental perspective. In addition it can be used when developing environmental product declarations (ISO 14044 2006).

Figur 1. The different phases of an LCA. The impact assessment phase is the phase relevant in this study since it is the step where the LCIA is conducted (Baumann and Tillman 2009).



A life cycle assessment (LCA) is often described as a “cradle to grave” analysis, and it investigates the different processes involved, from the manufacturing and use to the disposal of a product or service. When an LCA is conducted, the resources used as well as emissions to air, water and soil have to be quantified. ISO describes how the LCA investigation should be carried out and interpreted according to standards and guidelines authored. In the beginning of an LCA the aim of the study and product examined has to be described and defined. Once the aim of the study is defined the inventory analysis phase can start where the life cycle model is developed and the emissions released during the life cycle are calculated as well as the resources consumed. This step is called life cycle inventory (LCI) (Baumann and Tillman 2009). See figure 1.

In order to carry out an LCA, the various emissions and resources from the LCI have to be connected to different impact categories. This is done in the stage called life cycle impact assessment (LCIA). The LCIA is a phase in the LCA that aims to “translate” the results from the inventory analysis into environmental impacts. The purpose of this translation is because it is easier to relate to an environmental impact rather than to the species causing it. For example, most people can better relate and comprehend to ground level ozone formation than to nitrogen oxides. In this study the model is conducted according to an LCA methodology in order to evaluate the LCIA methods. The impact categories comprise of eutrophication, acidification, photochemical ozone formation, stratospheric ozone depletion and global warming and this step is therefore referred to as the impact assessment phase. Once the LCIA has been carried out it would also be possible to continue the analysis with weighing of the environmental impact categories (Baumann and Tillman 2009). However, this step is optional and has been excluded in this study since it prevents a scientific transparency in the results and would hinder comparison. Finally the LCIA results are interpreted.

ISO 14040-14044 has authored a series of international standards on how an LCA should be conducted. The first edition, ISO 14040 is from 1997 but has been updated several times since then (ISO 14044 2006).

#### 2.4.1 Methods of assessing the environmental impacts

Calculations of the emissions and resource use, and the sorting to impact categories are often incorporated into LCA modelling software. However, in this study, to be able to evaluate the

impacts assessment methods and results for the case and compare it with the nitrogen footprint approach a deeper understanding of how the LCIA method evaluates and calculates the environmental impacts is needed. The LCIA method used in this study is the CML 2001 impact assessment method developed by the Institute of Environmental Sciences, Leiden University, The Netherlands.

#### **2.4.1.1 Global Warming Potential (GWP)**

The Global Warming Potential (GWP) was developed to quantify the impact the different greenhouse gases have on the climate. The assigned GWP of a substance depends on its contribution to the greenhouse effect integrated over a chosen time scale, in this study the time scale is 100 years. The ratio between the release of one kilogram of a substance along with its impact on the greenhouse effect, compared to the impact of the equivalent amount of the reference substance (most often carbon dioxide), is calculated to obtain a factor of the GWP for a certain greenhouse gas. It is not uncomplicated to estimate a GWP because the persistency of a greenhouse gas varies depending on the substance and the persistency depends on the atmosphere's background concentration of certain substances, which varies over time. A change in the background concentration would consequently alter the GWPs. Substances that are subjected to change over time are methane, carbon monoxide and nitrogen oxides when eliminated by the hydroxyl radical (OH). Projecting the GWP for different time scales for these species is therefore difficult and associated with uncertainties and should thus be modified according to developments in the scientific research (Heijungs et al 1992).

The GWP of carbon dioxide, nitrous oxide and methane based on IPCCs fourth assessment report: climate change 2007 (Forster et al 2007) are presented in table 1 for a time scale of 100 years CO<sub>2</sub>-equivalents.

**Table 1. The global warming potential for three common greenhouse gases in the unit kilogram CO<sub>2</sub>-equivalents (Forster et al 2007).**

Greenhouse gas	GWP for a 100 year time horizon
Carbon dioxide	1
Methane	25
Nitrous oxide	298

#### **2.4.1.2 Ozone Depletion Potential (ODP)**

The depletion of ozone (O<sub>3</sub>) in the stratosphere was one of the most actively discussed environmental topics of the late 20<sup>th</sup> century. The chlorine- and bromine containing substances were the main ozone-depleting substances (ODSs) and subsequently responsible for the destruction of the ozone layer (Ravishankara 2009). The Montreal Protocol on Substances That Deplete the Ozone Layer (MP) listed the ODSs that should be phased out and it was successful in regulating the emissions of chlorine- and bromine containing substances (UNEP 2009) and thus limited the depletion of the ozone layer.

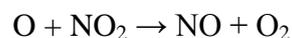
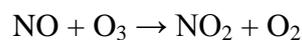
The ODSs ability to deplete the ozone layer is often quantified by the ozone depletion potential (ODP). ODP describes the ratio, in equilibrium state, between the ozone depleted

due to emission of a quantity of chemical being analysed, and the amount ozone depleted by the emission of an equal quantity of chlorofluorocarbon 11 (CFC-11) (Ravishankara 2009).

The ODSs destroy ozone catalytically but the destruction of ozone already occurred before the atmosphere became polluted by ODSs. Nitric oxide (NO) is one natural catalyst which depletes ozone and originates from when nitrous oxide (N<sub>2</sub>O) reaches the stratosphere from the troposphere. NO is produced when nitrous oxide reacts with an excited oxygen atom. The same reaction mostly yields nitrogen gas (N<sub>2</sub>) and oxygen gas (O<sub>2</sub>) but some quantities result in the production of nitrous oxide (Baird and Cann 2008):



The product of the reaction above catalytically destroys ozone via the following reactions:



The nitric oxide molecule extracts an oxygen atom from an ozone molecule and nitrogen oxide (NO<sub>2</sub>) is formed. The overall reaction results in that two diatomic oxygen molecules are formed (Baird and Cann 2008). Nitrous oxide has both natural and anthropogenic sources and it is estimated that less than 40% originates from anthropogenic emissions where agriculture and its use of fertiliser stands for the greater portion of these emissions. Due to its connection with food production the management of controlling the nitrous oxide emissions will be difficult.

Currently nitrous oxide is not incorporated into the impact assessment models for stratospheric ozone depletion although atmospheric modelling shows that the recovery of the ozone layer could be heavily affected by nitrous oxide. The reason to why nitrous oxide is not included as an ODS in the LCIA models is because nitrous oxide is not listed as an ODS in the Montreal Protocol. The exclusion of nitrous oxide will not reflect the impact nitrous oxide has on the ozone layer and the purpose with LCIA will be disturbed. When including nitrous oxide in an LCIA model, one challenge will be to calculate a representable ODP factor for nitrous oxide (Lane and Lant 2011). Since nitrogen oxides interact with chlorine, the ODP of nitrous oxide thus depends on the level of CFCs. The ozone destruction can be reduced when nitrogen oxides react with chlorine containing substances and form ClONO<sub>2</sub>. In contrast other reactions can take place, which counterbalance the reduction e.g. when ClO is converted to Cl by NO. However, Ravishankara et al (2009) concluded that if the chlorine concentration in the stratosphere returned to the pre-industrial concentration the ODP for nitrous oxide would be 50% higher than today. As the chlorine concentration will decrease in the future the ODP for nitrous oxide will increase. Additionally, volcano eruptions introducing sulphate aerosols into the stratosphere can decrease the ODP of nitrous oxide by converting NO<sub>x</sub> into HNO<sub>3</sub> while the destruction of ozone by chlorine becomes more effective. The effects from a volcano eruption are of short duration and sporadic but they result in difficulties when determining the ODP factor. Ravishankara et al (2009) have determined an ODP factor for

nitrous oxide with respect to these different influences and assigned a value of 0.017. However, the largest uncertainty when determining a weighed ODP for nitrous oxide is the uncertainty associated with estimates of future nitrous oxide emissions. The ODP value of 0.017 is a moderate choice and in relation to other ODP factors comparatively low. The CFC-11, for example, has an ODP factor approximately sixty times higher than the nitrous oxide but due to the large anthropogenic emissions of nitrous oxide the effect it has on ozone depletion could still be substantial. In fact, Ravishankara et al (2009) concluded that nitrous oxide emissions of anthropogenic origin is the ODS emission impacting the ozone layer to the greatest extent today, and will remain so this century. According to Ravishankara the global emissions of anthropogenic nitrous oxide are approximately 10 million metric tons per year compared to CFCs which, at their emission peak, were at a million metric tons. In addition, the emissions of nitrous oxide are not predicted to decrease in the future. The future emissions of nitrous oxide heavily depend on agriculture and industrial sources (Ravishankara et al 2009).

#### **2.4.1.3 Photochemical ozone creation potential (POCP)**

During events of photochemical smog tropospheric ozone is formed when the catalyst nitrogen oxides react with volatile organic compounds (VOC) and carbon monoxide (CO) in the presence of UV light. VOC includes all derivatives of hydrocarbons with a boiling point between 50°C and 260°C. VOCs typically originate from evaporation of unburned gasoline but VOC can also be of natural origin. For example, deciduous trees and shrubs emit the VOC isoprene and conifers emit the VOCs pinene and limonene. Some urban areas, situated in the vicinity of a large forest, can therefore still experiences episodes of smog even though the anthropogenic emissions of VOCs are low. However, most episodes of smog are caused by anthropogenic emissions of VOC (Baird and Cann 2008). The magnitude in which different VOCs contribute to the formation of tropospheric ozone varies substantially and to capture this variation the photochemical ozone creation potential (POCP) was developed (Heijungs et al 1992).

The POCP of a given VOC is the ratio of the change in  $[O_3]$  as a result of a change in the concentration of that VOC and the change in  $[O_3]$  caused by an equally relative change in the emission of ethylene ( $C_2H_4$ ). The POCP can also be expressed as the formula:

$$POCP_X = [a_x / b_x] / [a C_2H_4 / b C_2H_4] \quad (\text{eq. 1})$$

$a_x$  is the change in  $[O_3]$  resulted by the emission of VOC X,  $b_x$  is the integrated emission of VOC X to that time. The denominator represents the parameters for the reference substance ethylene (Heijungs et al 1992; Labouze et al 2004).

Meteorological conditions and the background concentrations are only considered based on averages of European conditions when accounting for POCP. In reality nitrogen oxides, VOCs and the meteorological conditions greatly affect the photochemical pathway of the atmospheric system and it is too coarse to assume an average for these parameters. As seen in equation 1 only VOCs are incorporated, whereas nitrogen oxides are excluded even though it greatly contributes to a build-up of ozone. Since the method developed by Heijungs et al

(1992) POCPs have also been developed for nitrogen oxides but it is not clear how these are calculated.

#### 2.4.1.4 Acidification potential (AP)

Since the 1980s the problems concerning acidification and eutrophication have been taken seriously by the EU and several international actions have been taken in order to decrease the emissions causing acidification. The areas affected by acidification have, as a result of the actions, decreased in Europe since the 1980s (Sutton et al 2011).

The number of hydrogen ions ( $H^+$ ) that a potential substance can form is of interest in the context of acidification potential. One mole of sulphur dioxide ( $SO_2$ ) emissions will be able to produce two moles of hydrogen ions. Similarly one mole of nitrogen oxides will produce one mole of hydrogen ions (Heijungs et al 1992).

The acidification potential for a substance  $x$  is calculated by the number of moles of hydrogen ions  $H^+$  that can be produced per substance, as explained above, and is denoted by  $\nu$  in equation 2. To convert the emissions from moles into kilogram,  $\nu$  has to be divided by the molar mass  $M(kg \cdot mol^{-1})$  of the substance.

$$\eta_x = \nu_x / M_x \quad (\text{eq. 2})$$

Where  $\eta_x(mol \cdot kg^{-1})$  is the number of hydrogen ions in moles that a substance can potentially produce per kilogram substance  $x$ . The acidification potential of a substance  $x$  is then calculated by dividing  $\eta_x$  by  $\eta_{ref}$ , where the reference substance is sulphur dioxide.

$$AP_x = \eta_x / \eta_{SO_2} \quad (\text{eq. 3})$$

In table 2 the compounds of relevance in this study and their respective acidification potential can be seen. The molar mass of  $NO_x$  is calculated based on assigning a value of two for  $x$  (Heijungs et al 1992).

**Table 2. The acidification potential for three common substances in the unit kilogram  $SO_2$ -equivalents (Heijungs 1992).**

Compound	$\nu$	$M(kg \cdot mol^{-1})$	$\eta(mol \cdot kg^{-1})$	AP
$SO_2$	2	64	2/64	1
NO	1	30	1/30	1.07
$NO_2$	1	46	1/46	0.7
$NO_x$	1	46	1/46	0.7
$NH_3$	1	17	1/17	1.88

#### 2.4.1.5 Eutrophication potential (EP)

The leakage of substances causing eutrophication and hypoxia occur along the life cycle of tomatoes when nitrate, ammonia, nitrogen oxides and nitrous oxide are emitted (Xue & Landis 2010), which is virtually all the nitrogen containing species associated with the production of tomatoes.

The eutrophication potential (EP) is based on the compound  $C_{106}H_{263}O_{110}N_{16}P$  that represents the average composition of algae contributing to biomass formation during events of eutrophication. Only nitrogen and phosphorus containing substances are considered to contribute to eutrophication potential according to the LCIA method, due to the assumption that those two nutrients limit the biomass production, and that the other compounds needed in algae formation are non-limiting (Heijungs 1992).

The effect that eutrophication gives rise to differs depending on if the eutrophication takes place in the surface water of a water body or in the soil. The excess in nutrients will in both cases result in an alteration in the biodiversity in the respective ecosystem (Heijungs 1992). In water bodies this will be observed by an increase in the algae production. When the consumption of oxygen by algae is larger than the production which at times occur when the algae die or during nights the oxygen level decreases. A decrease in oxygen can also be of a more serious nature and result in hypoxia if it occurs on a more permanent level. This occurs when oxygen is consumed in the process of biological degradation of organic matter (C). The consumption of oxygen is often expressed as the biological oxygen demand (BOD) or chemical oxygen demand (COD) and the unit is in kilogram  $O_2$ . The eutrophication potential has been developed on the assumption that nitrogen, phosphorous and carbon (measured as  $O_2$ ) can be grouped by quantifying their potential contribution to biomass formation, which can be based on the ratio of N and P in biomass and the oxygen needed to degrade the biomass (Heijungs 1992).

In order to calculate the eutrophication potential for each nutrient, it is first necessary to determine the extent to which nutrient X contributes to the biomass formation if the other nutrients exist in abundance. Looking back at the algae compound it becomes clear that in order to produce one algae one phosphorous atom and 16 nitrogen atoms are needed. Hence the ratio of phosphor atoms to nitrogen atoms is 1/16 which is denoted as  $\nu$ . The oxygen needed to degrade the biomass is measured as the chemical oxygen demand (COD). 138 moles of oxygen is needed for one mole of biomass and is also denoted as  $\nu$ . The next steps follow the same procedure as for calculation of the acidification potential,  $\nu$  is divided by the molar mass (M) of the substance in question (Heijungs 1992).

$$\eta_x = \nu_x / M_x \quad (\text{eq. 4})$$

The eutrophication potential can then be calculated by dividing  $\eta_x$  by  $\eta_{\text{ref}}$ , where phosphate ( $PO_4^{-3}$ ) is the reference substance.

**Table 3. The eutrophication potential for common substances including the COD in the unit kilogram PO<sub>4</sub><sup>-3</sup>-equivalents (Heijungs et al 1992).**

Compound	v	M(kg×mol <sup>-1</sup> )	η(mol×kg <sup>-1</sup> )	EP
N	1/16	14	1/224	0.42
NO <sub>2</sub>	1/16	46	1/736	0.13
NO <sub>3</sub> <sup>-</sup>	1/16	62	1/736	0.10
NH <sub>4</sub> <sup>+</sup>	1/16	18	1/288	0.33
P	1	31	1/31	3.06
PO <sub>4</sub> <sup>-3</sup>	1	95	1/95	1.00
COD	1/138	32	1/4416	0.022

The classification of eutrophication potential has the advantage that it includes both the nitrogen and phosphorous contribution to the biomass formation and can be applied for both water and soil systems (Heijungs 1992).

#### **2.4.2 Double counting**

The release of a certain emission can sometimes contribute to more than one impact category. In this study the emission of nitrogen oxides can first participate as a catalyst in the photochemical ozone formation and then cause the release of a hydrogen ion (H<sup>+</sup>) when it is deposited, which results in acidification. Lastly, the nitrogen atom can contribute to eutrophication. The release of nitrogen oxides is therefore assigned to three impact categories. In this instance there is no conflict in assigning nitrogen oxides to three different impact categories since one molecule of nitrogen oxides can actually participate in several reactions (Baumann and Tillman 2009). However, emissions with parallel impacts, such as emissions that may theoretically participate in more than one impact category but in reality only participate in one impact category, will result in double counting. For example, sulphur dioxide (SO<sub>2</sub>), which will have either toxic or acidifying impact (Guinée 2002). The impact categories therefore describe the *potential* impacts and do not necessarily reflect the actual effects. Another example that highlights the complexity of describing environmental problems is seen in the case of acidification. The number of hydrogen ions released by acidifying pollutants gives an indication of the *potential* impact of the pollutants but does not tell us anything of the actual impact because no consideration is taken to where the pollutants are deposited. If the acidifying pollutants are deposited on soil rich in limestone the acidifying ions are buffered and the acidifying impact is limited. Due to these problems related to the assignation of pollutants to the different impact categories the potential impact is described instead of the actual impact in order to avoid double counting (Baumann and Tillman 2009).

## **3 Method**

### **3.1 General method**

In order to compare the nitrogen footprint method with the LCIA method a case study of one kilogram of Swedish tomatoes grown in a greenhouse heated by waste heat in southern Sweden was used. The same system model (see figure 2) and data (see appendix) were used for both methods to avoid differences in the outcome, which could be explained by the differences in the procedures.

A previous MSc thesis study performed by Jonatan Högberg (2010) formed the basis of the LCA method used in this study, but with modifications to better fit the processes important to a nitrogen perspective.

It was also necessary to further develop the system model by Högberg in order for the model to include the stages that are of importance in the tomatoes' life cycle from a nitrogen perspective.

A literature study was also conducted in order to gain knowledge about the methods analysed and to understand the nitrogen cycle and chemistry.

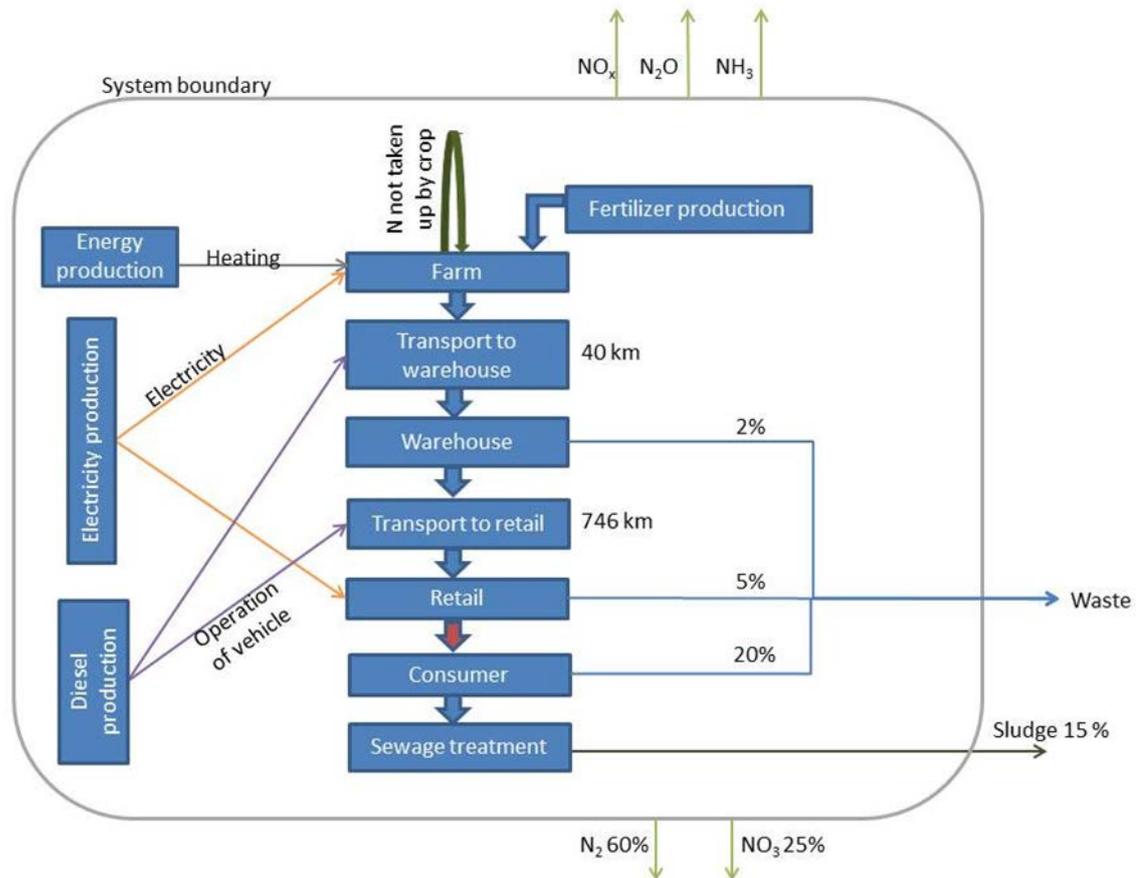
### **3.2 Case study of tomatoes**

#### **3.2.1 Structure of the system model**

##### ***3.2.1.1 System boundary and flow chart***

The design of the model only includes the most common and important inputs in the life cycle of tomatoes with the goal of keeping the model simple, which, in turn, would make the collection of data easier. The system boundary is defined according to a cradle to grave principle and includes all processes of importance in the system starting from the production of fertiliser (cradle) used for growing the tomatoes, to the sewage treatment (grave), see figure 2. The functional unit is set to one kilogram of tomatoes and the red arrow marks the reference flow.

**Figure 2.** The system model describing the different steps in the life cycle of Swedish tomatoes with its different inputs and outputs. The red arrow between the retail step and the consumer step marks the position of the functional unit.



### 3.2.1.2 Fertiliser production

During the production of fertilisers nitrous oxide, nitrogen oxides and ammonia is released to the environment. The fertilisers used in Sweden are often imported and the obtained data incorporated in the software for the fertiliser represents an average for the fertiliser used in Europe, which is a mixture of urea and ammonium nitrate.

### 3.2.1.3 Farm

The fertiliser used consists of 4.2 g of elementary nitrogen (Högberg 2010), which is applied to hydroponic system consisting of mineral-wool. Because the tomatoes are grown in mineral-wool no significant emissions of nitrous oxide are formed. Recirculation systems are becoming a more common practice on tomato farms, which prevent the waste water with its excess of nitrogen from reaching the sewage treatment plant and reduces the amount of water and nitrogen used (Hansson and Johansson 2007). The amount of nitrogen fertiliser used in the model is therefore most likely higher than what it is when recirculation is practiced. Since no data is available for the amount of fertiliser used when recirculation is practiced the data from Högberg (2010) is used.

The emissions connected to the production of the greenhouse have been neglected in this study, due to difficulties with finding reliable data. The greenhouse is heated with waste heat which is considered environmentally “free”. Waste heat is heat from a nearby industry produced as a by-product of the process and has no value for the industry. Accounting for the

energy used to produce the waste heat, by comparing the share of pollution from the process of the industry and the greenhouse, is one way of calculating for the pollutions that the industry gives rise to. However, to avoid double counting and for the simplicity's sake the waste heat was considered environmentally "free", and it is assumed that no emissions occur except for when the industry is shut down for maintenance one week every 18 months. The greenhouse is heated with oil during that week. An additional input is the electricity that the farm is powered with (see appendix for details).

#### **3.2.1.4 Transports**

The tomatoes were transported with a Euro 3 class truck with a 90% load factor powered by diesel. The transport value includes the production of diesel and the emissions of nitrogen oxides that are related to its use.

#### **3.2.1.5 Warehouse**

Approximately 2% of the tomatoes are wasted in the warehouse. The model does not include any waste treatment which results in that the waste is not calculated for and the environmental impact it would give rise to is not included in the impact categories. This post is therefore excluded in the results section.

#### **3.2.1.6 Retail**

At the retailer 5% of the tomatoes go to waste. The emissions comprises of nitrogen oxides and originates from the electricity use and production of consumer packaging which is the small plastic bag used to collect the tomatoes by the consumer in Sweden.

The transport from the retailer to the consumer can be carried out with different means of transportation and as a simplification it is therefore assumed that no emissions occur from this step.

#### **3.2.1.7 Consumer**

The Swedish National Food Administration estimated that consumers dispose of approximately 20% (Livsmedelsverket 2012) of purchased share of tomatoes as household waste. However, this figure is connected to a number of uncertainties (Pernler and Hansson 2009) and susceptible to variation on an individual basis depending on the personal waste habits. The remaining 80% of the tomatoes are consumed and subsequently excreted from the body as ammonia. The functional unit of one kilogram tomatoes (containing 4.2 grams of nitrogen) is set before the consumer stage, which means that in order to produce one kilogram of tomatoes purchased by the individual more than one kilogram of tomatoes has to be produced since some waste occur along the life cycle.

#### **3.2.1.8 Sewage treatment**

Once excretion of nitrogen, in the form of ammonia, has reached the sewage treatment plant approximately 60% of it is denitrified into harmless nitrogen gas (N<sub>2</sub>). The denitrification potential for different sewage treatment plants varies substantially and 60% represents the potential for the Stockholm region and is considered to be a rather high factor compared to other sewage treatment plants in other parts of Sweden. Of the remaining that is not denitrified, 15% of the nitrogen will eventually leave the sewage treatment plant as sludge and

the remaining 25% as nitrate (Svenskt Vatten 2007). The model does not include any treatment of sludge and thus the environmental impact it would give rise to is not incorporated in the LCIA.

### **3.2.2 Simplifications and excluded parts in the system model**

When constructing the life system model (figure 2) for one kilogram of Swedish tomatoes several simplifications and assumptions had to be made in order to run the model. This has meant that some processes are excluded in the model. Excluded areas of importance are the production of the greenhouse and the treatment of sludge, mineral-wool and waste. These exclusions are done because of difficulties with finding adequate data.

The nitrogen fertiliser used in the modelling is a mixture of urea and ammonium nitrate. This choice was made due to time limitations and to facilitate the modelling. The type of fertiliser used in the model does not affect the comparison of the methods as such.

Nitrogen as the output of “organically bounded” has been excluded from the results but it was less than one per cent of the result for EP, which is the only category where it was present. This exclusion was made to facilitate calculations.

It was assumed that no nitrous oxide emissions occur from the hydroponic soil because no microbiological processes occur in the mineral-wool. However, it may be possible that the biomass residual from the tomato plant release quantities of nitrous oxide but due to the uncertainties this has not been accounted for in the models because the emissions were regarded to be insignificantly low, based on Högberg’s (2010) study.

The LCIA methods do not always distinguish between ammonia and ammonium, furthermore when the two substances are distinguished ammonium represents an amount that is insignificant. Hence, ammonia and ammonium are merged together in the results. The same simplification is made for nitrate which also represents nitrite since nitrite comprises an insignificant amount in this study’s result.

During the denitrification process in the sewage treatment plant and the treatment of sludge, some amounts of nitrous oxide is released. The quantities of the nitrous oxide emissions released are debated in the literature and relatively unknown. The emissions of nitrous oxide are related to a number of processes in the sewage treatment plant and depend on several parameters, which results in that the size of the emission can vary greatly (Kampschruer et al 2009). Of the incoming nitrogen to the sewage treatment plant, between 0.01% (Candran 2010) to 3% (Foley et al 2008) will result in nitrous oxide emissions, irrespective of the denitrification potential. The nitrous oxide produced during the sewage treatment process is neglected due to the uncertainties associated with these emissions. For studies focusing on the nitrous oxide emissions this process should be investigated further.

The Swedish National Food Administration (Livsmedelsverket 2012) estimates that 10 to 20% of the food is wasted in the Swedish households unnecessarily since the food could have been eaten if treated differently. Due to that tomatoes have a short durability span the figure of 20 % was chosen to represent tomato waste.

### 3.2.3 Calculations made for the life cycle impact assessment

The calculations were made using the LCA modelling software GaBi 4.4 from PE International and the LCIA model CML 2001. The result from the relevant impact categories were extracted from GaBi 4.4 and processed in Excel. The input of data used can be found in the appendix.

### 3.2.4 Calculations of the nitrogen footprint

The nitrogen footprint was calculated based on results from LCA modelling software but were recalculated into elementary nitrogen using Excel.

Nitrogen containing substances are also produced during the manufacturing of fertilisers and are emitted as nitrogen oxides, nitrous oxide and ammonia. The nitrogen content for different emissions is calculated by dividing the molar mass of the nitrogen for a specific substance with the total molar mass of the substance. The quotient is then multiplied with the known mass (m) of the substance. E.g. the molar mass for nitrogen in a nitrous oxide (N<sub>2</sub>O) molecule is 28 g/mole (2×14 g/mole) and the total molar mass for nitrous oxide is 44 g/mole (28+16 g/mole), which also can be expressed as:

$$\text{N content} = M(\text{N}_2) / M(\text{N}_2\text{O}) \times m(\text{N}_2\text{O}) \quad (\text{eq. 5})$$

The nitrogen content in a nitrous oxide molecule is thus 64%. Similarly this is done when calculating the nitrogen content for other substances.

The nitrogen content in one kilogram tomatoes is extracted by using a conversion factor of 16% (Leach et al 2012) for the protein content found in one kilogram tomatoes. The protein content is 9 gram per kilogram of tomatoes based on the National Food Administration of Sweden's database (Livsmedelsverket 2012).

## 4 Results

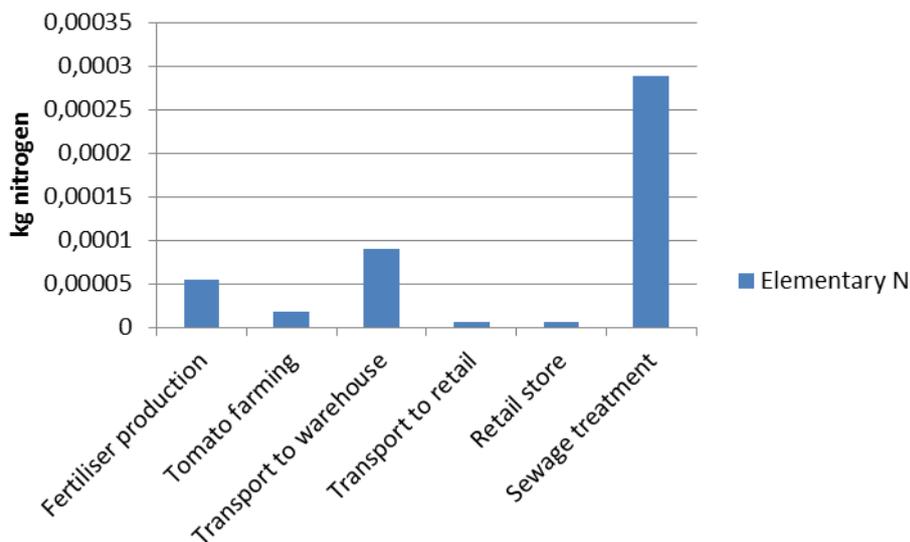
When interpreting the results of the two methods it is important to remember that the results only reflect the impacts from a nitrogen and environmental perspective and that other impacts caused by other substances are neglected. The result of the nitrogen footprint is presented as the total amount of elementary nitrogen in the unit kilogram nitrogen per kilogram tomatoes. The results of the LCIA have been divided into different categories depending on the environmental impact, namely the global warming potential (GWP), the eutrophication potential (EP), the acidification potential (AP) and the photochemical ozone creation potential (POCP), in order to facilitate the comparison of the results of the two methods. The results are further divided into the different stages of the tomato's life cycle, from the production of fertiliser used in the production of tomatoes to the sewage treatment at the end of the cycle (see figure 2).

### 4.1 Nitrogen footprint

#### 4.1.1 Results per activity

The nitrogen footprint result is presented in figure 3 with the unit kilogram nitrogen per kilogram tomato. The process resulting in the highest amount of elementary nitrogen is the sewage treatment and consists solely of nitrate. The second greatest contributor to the nitrogen footprint is transportation, followed by the production of fertiliser, where ammonia, nitrogen oxides and nitrous oxide are the main contributing nitrogen containing substances. The four remaining categories comprise nitrogen oxides emissions.

**Figure 3. The allocation of nitrogen for the different processes in the unit kilogram elementary nitrogen per kilogram purchased tomatoes. The treatment of sewage is the process which results in the highest amount of elementary nitrogen.**



The nitrate released from the sewage treatment plant originates from the initial input of nitrogen fertiliser. The calculated amount of elementary nitrogen, released as nitrate, amounts to 0.29 g per kilogram tomato produced at the consumer level. When the additional emissions connected to the production of one kilogram of tomatoes are added, in order to obtain the outcome of the nitrogen footprint, the result is 0.46 g. The various emissions of reactive

nitrogen, which do not originate from the nitrogen fertiliser input, recalculated into elementary nitrogen amounts to 0.17 g. The fertiliser production represents the nitrogen containing species emitted during the production of fertilisers, and does not represent the fertiliser used in the cultivation.

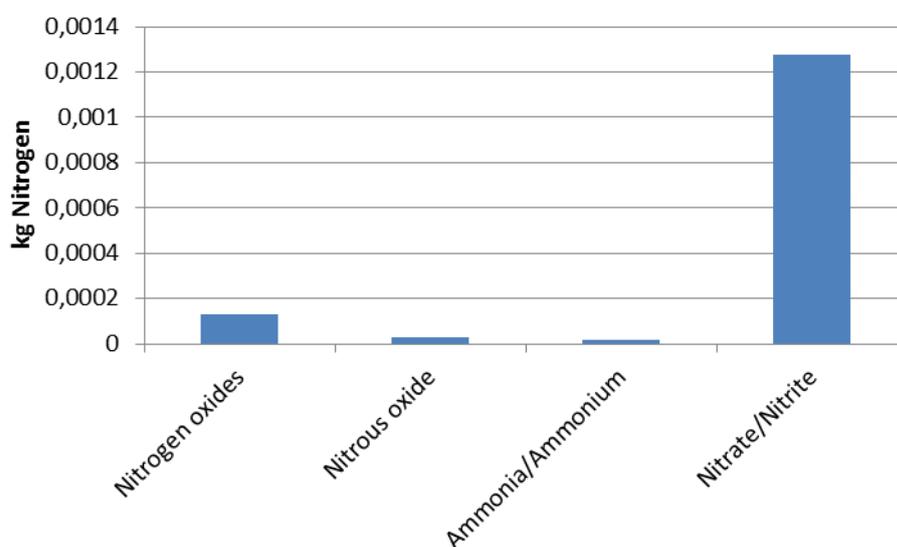
**Table 4. The nitrogen species emitted during the life cycle of Swedish tomatoes recalculated into elementary nitrogen and the nitrate from the sewage treatment recalculated into elementary nitrogen together makes up the nitrogen footprint.**

	Elementary nitrogen
Emissions not originating from the fertiliser input	0.17 g
Emissions of nitrate	0.29 g
<b>Nitrogen Footprint</b>	<b>0.46 g</b>

#### 4.1.2 Species distribution

The distribution of the nitrogen species associated with the production of one kilogram of tomatoes confirms that the mass of elementary nitrogen heavily comprises of nitrate and nitrite that exits the sewage treatment plant. These emissions of nitrate and nitrite originates from the fertiliser input which was taken up by the tomatoes and later consumed. Nitrogen oxides comprises of the second largest volume and nitrous oxide of the third largest. The lowest emissions are of ammonia.

**Figure 4. The distribution of nitrogen species during the life cycle of Swedish tomatoes recalculated into kilogram elementary nitrogen. The sewage treatment process causes the high release of nitrate during the life cycle.**

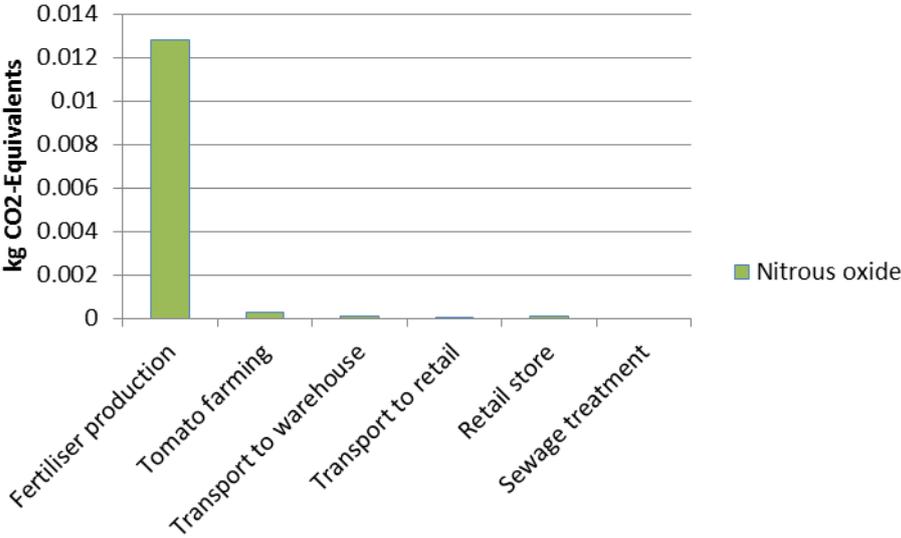


## 4.2 Life Cycle Impact Assessment

### 4.2.1 Global warming potential

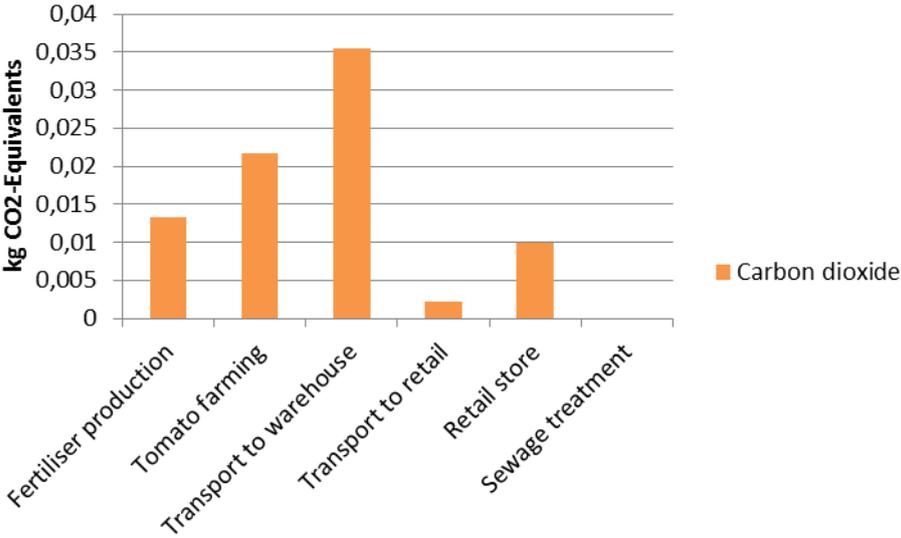
Fertiliser production result in the largest part of the GWP in the life cycle of tomato production from a nitrogen perspective, see figure 5. Nitrous oxide is the only nitrogen containing greenhouse gas associated with the production of tomatoes and is thus the greenhouse gas producing the effect of the GWP.

**Figure 5. The results from the global warming potential. The fertiliser production results in high emissions of nitrous oxide and is therefore the process which yields the highest result.**



The GWP of the life cycle of the tomatoes when the carbon dioxide is considered gives a different perspective on results, compared to when only nitrous oxide is considered (see figure 6). The GWP of the carbon dioxide is included in the results to compare the distribution and size of carbon dioxide with nitrous oxide. The largest emissions of carbon dioxide are seen for transportation and the second largest emissions for cultivation of the tomatoes. The GWP of fertiliser production process is larger from a nitrous oxide perspective. However, the GWP from a carbon dioxide perspective is six times larger than the GWP from a nitrous oxide perspective.

**Figure 6. The allocation of carbon dioxide emissions during the life cycle of Swedish tomatoes. The transportation comprises of the largest carbon dioxide emissions followed by the tomato farming and fertilizer production.**

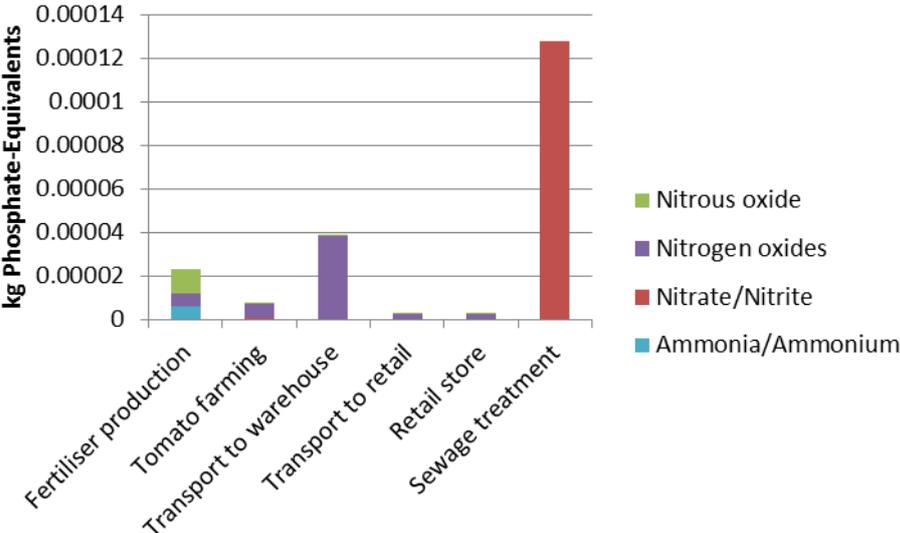


**4.2.2 Eutrophication potential**

The last process of the life cycle, sewage treatment, has the largest impact on the eutrophication potential, see figure 7. Due to that the sewage treatment in this study denitrifies

60% of the nitrogen reaching this stage and 15% of the nitrogen is lost in the sludge the remaining 25% results in nitrate reaching the environment. The second largest figure is for nitrogen oxides emissions associated with the first transport route, which yields higher emissions than the second transport route, since it travels a greater distance. The production of fertiliser is contributing third most to the eutrophication potential and the nitrous oxide emissions are responsible for approximately half of the share of that post while ammonia and nitrogen oxides contributes to the remainder of the share. Nitrogen oxides are contributing to most of the eutrophication potential during the tomato farming, transports and at the retail store but nitrous oxide are also contributing. The sewage treatment in Stockholm is considered to be relatively efficient compared to other parts of the country and denitrifies large proportions of the nitrogen substances reaching that post but if the sewage treatment would be less efficient it would result in that more nitrate reached the environment.

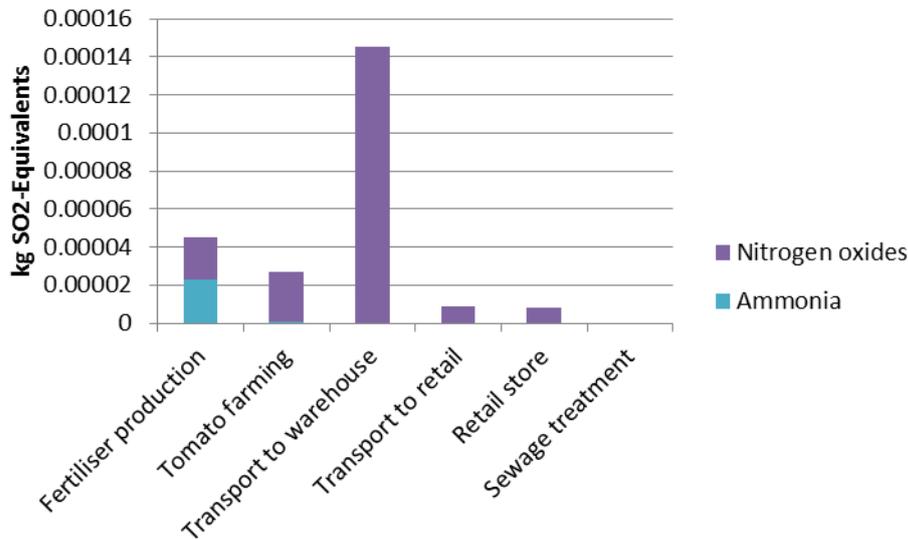
**Figure 7. The results from the eutrophication potential shows the distribution and allocation of the various nitrogen species emitted during the life cycle of Swedish tomatoes. The process yielding most nitrogen is the sewage treatment which emits high amounts of nitrate.**



**4.2.3 Acidification Potential**

Ammonia and nitrogen oxides are the nitrogen containing substances that contribute to the acidification potential. Transportation is contributing substantially to the acidification, while fertiliser production emits both ammonia and nitrogen oxides. The following categories that give rise to acidification do so in the form of nitrogen oxides emissions. Since waste heat, counted as environmental free, is used to heat the greenhouses in the case study the impact at farm level is not as large as it would have been if other non-environmentally free heating options would have been used.

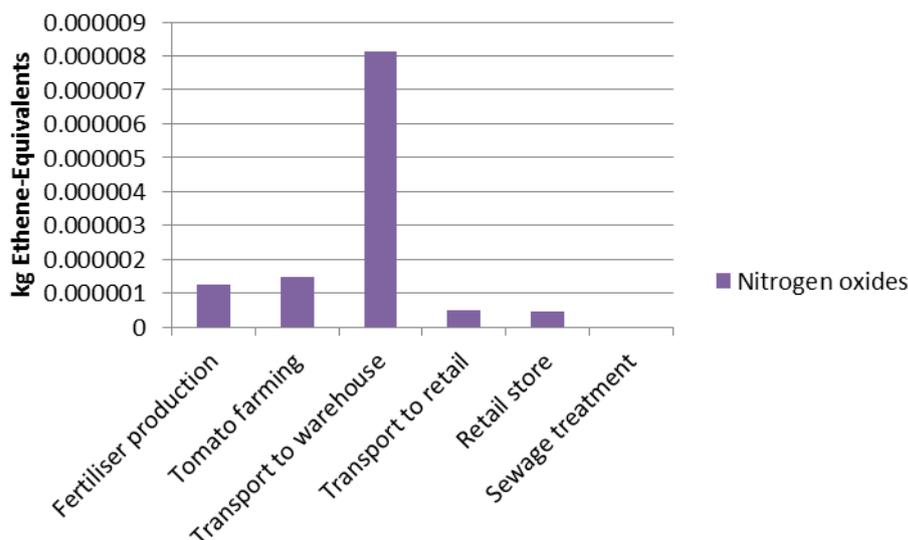
**Figure 8.** The result from the acidification potential shows that the eutrophication in this study is mainly caused by nitrogen oxides where transportation contributes the most. The process contributing second most is the fertilizer production caused by both ammonia and nitrogen oxides.



#### 4.2.4 Photochemical Ozone Creation Potential (POCP)

Nitrogen oxides are the only nitrogen containing substances that impact the photochemical ozone creation potential (POCP) and are therefore responsible for the tropospheric ozone formation for all the categories that produce a reading on the graph. The category that impacts the tropospheric ozone formation the most is by far transportation. However, tomato farming and fertiliser production are also important sources of nitrogen oxides, originating from the energy use, that contributes to the tropospheric ozone formation.

**Figure 9.** The result of the photochemical ozone creation potential shows that the transportations emit most nitrogen oxides and are consequently responsible for the largest proportion of the ground-level ozone formation.



#### 4.2.5. Ozone Depletion Potential (ODP)

As was explained in section 2.4.1.2, nitrous oxide is the only nitrogen species that can have an impact on the stratospheric ozone layer. The LCIA models for the ODP do currently not

include the nitrous oxide as an ODS and therefore they do not reflect the impact that nitrous oxide has on the stratospheric ozone. This is misleading, especially from a nitrogen perspective because the other ozone depleting substances listed in the Montreal Protocol do not contain any nitrogen. Thereby, there is no indication of impact on ozone depletion in the case study, despite the actual ozone-depleting nature of nitrous oxide.

## **5 Discussion**

The nitrogen footprint and the LCIA conducted in this study focus on emphasising the nitrogen perspective of the life cycle of tomatoes. Consequently, other emissions contributing to the impacts are completely neglected, this is important to remember when interpreting the results of this study.

### **5.1 Life cycle impact assessment contra nitrogen footprint**

The results of the nitrogen footprint and the eutrophication impact category are strikingly similar (see fig 3 and 7). The similarities are due to the nitrogen footprint representing all nitrogen containing species involved in the production of tomatoes; and the eutrophication impact category is also driven by all nitrogen containing species. The features of the figures are therefore visually identical but with different units. The nitrogen footprint is in that respect biased toward the eutrophication category.

The impact categories for acidification and photochemical ozone formation also have similar features with the exception of the fertiliser production stage. In this study the POCP is solely governed by the nitrogen oxides concentrations while the AP depends on the concentrations for nitrogen oxides and ammonia. However, ammonia is mainly present in the fertiliser production stage, which explains why that stage has a different feature. This study only considers tomatoes grown in southern part of Sweden and transported to Stockholm but if the tomatoes were transported longer or shorter distances within the country the nitrogen oxides would vary accordingly. Furthermore, if the tomatoes were transported from another country the nitrogen oxides emissions would be higher.

From the result of the GWP it becomes evident that the nitrous oxide associated with fertiliser production has the largest climate impact of the different stages in the life cycle. It would therefore not be incorrect to state that the fertiliser production has the largest impact on the stratospheric ozone depletion potential.

The nitrogen footprint gives the impression that emissions from the last process, sewage treatment, will yield the largest effect on the environment but in practice it is only partially true because it only gives a large effect on the eutrophication but no effect on the other impact categories.

For the nitrogen footprint nitrous oxide has a greater significance during the calculations than the other substances because nitrous oxide has two nitrogen atoms and the other substances only have one nitrogen atom. The nitrous oxide is therefore double weighed compared to the other substances. Thus the nitrous oxide is favoured compared to other species when calculating the nitrogen footprint.

### **5.2 Advantageous and disadvantageous of the two methods**

The advantage of an LCIA compared to any footprint method is that the LCIA has more developed standards and guidelines authored than the footprint approach, which in comparison is a very simple method. When evaluating a footprint approach the underlying method and procedure may vary for different footprints because no standards are developed yet or the authored standards are not sufficiently developed. While interpreting different

LCIA's methods and procedures are more consistent. Variations may still occur but they are limited and found within a defined framework. However, the LCIA procedure is also the downside of the LCIA methodology because it takes a lot of time to gain an understanding on how an LCIA should and can be conducted. The danger with the nitrogen footprint and its lack of standards and guidelines is that the performer may easily exclude processes in the life cycle that are of importance. For example, excluding the fertiliser production in the nitrogen footprint would further diminish the importance of nitrous oxide in this study.

Despite the fact that the nitrogen footprint method is a simpler approach, which does not demand the same level of detail, it can still be a very time consuming procedure to conduct a nitrogen footprint investigation due to the considerable difficulties with finding and collecting sufficient data. The difficulty of collecting data is a problem for both methods.

Yet, approaching the climate and environmental problems from a nitrogen perspective is of interest and importance. The alteration of the nitrogen cycle causes environmental problems that are very complex and affects the atmospheric chemistry as well as the marine and terrestrial ecosystems. The concept of the nitrogen footprint has been overshadowed by its counterpart, the carbon footprint, which has received substantially more attention. The carbon footprint reflects and emphasises on communicating the climatic problems contributed by carbon emissions, which is of great importance but there is a danger when a single footprint receives attentions at the expense of others. It is not necessarily so that the footprints always are consistent with each other, which has already been proven to be the case for the nitrogen and carbon footprint with respects to different food types. It is therefore necessary to consider the aspects of more than one footprint in order to capture the full spectra of impacts. The nitrogen footprint concept is a tool that can be used to communicate the nitrogen impacts to policymakers and the public and help bring the nitrogen perspective further into the climate and environment debate.

### **5.3 System model**

In this study two factors are prone to change significantly, which would be accompanied by a change in the results. Those are the factors which govern the denitrification capacity of the sewage treatment plant and the factor that is set for the consumer's waste habits. If the treatment of waste and sludge would be included in the model it would further affect and improve the results. There are also uncertainties regarding the nitrous oxide emissions, see section 5.6.

### **5.4 Environmental impact categories**

The extent of the environmental impact of the different stages in the LCIA varies depending on the impact category. The environmental impacts of the nitrogen containing species from a GWP perspective are greatly connected to the fertiliser production. However, in comparison, the fertiliser production is associated with the eutrophication potential to a lesser extent. The opposite also applies, because the sewage treatment process gives a high value for the eutrophication potential but no value for the GWP. The LCIA results have to be analysed together and not in isolation in order to capture the impacts of the whole environmental spectrum. Even though the impact categories for the LCIA have different units and cannot be

compared with each other based on its respective value the allocation of the impact potentials can be useful to analyse in order to investigate where in the life cycle possible improvements can be made. Transportation constitutes a substantial process in the LCIA and in the nitrogen footprint. The same conclusion can be drawn from the fertiliser production and the sewage treatment.

#### **5.4.1 Photochemical Ozone Creation Potential**

The POCP is based on average values of VOC, nitrogen oxides and meteorological conditions representative for Europe, which are important parameters that in reality varies greatly and have a vast effect on the outcome of the results. The calculated values of POCP should therefore be taken with precautions because in practice it is very difficult to estimate a reliable POCP due to the complex chemistry in the atmosphere. Furthermore, it is not clearly explained how the POCPs for the nitrogen oxides is calculated in the CML 2001 model.

#### **5.4.2 Ozone Depletion Potential**

An unexpected finding was that nitrous oxide is excluded from the stratospheric impact category in the LCIA. The aim of the LCIA is to connect the emissions with its corresponding impacts and in this instance when evaluating the stratospheric ozone from a nitrogen perspective it fails to do that. If nitrous oxide will be recognized as an ODS in the future, similar sets of problems as the POCP experienced, will be faced due to the complex atmospheric chemistry. The LCIA does not take into consideration the fact that this impact category is neglected and it is therefore up to the user to be cautious when interpreting the results of an LCA for a specific product.

#### **5.4.3 Warming Potential**

The GWP also depends heavily on the background concentrations which are projected to change and subsequently the assigned value of GWP for respective greenhouse gas will have to be updated in the future. The nitrous oxide is a very strong greenhouse gas and therefore has a high GWP value. The nitrogen aspect in the climate debates should therefore not be forgotten, especially since emissions of nitrous oxide are projected to continue increasing (Ravishankara et al 2009). Because the emissions of nitrous oxide are closely linked to the food production it will be a challenge to decrease the emission while keeping the food supply secured. The importance of nitrous oxide should therefore be stressed.

### **5.5 Nitrous oxide**

Weighing is not implemented in this study although the impact categories affect the environment to a varying extent. The nitrous oxide molecule, for example, is a greenhouse gas that is 298 times stronger than a carbon dioxide molecule, which means that even small emissions can be of concern and have an impact on the climate. Furthermore, nitrous oxide is a long-lived gas and affects the climate for a longer period of time as well as on a global scale. Conversely, nitrogen oxides are very short-lived pollutants and impact the environment on a regional scale. In the case of eutrophication the affected ecosystems globally covers an area in the same size range as New Zealand. However, this means that the rest of the ecosystems are nitrogen-limited. Nitrous oxide thus has a spatially and temporally greater impact than the nitrogen-oxides-caused impacts. Because weighting is not implemented in

this study it is important to stress the impacts of nitrous oxide since the LCIA only partially reflects the effect of nitrous oxide while the nitrogen footprint does not at all. The way this study is conducted brought attention to the fact that the impact category of stratospheric ozone depletion is not incorporated in the LCIA method from a nitrogen perspective. Because nitrous oxide is not accounted for as an ODS, it again has to be emphasised that the role of nitrous oxide should not be neglected.

There are also uncertainties regarding the quantities of nitrous oxide emitted during the sewage treatment and treatment of sludge. These uncertainties may result in that the importance of nitrous oxide is not fully reflected. In addition, since nitrous oxide is a strong greenhouse gas even a small emission of nitrous oxide released from the sewage treatment plant can be of significance. It is however certain that the release of nitrous oxide from sewage treatment plants should be monitored and techniques that promote a reduction in nitrous oxide emissions should be implemented in the sewage treatment plants.

The GWP of carbon dioxide is larger than the GWP of nitrous oxide. Nevertheless, nitrous oxide still contributes substantially to the GWP in this study and should not be forgotten in the climate debate.

## 6 Conclusion

The nitrogen footprint and LCIA method give different results because the nitrogen footprint method does not specify the nitrogen species emitted but the LCIA method does. In addition the LCIA method connects the nitrogen species with its corresponding impact. The LCIA is thus more successful with reflecting the environmental impacts from a nitrogen perspective compared to the nitrogen footprint. Due to that the nitrogen footprint is a new method it has not yet been developed to reach the same level of standard and comprehensiveness as the LCIA method. Other conclusions that can be drawn from this study are:

- The nitrogen footprint did not give a justifying result that reflects the environmental spectrum of impacts caused by the nitrogen species, because the sewage treatment yielded high amounts of nitrates and nitrate only causes an effect on the eutrophication. The applicability is thus limited.
- The nitrogen footprint method has to be developed further before it can be used for public awareness.
- Nitrous oxide should be incorporated in the LCIA method as an ODS.
- The LCIA method does not give a justifying result of the extent that nitrous oxide impacts the climate unless weighting is implemented.
- The method used in the LCIA model for calculating the photochemical ozone creation potential does not give results that are reliable due to extreme coarse assumptions of chemistry.

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## Appendix

**A1. The transport distances from where the tomatoes are grown in southern Sweden to where they are sold in Stockholm (Högberg 2010).**

Transport route	Swedish 40 ton truck 90 % load factor
Farm to warehouse	746 km
Warehouse to retail store	40 km

**A2. The factors used during the calculations of LCIA and nitrogen footprint (Högberg 2010 (1), Svenskt Vatten 2007 (2), National Food Administration 2011 (3))**

	Factor
Waste from warehouse <sup>1</sup>	2 %
Waste from retail <sup>1</sup>	5 %
Waste in household <sup>3</sup>	20 %
Sewage treatment denitrification potential <sup>2</sup>	60 %
Sludge <sup>2</sup>	15 %

**A3. The nitrogen fertiliser consists of a mixture of urea and ammonium nitrate. The nitrogen content found in one kilogram of tomatoes purchased at the retailer.**

Nitrogen fertiliser	4.2 g
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Other inputs used in the system model are (Högberg 2010):

- Diesel truck Euro 3<sup>rd</sup> class
- Swedish electricity mixture 0.54 MJ
- Polyethylene 1.54 g

A4. The table shows the obtained results from the LCIA and the nitrogen footprint methods for the respective process included in the system model.

		Fertiliser production	Tomato farming	Transport to warehouse	Transport to retail	Retail store	Sewage treatment
Nitrogen Footprint (kg elementaryN)	Elementary N	5,46E-05	1,73E-05	8,93E-05	5,58E-06	5,81E-06	2,88E-04
GWP ( kg CO2-Equivalent)	Nitrous oxide	1,28E-02	2,69E-04	8,66E-05	5,73E-06	7,62E-05	0
	Carbon dioxide	1,33E-02	2,17E-02	3,55E-02	2,20E-03	9,85E-03	0
EP (kg PO4-Equivalents)	Ammonia/Ammonium	5,82E-06	3,08E-07	2,89E-07	1,82E-08	3,05E-07	0
	Nitrate/Nitrite	6,89E-09	6,20E-08	1,33E-09	8,28E-11	1,38E-08	1,28E-04
	Nitrogen oxides	5,72E-06	6,77E-06	3,78E-05	2,36E-06	2,09E-06	0
	Nitrous oxide	1,16E-05	2,44E-07	7,85E-08	5,19E-09	6,91E-08	0
AP (SO2-Equivalents)	Ammonia	2,29E-05	8,61E-07	3,20E-07	2,13E-08	1,89E-07	0
	Nitrogen oxides	2,20E-05	2,60E-05	1,45E-04	9,07E-06	8,02E-06	0
POCP (Ethene-Equivalents)	Nitrogen oxides	1,23E-06	1,46E-06	8,13E-06	5,08E-07	4,49E-07	0

A5. The extracted results from the LCIA of one kg of tomatoes grown in Sweden. The table only includes the nitrogen containing species and includes the six following pages.

Raw results from LCA model "Swedish tomatoes - waste heat"	Activities ("dummy processes" with zero result excluded)	Total all activities	01 Fertilizer production	02 Tomato farming	02 Tomato farming	03 Transport to warehouse	03 Transport to warehouse	05 Transport to retail	05 Transport to retail	06 Retail store	06 Retail store	08 Sewage treatment [consumed tomatoes, excreted N] <u-so>
Mass [kg]	Subactivities (if applicable)			SE (Sweden): Electricity 2006 (medium voltage, 2.1 %)	EU-25: Thermal energy from light fuel oil ELCD/PE -GaBi	EU-15: Diesel ELCD/PE -GaBi	GLO: Truck ELCD/PE -GaBi <u-so>	EU-15: Diesel ELCD/PE -GaBi	GLO: Truck ELCD/PE -GaBi <u-so>	SE (Sweden): Electricity 2006 (medium voltage, 2.1 %)	DE: Polyethylene high density granulate mix (PE-HD) PE	
Inorganic emissions to air	Ammonia	<b>1,52E-05</b>	1,43E-05	4,90E-07	4,75E-08	3,49E-08	1,65E-07	2,17E-09	1,11E-08	6,41E-08	5,43E-08	0,00E+00
Inorganic emissions to air	Ammonium	<b>3,30E-14</b>	0,00E+00	0,00E+00	1,17E-15	3,98E-15	0,00E+00	2,47E-16	0,00E+00	0,00E+00	2,76E-14	0,00E+00
Inorganic emissions to air	Ammonium carbonate	<b>1,53E-12</b>	1,06E-12	4,18E-13	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	5,46E-14	0,00E+00	0,00E+00
Inorganic emissions to air	Ammonium nitrate	<b>4,90E-15</b>	0,00E+00	0,00E+00	5,83E-16	8,11E-16	0,00E+00	5,03E-17	0,00E+00	0,00E+00	3,45E-15	0,00E+00
Inorganic emissions to air	Carbon dioxide	<b>8,25E-02</b>	1,33E-02	1,21E-02	9,63E-03	3,22E-03	3,23E-02	2,00E-04	2,00E-03	1,58E-03	8,27E-03	0,00E+00
Inorganic emissions to air	Carbon dioxide (biotic)	<b>1,76E-02</b>	1,40E-04	1,55E-02	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,02E-03	0,00E+00	0,00E+00

<b>Raw results from LCA model "Swedish tomatoes - waste heat"</b>	Activities ("dummy processes" with zero result excluded)	<b>Total all activities</b>	01 Fertilizer production	02 Tomato farming	02 Tomato farming	03 Transport to warehouse	03 Transport to warehouse	05 Transport to retail	05 Transport to retail	06 Retail store	06 Retail store	08 Sewage treatment [consumed tomatoes, excreted N] <u-so>
Mass [kg]	Subactivities (if applicable)			SE (Sweden) : Electricity 2006 (medium voltage, 2.1 %)	EU-25: Thermal energy from light fuel oil ELCD/PE -GaBi	EU-15: Diesel ELCD/PE -GaBi	GLO: Truck ELCD/PE -GaBi <u-so>	EU-15: Diesel ELCD/PE -GaBi	GLO: Truck ELCD/PE -GaBi <u-so>	SE (Sweden) : Electricity 2006 (medium voltage, 2.1 %)	DE: Polyethylene high density granulate mix (PE-HD) PE	
Inorganic emissions to air	Carbon dioxide (biotic)	<b>1,82E-03</b>	0,00E+00	0,00E+00	1,10E-06	6,15E-06	1,70E-03	3,82E-07	1,05E-04	0,00E+00	1,38E-05	0,00E+00
Inorganic emissions to air	Carbon dioxide, land transformation	<b>7,42E-07</b>	1,87E-07	4,91E-07	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	6,42E-08	0,00E+00	0,00E+00
Inorganic emissions to air	Carbon monoxide	<b>1,01E-04</b>	2,35E-05	7,24E-06	3,14E-06	4,45E-06	5,43E-05	2,76E-07	3,54E-06	9,46E-07	3,76E-06	0,00E+00
Inorganic emissions to air	Carbon monoxide (biotic)	<b>2,49E-06</b>	1,00E-06	1,32E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,72E-07	0,00E+00	0,00E+00
Inorganic emissions to air	Nitrate	<b>3,60E-11</b>	1,65E-11	1,73E-11	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,26E-12	0,00E+00	0,00E+00
Inorganic emissions to air	Nitrogen (atmospheric nitrogen)	<b>4,23E-04</b>	0,00E+00	0,00E+00	1,45E-07	6,05E-07	0,00E+00	3,75E-08	0,00E+00	0,00E+00	4,22E-04	0,00E+00

Raw results from LCA model "Swedish tomatoes - waste heat"	Activities ("dummy processes" with zero result excluded)	Total all activities	01 Fertilizer production	02 Tomato farming	02 Tomato farming	03 Transport to warehouse	03 Transport to warehouse	05 Transport to retail	05 Transport to retail	06 Retail store	06 Retail store	08 Sewage treatment [consumed tomatoes, excreted N] <u-so>
Mass [kg]	Subactivities (if applicable)			SE (Sweden): Electricity 2006 (medium voltage, 2.1 %)	EU-25: Thermal energy from light fuel oil ELCD/PE -GaBi	EU-15: Diesel ELCD/PE -GaBi	GLO: Truck ELCD/PE -GaBi <u-so>	EU-15: Diesel ELCD/PE -GaBi	GLO: Truck ELCD/PE -GaBi <u-so>	SE (Sweden): Electricity 2006 (medium voltage, 2.1 %)	DE: Polyethylene high density granulate mix (PE-HD) PE	
Inorganic emissions to air	Nitrogen dioxide	<b>2,56E-16</b>	0,00E+00	0,00E+00	6,54E-19	1,56E-18	0,00E+00	9,70E-20	0,00E+00	0,00E+00	2,54E-16	0,00E+00
Inorganic emissions to air	Nitrogen monoxide	<b>2,06E-13</b>	0,00E+00	0,00E+00	2,88E-14	8,08E-14	0,00E+00	5,01E-15	0,00E+00	0,00E+00	9,09E-14	0,00E+00
Inorganic emissions to air	Nitrogen oxides	<b>4,21E-04</b>	4,40E-05	3,58E-05	1,63E-05	9,39E-06	2,81E-04	5,82E-07	1,76E-05	4,67E-06	1,14E-05	0,00E+00
Inorganic emissions to air	Nitrous oxide (laughing gas)	<b>4,44E-05</b>	4,30E-05	7,58E-07	1,44E-07	7,46E-08	2,16E-07	4,62E-09	1,46E-08	9,91E-08	1,57E-07	0,00E+00
ecoinvent long-term to fresh water	Ammonium / ammonia	<b>3,34E-09</b>	1,70E-09	1,45E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,89E-10	0,00E+00	0,00E+00
ecoinvent long-term to fresh water	Nitrate	<b>7,65E-09</b>	5,37E-09	2,01E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,63E-10	0,00E+00	0,00E+00

<b>Raw results from LCA model "Swedish tomatoes - waste heat"</b>	Activities ("dummy processes" with zero result excluded)	<b>Total all activities</b>	01 Fertilizer production	02 Tomato farming	02 Tomato farming	03 Transport to warehouse	03 Transport to warehouse	05 Transport to retail	05 Transport to retail	06 Retail store	06 Retail store	08 Sewage treatment [consumed tomatoes, excreted N] <u-so>
Mass [kg]	Subactivities (if applicable)			SE (Sweden): Electricity 2006 (medium voltage, 2.1 %)	EU-25: Thermal energy from light fuel oil ELCD/PE -GaBi	EU-15: Diesel ELCD/PE -GaBi	GLO: Truck ELCD/PE -GaBi <u-so>	EU-15: Diesel ELCD/PE -GaBi	GLO: Truck ELCD/PE -GaBi <u-so>	SE (Sweden): Electricity 2006 (medium voltage, 2.1 %)	DE: Polyethylene high density granulate mix (PE-HD) PE	
ecoinvent long-term to fresh water	Nitrite	<b>1,82E-10</b>	9,26E-11	7,88E-11	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,03E-11	0,00E+00	0,00E+00
ecoinvent long-term to fresh water	Nitrogen organic bounded	<b>5,45E-09</b>	2,78E-09	2,36E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	3,08E-10	0,00E+00	0,00E+00
Inorganic emissions to fresh water	Ammonia	<b>3,85E-11</b>	0,00E+00	0,00E+00	4,52E-12	1,66E-11	0,00E+00	1,03E-12	0,00E+00	0,00E+00	1,64E-11	0,00E+00
Inorganic emissions to fresh water	Ammonium / ammonia	<b>2,96E-06</b>	2,49E-06	1,86E-07	1,35E-08	2,97E-08	0,00E+00	1,84E-09	0,00E+00	2,43E-08	2,07E-07	0,00E+00
Inorganic emissions to fresh water	Nitrate	<b>1,28E-03</b>	5,17E-08	2,52E-07	3,01E-08	4,06E-09	0,00E+00	2,52E-10	0,00E+00	3,30E-08	5,79E-08	1,28E-03

<b>Raw results from LCA model "Swedish tomatoes - waste heat"</b>	Activities ("dummy processes" with zero result excluded)	<b>Total all activities</b>	01 Fertilizer production	02 Tomato farming	02 Tomato farming	03 Transport to warehouse	03 Transport to warehouse	05 Transport to retail	05 Transport to retail	06 Retail store	06 Retail store	08 Sewage treatment [consumed tomatoes, excreted N] <u-so>
Mass [kg]	Subactivities (if applicable)			SE (Sweden): Electricity 2006 (medium voltage, 2.1 %)	EU-25: Thermal energy from light fuel oil ELCD/PE -GaBi	EU-15: Diesel ELCD/PE -GaBi <u-so>	GLO: Truck ELCD/PE -GaBi <u-so>	EU-15: Diesel ELCD/PE -GaBi	GLO: Truck ELCD/PE -GaBi <u-so>	SE (Sweden): Electricity 2006 (medium voltage, 2.1 %)	DE: Polyethylene high density granulate mix (PE-HD) PE	
Inorganic emissions to fresh water	Nitrite	<b>5,66E-10</b>	3,83E-10	1,63E-10	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,12E-11	0,00E+00	0,00E+00
Inorganic emissions to fresh water	Nitrogen	<b>1,41E-06</b>	1,26E-06	1,35E-07	2,32E-12	5,60E-12	0,00E+00	3,47E-13	0,00E+00	1,77E-08	7,51E-10	0,00E+00
Inorganic emissions to fresh water	Nitrogen organic bounded	<b>2,82E-07</b>	3,64E-08	5,91E-09	3,70E-08	1,37E-07	0,00E+00	8,48E-09	0,00E+00	7,72E-10	5,65E-08	0,00E+00
Inorganic emissions to sea water	Ammonia	<b>2,86E-12</b>	0,00E+00	0,00E+00	5,03E-13	1,74E-12	0,00E+00	1,08E-13	0,00E+00	0,00E+00	5,10E-13	0,00E+00
Inorganic emissions to sea water	Ammonium / ammonia	<b>3,53E-09</b>	2,46E-09	9,39E-10	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,23E-10	0,00E+00	0,00E+00

<b>Raw results from LCA model "Swedish tomatoes - waste heat"</b>	Activities ("dummy processes" with zero result excluded)	<b>Total all activities</b>	01 Fertilizer production	02 Tomato farming	02 Tomato farming	03 Transport to warehouse	03 Transport to warehouse	05 Transport to retail	05 Transport to retail	06 Retail store	06 Retail store	08 Sewage treatment [consumed tomatoes, excreted N] <u-so>
Mass [kg]	Subactivities (if applicable)			SE (Sweden): Electricity 2006 (medium voltage, 2.1 %)	EU-25: Thermal energy from light fuel oil ELCD/PE-GaBi	EU-15: Diesel ELCD/PE-GaBi <u-so>	GLO: Truck ELCD/PE-GaBi <u-so>	EU-15: Diesel ELCD/PE-GaBi	GLO: Truck ELCD/PE-GaBi <u-so>	SE (Sweden): Electricity 2006 (medium voltage, 2.1 %)	DE: Polyethylene high density granulate mix (PE-HD) PE	
Inorganic emissions to sea water	Nitrate	<b>3,96E-07</b>	1,13E-08	3,27E-07	2,41E-09	9,29E-09	0,00E+00	5,76E-10	0,00E+00	4,27E-08	3,55E-09	0,00E+00
Inorganic emissions to sea water	Nitrite	<b>7,74E-09</b>	1,17E-10	6,74E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	8,81E-10	0,00E+00	0,00E+00
Inorganic emissions to sea water	Nitrogen	<b>2,77E-10</b>	2,19E-10	5,15E-11	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	6,73E-12	0,00E+00	0,00E+00
Inorganic emissions to sea water	Nitrogen organic bounded	<b>1,57E-08</b>	1,16E-08	3,60E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	4,70E-10	0,00E+00	0,00E+00
Inorganic emissions to industrial soil	Ammonia	<b>1,32E-06</b>	0,00E+00	0,00E+00	1,52E-07	5,98E-07	0,00E+00	3,71E-08	0,00E+00	0,00E+00	5,34E-07	0,00E+00

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