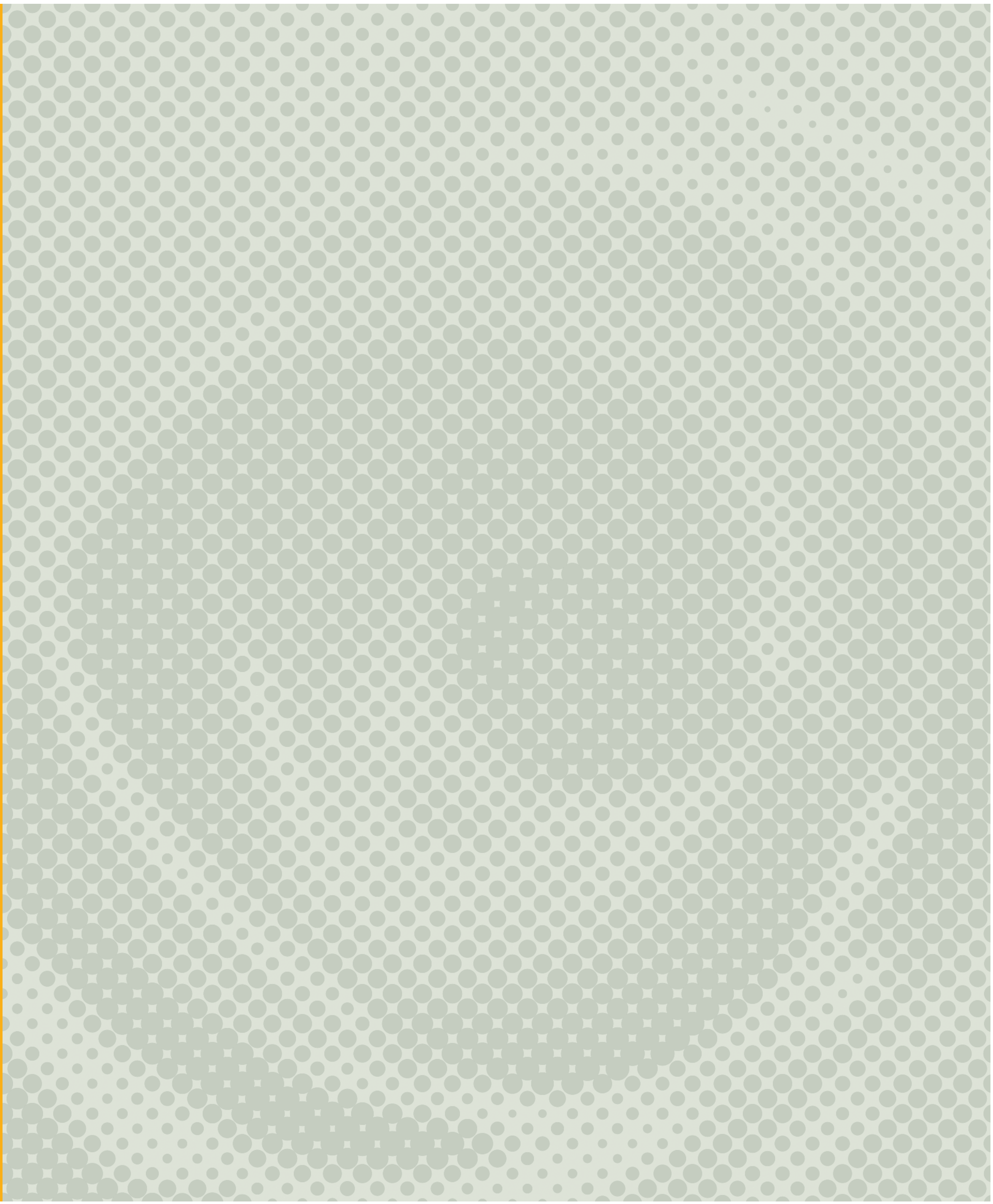
Norwegian University of Life Sciences



Seasonal Vegetables

An Environmental Assessment of Seasonal Food

Hanna Karlsson

Supervisor: Geir Lieblein (Norwegian University of Life Sciences)

Assisting supervisor: Tor Arvid Bredland (Norwegian University of Life Sciences)

External supervisor: Elin Röös (Swedish University of Agricultural Sciences)

ABSTRACT

The environmentally conscious consumer is advised to consume seasonal food even though there is not a universally accepted definition of the term seasonal food. The ambiguity around the term seasonal food concerns the size of the geographical area and the permitted production systems from which the consumer may acquire seasonal food. This study addresses the ambiguity of the term by focusing on the Swedish per capita consumption of carrots and tomatoes and by assessing the environmental impact of four different definitions of seasonal food. The four definitions are Swedish season (Habit A), Swedish season without climate controlled greenhouses (Habit B), European season (Habit C) and European season without climate controlled greenhouses (Habit D). Life Cycle Assessment (LCA) was used to assess the environmental impact of tomato and carrot production in Sweden and in the two main import countries for tomatoes, the Netherlands and Spain, and carrots, the Netherlands and Italy. The impact categories included were global warming potential*,* fossil fuel depletion*,* arable land use*,* acidification potential and eutrophication potential. Habit B with neither climate controlled greenhouses nor long transportation distances had a significantly lower impact for global warming potential, fossil fuel depletion and acidification potential and the second lowest eutrophication potential but the highest arable land use. The energy use and energy sources for heating in the tomato production were the most important factors for the aggregated impact from tomato and carrot consumption for Habit A and C. Impacts from transportation were significant for Habit D. Generally, the consumption of carrots contributes 10-30% to the aggregated impact, except for arable land use where carrot consumption dominates the impact. The study also showed that for produce from climate controlled greenhouses seasonality is less important for the environmental impact because the impact from energy use and energy source for climate control is significant the whole year around. Meaning that, for tomatoes and probably also other greenhouse grown produce in the Swedish market, consuming seasonal food is inaccurate advice for encouraging environmentally friendly consumption, and instead production methods should be emphasized more. For open field produced carrots, on the other hand, seasonality is a significant parameter because the environmental impact increases with storage time as energy use and storage losses increase.

FOREWORD

This thesis was part of a cooperative research project called “Klimatmärkt livsmedelsbutik” (Climate Labeled Grocery Store) which is a cooperation between the Swedish University of Agricultural Sciences, the Swedish Society for Nature Conservation (SSNC) and COOP (a large national grocery store chain in Sweden). The aim of this cooperative research project is to investigate to “*what extent the food retailing sector can stimulate consumers to make climate friendlier food choices by using tools such as displaying and exposing [relevant climate change information], and how these activities affect the profitability for the retailer*” (Projektbeskrivning, Klimatsmärkt livsmedelsbutik). I would like to thank all the participants of this research project for providing motivation, valuable comments on my work and interesting new angles for the discussion of issues concerning seasonal vegetables. A special thanks to Elin Röös, my supervisor at the Swedish University of Agricultural Sciences, for encouragement, supportive and enriching advice and pleasant discussions. I am also grateful for the many helpful suggestions and comments from Geir Lieblein and Tor-Arvid Breland, my supervisors at the Norwegian University of Life Sciences.

REFLECTION

When I chose this subject I wanted to learn more about the method used in this study, Life Cycle Assessment (LCA), a method that has been increasingly used to assess the environmental performance of agricultural production systems. I find the method interesting because it attempts to embrace entire production systems, which in my opinion raises interesting questions about how to assess the immeasurable aspects of the system. Personally, I believe that the method´s popularity can be at least partly explained by the communicability of the results. Results are often presented in stable bar diagrams easy to read and interpret. Although it is utterly important that research results are being made accessible I believe that it is a challenge to communicate the complexity beyond the stable bar diagrams. Working within this research project (klimatmärkt livsmedelsbutik) encouraged me to think about a subject that I have been interested in for a long time, namely food advice, and especially environmental food advice given to consumers. This is what led me to study seasonal foods which are not only fresh vegetables or harvest seasons, but also advice on how to eat environmentally friendly. To be given the opportunity to work with these issues has been meaningful for me. Writing a thesis is a lonely task. Even though I appreciate the opportunity and time to learn more and reflect, I have learned to value and appreciate even more reflections, advice and input from others.

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1. INTRODUCTION

The environmental impact of food production and the global food system has gained increased interest, especially during the climate change debate of recent years. In Swedish grocery stores a great diversity of fresh fruits and vegetables are available throughout the year, despite the fact that Sweden is a northern country with a short growing season. The availability of and access to fruits and vegetables has increased (Elmadfa & Weichselbanm, 2005), which most likely has enabled Swedes to have a healthier diet, widen our perspective of foods and provide a richer “food life”. However, this increased availability of fresh fruits and vegetables involves long transportation distances or energy demanding climate control of greenhouses. As more and more consumers demand environmentally certified foods such as climate labeled (Swedish Environmental Protection Agency, 2009) and organic (European Commission, 2011), the demand for increased knowledge about the environmental impact from the food chain is rising.

Seasonal food is associated with a number of qualities; it is argued to be tastier, more fun, cheaper (SSNC, 2010; Eco Food Center, 2011) and more nutritious (SSNC, 2011; Sund.nu, 2005). In addition, seasonal food is often argued to be environmentally friendly, and the environmentally conscious consumer is advised to consume seasonal vegetables and fruits. Different entities such as food and agricultural organizations and governmental bodies have defined seasonal food differently (Clarin & Johansson, 2009; Lagerberg- Fogelberg, 2008; SSNC, 2010; Eco Food Center, 2011; EU, 2011); there is no universally accepted definition of the term. There are contradicting recommendations on how to consume seasonal food which can be confusing for consumers looking for advice on how to eat seasonal food and can potentially prevent them from trying to eat seasonal food. One interpretation of seasonal food could be consuming locally produced food, which has the benefit of decreased transportation time and the associated emissions. Another definition of seasonal food recommend foods that are in season somewhere, or at least in a larger region, with the main benefits being that the product is abundant on the market, has not been stored and is cheaper. A third aspect, sometimes included in some definitions of seasonal food, is that seasonal foods have to be produced without climate controlled greenhouses—which saves energy. Consequently, the main aspects of seasonal food are spatial distance from the production to the consumer, harvest season, storage durability and production methods.

Humans have tried to bridge the limits that seasonality imposes on the diet for a long time—by techniques for preserving food such as drying, salting and souring foods (Bringéus, 1988) and to extending the growing season; greenhouses have been used in Sweden on a small scale since the 1600s (Andersson, 2000b). Improved transportation and development of climate controlled greenhouse technologies are yet other means to provide foods that are “out of season”. The extensive energy use for climate control of greenhouses and transportation has been enabled by access to and use of energy sources such as fossil fuels. This brings to light the issue of seasonal food and, more specifically, how products produced in climate controlled greenhouses or transported long distances relate to seasonal consumption, and more specifically environmentally friendly seasonal consumption.

Tomatoes and carrots are the two vegetables with the highest fresh per capita consumption in Sweden. 2006 per capita fresh consumption was 10.4 kg tomatoes and 9.2 kg carrots (SJV, 2009a). Most carrots consumed in Sweden are also produced in Sweden. Tomatoes on the other hand are imported to a great extent. Swedish degree of self-sufficiency of tomatoes was 20% in 2005. Carrot production in Sweden supported about 92% of the domestic consumption in 2005; it is the highest degree of self-sufficiency of all fruits and vegetables in Sweden. (SJV, 2009b) Tomatoes and carrots differ in two properties central for the term seasonal food. Tomatoes for the Swedish market are often produced in heated greenhouses as compared to carrots that are produced in open fields. Fresh carrots can be stored for up to 9 months, in contrast with fresh tomatoes that have to be consumed within a few weeks.

Life Cycle Assessment (LCA) is an environmental impact assessment method. LCA may be used to compare the environmental impact of different products with the same or similar function, investigate alternative life cycles and identify which phase in the life cycle that contributes most to the total environmental impact of the product. LCAs assess life cycles of a product or service, usually by applying a “cradle-to-grave” method where all steps in a life cycle of a product are accounted for—from the extraction of raw materials to the disposal of the product. LCA was developed in the 1960s initially for assessing the environmental impact of industrial products. (Baumann & Tillman, 2004) LCA has been used to analyze the environmental impact of a wide variety of agricultural products by researchers, authorities and companies. It is common that studies on agricultural production systems limit their focus to the environmental impact of primary production, referred to as "cradle-to-farm-gate" studies (Basset-Mens & van der Werf, 2007 and Andersson, 2000a). However a number of studies also consider processed food, for example, beer production (Takamoto et al. 2004) and ketchup (Andersson et al., 1998; Andersson & Ohlsson, 1999) (Roy et al. 2008). The user or consumer phase however, is often not included in many LCA studies on food products (Andersson, 2000a). LCA studies on agricultural systems show that a system approach for analyzing the environmental impact of agricultural systems is preferable. It is often less meaningful to look at one single phase in the life cycle, such as transportation or packaging alone, when examining the environmental impact. LCA is also a useful tool for learning about the environmental aspects of food products and for increasing environmental awareness. (Andersson, 2000a)

Previous LCA studies on tomato production include EUPHOROS, 2007; Theurl, 2008; Antón, 2005; Neinhuis & Vreede; Plumiers et al, 2000; Russo & Scarascia Mugnozza, 2005. The primary focus of most of these studies has been to compare the environmental impact of different production systems, such as closed and opened hydroponic systems and soil cropping or tomatoes from different countries. Previous LCA studies on tomatoes and carrots in the Swedish market have primarily been focusing on their carbon footprint (Lagerberg Fogelberg & Carlsson-Kanyama 2006; Högberg, 2010; Möller Nielsen, 2008; 2009; Carlsson Kanyama, 1998b). The carbon footprint of a product expresses the impact category global warming potential (of a LCA study) in kg CO_2-eq. Results from the different studies on tomatoes expressed in kg CO_2-eq per kg tomatoes delivered to Sweden can be seen in *Figure 1*. The fact that different studies have found inconsistent results depends on the choices made during the analysis, different production systems considered, different system boundaries, etc. as well as that the tomato sector changes over time.

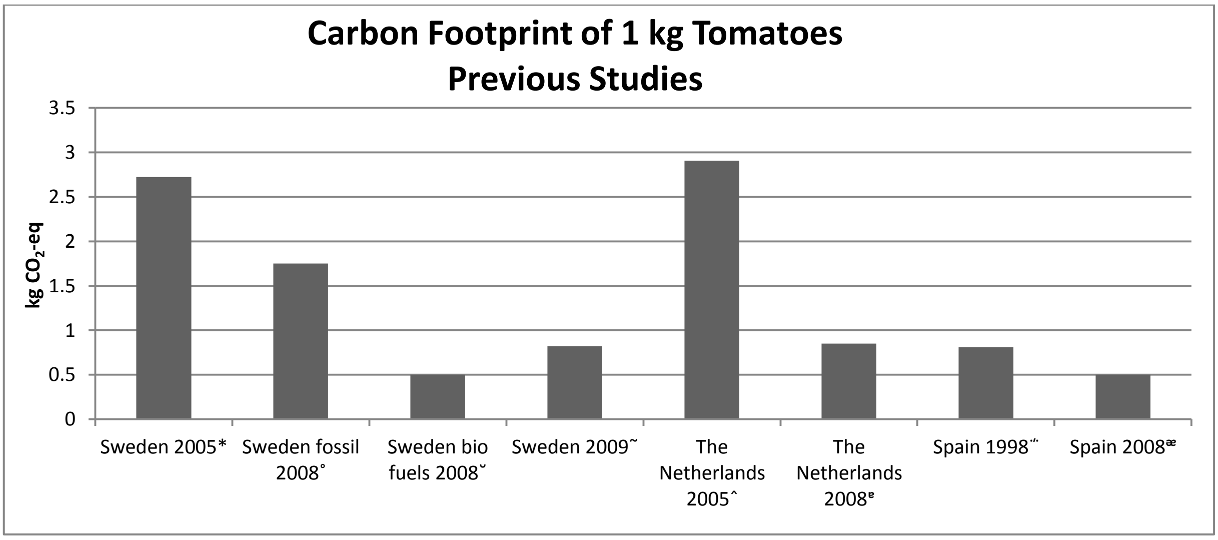

Figure 1. Carbon footprint of 1 kg tomatoes on the Swedish market from different studies. The results depend partly on the system boundaries chosen.
**Lagerberg-Fogelberg & Carlsson-Kanyama (2006)*
˚*Högberg (2010)*
˘*Högberg (2010)*
˜*Mölle- Nielsen (2009)*
ˆ*Lagerberg-Fogelberg & Carlsson-Kanyama (2006)*
ᵉ*Högberg (2010)*
˝*Carlsson-Kanyama (1998b)*
ᵆ*Möller Nielsen (2008)*

Generally, carrots have a lower carbon footprint than tomatoes. Carrots produced in Sweden have been estimated to have a carbon footprint of 0.069 kg CO_2-eq (Lagerberg Fogelberg & Carlsson-Kanyama, 2006) to 0.25 kg CO_2-eq (Carlsson-Kanyama, 1998b), whereas carrots imported to Sweden have been assessed to have a carbon footprint of approximately 0.12 kg CO_2-eq (Lagerberg Fogelberg & Carlsson-Kanyama, 2006) to 0.70 kg CO_2-eq (Carlsson-Kanyama, 1998b). Swedish tomatoes have been assessed to have a carbon footprint of 0.5 (Högberg, 2010) to 0.50 CO_2-eq (Lagerberg-Fogelberg & Carlsson-Kanyama, 2006).

1.2 OBJECTIVE OF THE PRESENT STUDY

In the present study, the objective was to assess the environmental impact of four different guidelines for consuming carrots and tomatoes as seasonal food. This was done by using LCA to quantify the environmental impact of the yearly per capita consumption of tomatoes and carrots in Sweden based on 1) four definitions of the term seasonal food and 2) seven production scenarios. The seven production scenarios were tomatoes produced in: climate controlled greenhouses in the Netherlands (NLH) and Sweden (SEH), greenhouses without climate control in Sweden (SEU) and Spain (ESS), as well as, carrots produced in the Netherlands (NLC), Italy (ITC) and Sweden (SEC). The four definitions were Swedish season (habit A), Swedish season no extra energy[1] (habit B), European season (habit C) and European season no extra energy (habit D).

The production scenarios were evaluated with respect to the following impact categories: global warming potential, fossil fuel depletion, arable land use, acidification potential and eutrophication potential.

Research Questions

- What is the difference in environmental impact from the yearly consumption of tomatoes and carrots depending on how seasonal food is defined?
- What is the global warming potential from the current tomato and carrot consumption? Could the global warming potential of current tomato and carrot consumption be decreased if tomatoes and carrots were consumed as seasonal food?
- What are the most important features of low environmental impact seasonal food?

2. MATERIALS AND METHODS

2.1 SEASONAL CONSUMPTION ACCORDING TO VARIOUS DEFINITIONS

2.1.1 SEASONAL CONSUMER HABITS OF SEASONAL VEGETABLES

In order to estimate the environmental impact of tomatoes and carrots consumed as seasonal food, according to different definitions of seasonal food, four hypothetical consumer habits were constructed. This was done based on a literature review of the term seasonal food. A summary of how seasonal food has been defined by governmental bodies and non-governmental organizations can be found in *Table 1*. The various definitions of seasonal food from literature can be characterized by the prescribed location of production and the allowed production systems. These characteristics were used in constructing the hypothetical seasonal consumer habits presented in
Table 2.

Table 1. Different interpretations of the term seasonal food in literature.

Organization/Author	**Location of Production**			**Cropping System**	
	Local Area	**Sweden**	**Europe**	**Climate control of greenhouses**	**No climate control**
Swedish Board of Agriculture*		X		X	
National Food Administration°		X		X (heated with biofuels)	
The Swedish Society for Nature Conservation ˟	X				X
Swedish Environmental Management Council˘	Not specified				X
The European Union˜	X				X
Eco Food Centerˆ		X(first priority)	X (second priority)		X

*Clarin & Johansson (2009)

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[1] *No extra energy* means that no produce from heated greenhouses is included in this consumer habit.

° Lagerberg- Fogelberg (2008)
˟ SSNC (2011)
˘ The Swedish Environmental Management Council (2011)
˜ EU (2011)
ˆEco Food Center (2011)

Table 2. Hypothetical seasonal consumer habits.

Consumer habit	Description	Transports	Includes produce from climate controlled greenhouses
Habit A	**Swedish season.** No restrictions on cropping system are made. Consumes only Swedish produce. Main argument: decreases transportations.	Short	Yes
Habit B	**Swedish season with no extra energy use for heating**. Consumes only Swedish produce that has been cultivated in unheated greenhouses. Main arguments: decreases transportations and energy use for greenhouses.	Short	No
Habit C	**European season.** No restrictions on cropping systems are made. Consumes European produce (but prioritizes Swedish produce when this is available). Main argument: decreases transportation.	Medium	Yes
Habit D	**European season with no extra energy use for heating.** Consumes European produce (but prioritizes Swedish produce when this is available) that has been produced in unheated greenhouses. Main arguments: decreases energy use for greenhouses.	Long	No

2.1.2 TOMATOES AND CARROTS

Tomatoes and carrots were chosen for the analysis for a number of reasons. First, they best represent the Swedish vegetable consumption since they are the vegetables with the highest fresh per capita consumption in Sweden (SJV, 2009a). Second, they represent two different production systems. Tomatoes for the Swedish market are mainly produced in greenhouses in highly protected and controlled systems, whereas carrots are produced in open fields and the carrot crop is suitable for the Scandinavian climate. Third, tomatoes and carrots are inherently different when it comes to durability: fresh carrots can be stored for a much longer period of time than fresh tomatoes. Fourth, the degree of Swedish self-sufficiency is 20% and 92% for tomatoes and carrots, respectively (SJV, 2009b).

Tomatoes and carrots are imported to Sweden from a wide variety of countries (SCB, 2009) and produced with various production methods. In order to limit the scope of this study two methodological decisions were made:

1. The number of import countries for tomato and carrot consumption in Sweden were limited to two main import countries: the Netherlands and Spain for tomato import and the Netherlands and Italy for carrot import. In the subsequent results, tomatoes from the Netherlands and Spain were separated due to the significantly different production methods in these countries. However, carrots from Italy and the Netherlands were aggregated into one unit called “imported carrots”, because their cropping systems are similar and also the environmental impacts.

2. Production methods vary between countries and between individual farms. Accounting for all these individual variations would be a huge task and is outside of the scope of this study. Instead, the most representative techniques for producing tomatoes and carrots were chosen for each country because the production methods were assumed to produce a majority of the tomatoes and carrots distributed in the Swedish market. The techniques that were identified as most representative are presented in 2.3.2 Scope and 2.3.2 Representative Techniques.

Amounts of Tomato and Carrot Consumed according to the Consumer Habits

Fresh carrots have long durability and can be stored for long periods of time. In this study, carrots were considered seasonal for as long as they can be stored. For example, in Sweden this is from the end of the harvest in October until March the following year. Fresh tomatoes on the other hand, cannot be stored for a long time and were therefore considered seasonal during the harvest season. *Table 3* shows how the consumption of tomatoes and carrots was distributed throughout the year for the four seasonal consumer habits (A-D). For example, in habit B tomatoes was assumed to be consumed from August to October, whereas both tomatoes and carrots were assumed to be consumed the whole year for habits C and D.

Table 3. Consumption according to the hypothetical consumer habits (kg).

Month		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
Habit														
A	Tomato				1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3		**10.4**
	Carrot	0.92	0.92	0.92	0.92			0.92	0.92	0.92	0.92	0.92	0.92	**9.2**
B	Tomato								3.47	3.47	3.47			**10.4**
	Carrot	0.92	0.92	0.92	0.92			0.92	0.92	0.92	0.92	0.92	0.92	**9.2**
C	Tomato	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	**10.4**
	Carrot	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0,77	0.77	**9.2**
D	Tomato	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	**10.4**
	Carrot	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0,77	0.77	**9.2**

Black is Swedish produce, orange is Dutch produce, red is Spanish produce and green is imported carrots.

Table 4 shows the total yearly tomato and carrot consumption that were derived from the different production scenarios (described below in *Table 4*) for all four seasonal consumer habits and for current consumption. With a degree of self- sufficiency of approximately 20% for tomatoes and 92% for carrots (SJV, 2009b), the current consumption of these two vegetables resembles consumer habit C and D which includes imported tomatoes and carrots. However, the import figures for tomatoes are higher for current consumption than in the analyzed consumer habits (*Table 5*). Import of tomatoes for current consumption is primarily derived from the Netherlands (SCB, 2009). Current consumption was estimated by letting Swedish self- sufficiency degree (2005) represent percentage of consumption with Swedish origin. It was also assumed that all the import of tomatoes (80% of the consumption) comes from the two main import countries: the Netherlands (87%) and Spain (22%), and all import of carrots were assumed to come from the two main import countries of carrots: the Netherlands (72%) and Italy (28%).

Table 4. Consumed amounts (kg) of tomatoes and carrots for the consumer habits and current consumption.

Consumer Habit	Tomatoes SEH	Tomatoes SEU	Tomatoes NLH	Tomatoes ESS	Carrots SEC	Carrots Import IC
Habit A	10.4				9.2	
Habit B		10.4			9.2	
Habit C	6.9		3.5		7.7	1.5
Habit D		2.6		7.8	7.7	1.5
Current Consumption	2.1		6.5	1.8	8.5	0.7

Table 5. Percentage of Swedish produced and imported produce for consumer habit A- D and current consumption.

	Tomatoes Swedish	Tomatoes Imported	Carrots Swedish	Carrots Imported
Habit A	100%	-	100%	-
Habit B	100%	-	100%	-
Habit C	67%	33%	83%	17%
Habit D	25%	75%	83%	17%
Current Consumption	20%	80%	92%	8%

2.2 THE STRUCTURE OF AN LCA STUDY

This section presents a short explanation of the phases in an LCA study for the reader that is not familiar with LCA. LCA involves a number of phases (illustrated *Figure 2*) defined by ISO 14040:2006 (ISO, 2006) standards. These phases are: The goal and scope definition phase that defines the aim of the study and its intended application. This phase describes the basic methodological choices for the subsequent modeling and these definitions guide the later phases of the study. The inventory analysis phase involves collecting data, model building and quantifying emissions. In the impact assessment phase the environmental impact from the emissions quantified during the inventory analysis is described and the quantified emissions are translated into environmental load. The different emissions are associated with a number of so called impact categories, which could be global warming potential or acidification potential. In order to sum the emissions affecting one impact category equivalency factors are used for each emission. For example, in order to sum the global warming potential of 100 grams of $C0_2$ and 10 grams of CH_4, two equivalency factors K1 and K2 are needed since CO_2 and CH_4 affect the climate differently; thus the total would be K1 * 100 + k2 * 10. The interpretation is where the results are assessed in order to draw conclusions, this phase is connected to all the other phases (**Fel! Hittar inte referenskälla.**), because the results in the inventory analysis and the impact assessment can only be interpreted in terms of the goal and scope definition. (Baumann & Tillman, 2009)

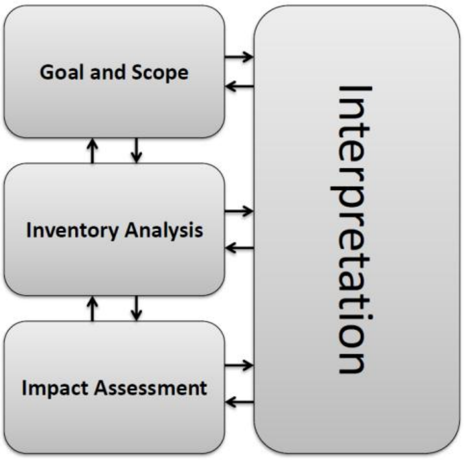

Figure 2. A schematic of LCA methodology showing that the different LCA phases influence each other. (modified from Baumann and Tillman, 2004)

2.3 GOAL AND SCOPE OF THE LCA STUDY

2.3.1 GOAL

The goal and objectives of the present study is presented above, in section 1.2 Objective of the Present Study. This study was an accounting[2] and comparative[3] LCA between tomatoes and carrots produced for the Swedish market by different production systems in four different countries. The results are intended to be communicated to participants in the "project climate labeled grocery" store from the Swedish University of Agricultural Sciences (SLU), the Swedish Society for Nature Conservation (SNCC) and the grocery store chain COOP. The LCA software SimaPro 7.2 was used for the analysis.

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[2] An accounting LCA study where the environmental impact of one product is described (Baumann & Tillman, 2004)

[3] A comparative LCA is a study where the environmental impact of two or more products are being compared (Baumann & Tillman, 2004)

2.3.2 SCOPE

The seven production scenarios shown in *Table 6* were analyzed.

Table 6. Production scenarios with representative techniques.

Scenario	Country	Description	Main energy source for climate control of greenhouses	Location
Tomato production				
NLH	The Netherlands	Hydroponic, climate controlled greenhouse for tomato production using fossil fuels as the energy source with CHP system and recirculation of drainage water	Natural gas	Westland, the Netherlands
ESS	Spain	Unheated greenhouse for tomato production is the most common greenhouse type, Parral, no recirculation of drainage water and cropping in soil	--	Almería, Spain
SHE	Sweden	Hydroponic, climate controlled for tomato production mainly using a non-fossil source of energy and recirculation of drainage water	Woodchips	Skåne, Sweden
SEU *	Sweden	Hydroponic unheated greenhouse for tomato production using recycling of drainage water	--	Skåne, Sweden
Carrot production				
SEC	Sweden	Carrot production assumed to not be grown on humus soils	--	Skåne, Sweden
CI (CNL and CIT)	The Netherlands and Italy	Carrots produced with similar production methods as in Sweden, which are imported to Sweden	--	The Netherlands and Italy

**The unheated greenhouse in Sweden is a hypothetical scenario, meaning that this scenario is not representative for tomato production in unheated greenhouses. The share of the Swedish tomato production that is produced in unheated greenhouses is small, therefore this scenario was based on data from a presently closed-down unheated greenhouse.*

FUNCTIONAL UNIT

The functional unit is the main function of the production system (Baumann & Tillman 2004). The functional units of this study were the total Swedish per capita consumption of tomatoes and carrots, which were respectively, 10.4 kg and 9.2 kg per capita (2006). The results from the production scenarios are also presented with the functional units 1 kg tomatoes and 1 kg carrots delivered to a wholesaler in Helsingborg.

SYSTEM BOUNDARIES AND FLOW CHART

System boundaries define which material flows, production steps, etc. that are included and excluded in the analysis. This study focused on and includes the primary production of tomatoes and carrots, transportation to the wholesale, as well as, storage of the products before delivery to the wholesale (Figure 3).

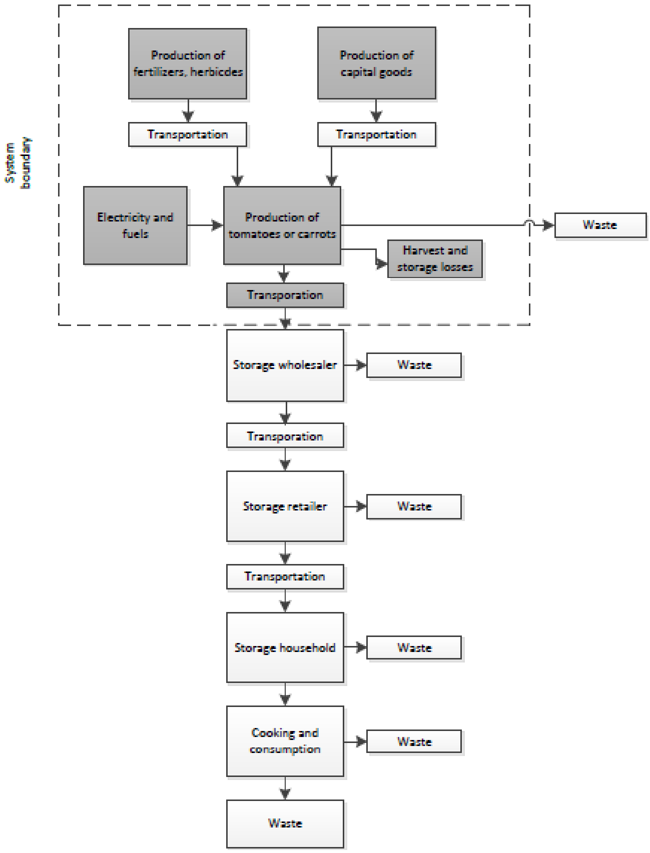

Figure 3. Simplified flow chart of the systems modeled. The dark grey boxes are included in the analysis. Primary production and inputs needed for growing tomatoes and carrots are included as well as transportation to the wholesaler. Storage of carrots is also included.

Included:

- Production of electricity and fuels
- Production of fertilizers and pesticides
- Production of growing substrates
- Energy use for tomato seedling production
- Field operations
- Storage of carrots
- Emissions related to fertilizer application
- Indirect emissions from nitrate leaching, volatilization and crop residues
- Production of building materials for the greenhouses and other buildings such as sheds for agricultural equipment (in the case of carrot production)
- Transportation from production sites to the wholesaler in Sweden

Excluded:

- Transportation of fertilizers, pesticides, building materials and other inputs
- Waste disposal of building materials, organic waste and non-organic waste
- Packaging
- Biological protection and pollination insects
- Everything that happens to the product after it reaches the wholesaler
- Human labor, transportation of workers, etc.

Transportation of inputs such as fertilizers, pesticides, building materials and other inputs were excluded because uncertainties of transportation distances are high and the contribution to the environmental impact from transportation of inputs is relatively small in comparison with the total impact and the manufacturing of the inputs (see for example EUPHPROS, 2007). Waste disposal of building materials, organic waste and non-organic waste from the production were not included due to lack of information. Antón et al. (2005) compared different waste managements. It was found that composting biomass had a positive environmental effect and that waste disposal of greenhouse construction materials into a landfill has a significant negative environmental impact, specifically to the impact categories global warming potential and eutrophication potential. Packaging was not included in this study. For potential contribution from primary and secondary packaging to the global warming potential of tomatoes and carrots see the recent study by Davis et al. (2011). Inputs of insects for biological protection and pollination for tomato production were not included due to lack of data. Furthermore, the contribution insects have to the environmental impact was expected to be small. The decreased pesticide use because of biological protection methods can be expected to have positive environmental consequences. Artificial fertilizers were assumed to be used in all of the analyzed production scenarios. Furthermore, it was assumed that all nitrogen fertilizers were produced with the N_2O abatement technology that significantly decreases the global warming potential of fertilizer production. N-fertilizers in the Scandinavian market produced with N_2O abatement technology have an average global warming potential of 3.1 kg CO_2-eq per kg N, compared with N-fertilizers produced without N_2O abatement technology that have a global warming potential of 7.8-8.1 kg CO_2-eq per kg N. (Yara, 2010) In this study it was assumed that all analyzed scenarios use N_2O abatement technology, even if the technology is not used at all fertilizer production plants that produce for the European market (Yara, 2010).

GEOGRAPHICAL AND TIME LIMITATIONS

Geographical limitations were that of the production sites in the focus countries (see *Table 6*) and transportation to Helsingborg, Sweden. The time limits are those of a cropping season in the focus countries. Most data was from the cropping season 2009-2010, although some data were based on average value of the last five years, as in the case of carrot yields.

ALLOCATION PROCEDURES

Allocation methods are used to allocate emissions between different products from the same production system. In this study allocation was relevant for carrot production as carrots for human consumption and fodder are produced in the same production system. Normally carrots that cannot be used for human consumption are either treated as waste or sold as fodder carrots. In this study, all emissions from carrot production were allocated to the production of carrots for human consumption, meaning that 100% of the emission was allocated to the carrots for human consumption. The proportion of produced carrots that was assumed to be lost as waste or used as fodder carrots range from 11-20% of the total production, depending on the production scenario. In this study, it was not known how much of the lost proportion was waste and how much was sold as fodder carrots (for a sensitivity analysis of how much this generalization affects the results see Appendix G. The Importance of Harvest and Storage Losses for the Results of the Carrot- LCA). The tomato production considered generally does not have any byproducts. With the exception of the Dutch production scenario where CHP systems produce both heat for the greenhouse and surplus electricity. The surplus from the CHP was treated as avoided Dutch national electricity production mix.

IMPACT CATEGORIES

Impact categories considered are: global warming potential, eutrophication potential, acidification potential, fossil fuel depletion and arable land use (*Table 7*).

Table 7. Impact categories considered in this study and equivalent units.

Impact categories	Equivalent unit
Global warming potential	kg CO_2- eq
Eutrophication potential	kg PO_4- eq
Acidification potential	kg SO_2- eq
Fossil fuel depletion	MJ eq
Arable land use	m^2

IMPACT ASSESSMENT METHOD

For the impact categories global warming potential*,* acidification and eutrophication potential the impact assessment method CML 2 basline 2000 was used. The impact category fossil fuel depletion was assessed using the EPD (2008) V1.03 impact assessment method.

Arable land use (L_a) in m^2 per functional unit was calculated as:

$$L_a = F/[(1 - lp/100) * h]$$

(Carlsson-Kanyama, 1997)

where, *F* is the functional unit in kg, *lp* is the harvest and storage loss in percent, *h* is the yield in $kg*m^{-2}*year^{-1}$.

DATA SOURCES AND DATA QUALITY

Data have been collected through literature studies and interviews with growers, horticultural experts and representatives from companies, such as, wholesalers and plant seedling producers. Data collected through interviews are considered to be of good quality. Data collected through national statistics and literature studies are considered to be of sufficient quality for the purpose of this study.

Table 8. Main data sources.

Scenario	Interviews	National statistics	Literature studies
Tomato, NLH	X	X	X
Tomato, ESS		X	X
Tomato, SHE	X	X	X
Tomato, SEU	X		X
Carrot, SEC	X	X	X
Carrot, CI		X	X

2.3 INVENTORY ANALYSIS

This section explains the choice of import countries, the production scenarios that were chosen as representative technique, assumptions made during the analysis and scenario specific data.

2.3.1 IMPORT COUNTRIES

Tomatoes are mainly imported to Sweden from the Netherlands and Spain (SCB, 2009). Tomatoes grown in Sweden are available to consumers from April to November. It can be seen in *Figure 4* that Dutch import is high almost the whole year, while the Spanish import is highest when there is not any tomato production in Sweden i.e. during winter. In 2009 around 68% of the imported tomatoes were from the Netherlands and 19% from Spain (SCB, 2009).

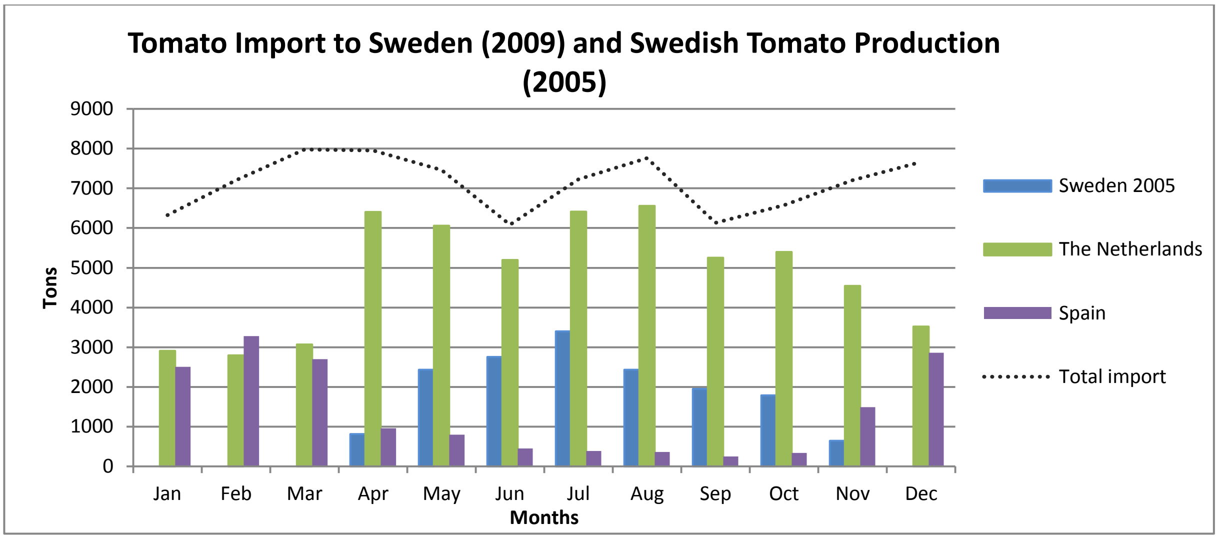

Figure 4. Tomato import to Sweden 2009, country of origin (SCB, 2009) and Swedish tomato production 2005 (SJV, 2009b).

Carrots grown in Sweden are available on the consumer market ten to eleven months of the year. In May and June none or small quantities of carrots grown in Sweden are available to the consumer. It is primarily during late winter and spring that carrots are imported to Sweden, mainly from the Netherlands and Italy (*Figure 5*). In 2009 around 63% of the import was from the Netherlands and 24% from Italy (SCB, 2009).

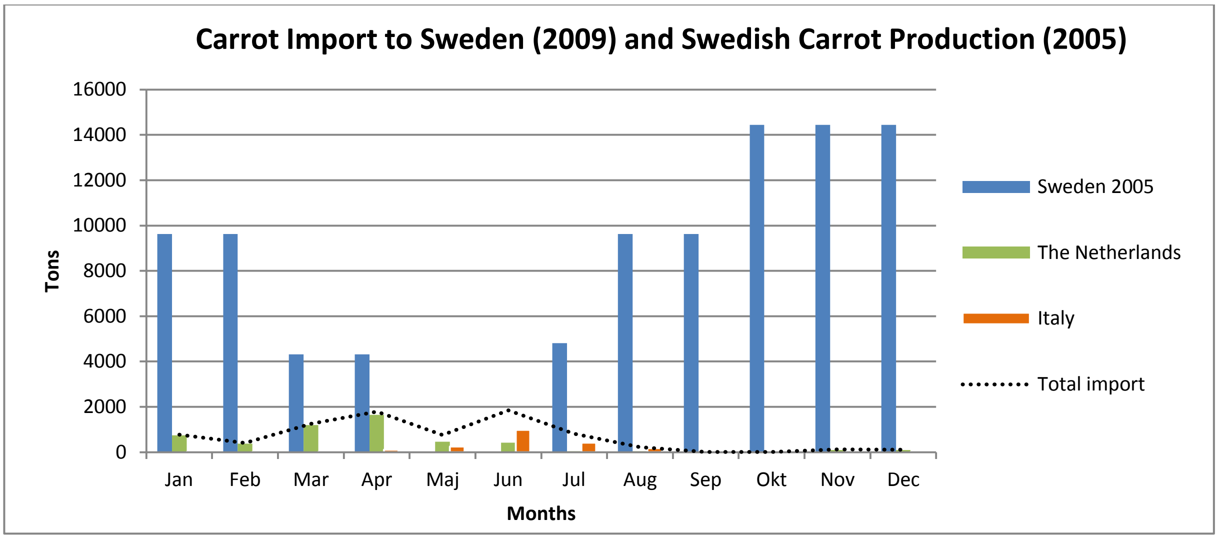

Figure 5. Carrot import to Sweden 2009, country of origin (SCB, 2009) and Swedish carrot production 2005 (SJV, 2009b)

2.3.2 REPRESENTATIVE TECHNIQUES

TOMATOES

THE NETHERLANDS (THE NLH SCENARIO)

In Dutch greenhouse horticulture for tomato production the greenhouses are heated and hydroponic systems are used (P. Vermeulen, pers. comm., 2011). In the Netherlands it is common that greenhouses are heated with natural gas. The share of renewable energy sources is low, only 1.3%, although geothermal energy and biofuels have shown some increase during recent years. (van der Velden & Smit, 2010) Nevertheless, a technology that is common for larger greenhouses (>2 ha) is the so called combined heat and power (CHP) technology, which generates electricity and thermal energy in a natural gas furnace (P. Vermeulen, pers. comm., 2011). As the average greenhouse size in the Netherlands was 4.5ha in 2009 (Statistics Netherlands, 2010), CHP was assumed to be used in the production scenario. Using this technology, the greenhouse horticulture sector in the Netherlands produces electricity for the national grid corresponding to 10% of the national consumption of electricity (van der Velden & Smit, 2010). Around 60% of Dutch tomato production is located in the region Westland (west of the Rotterdam) (Terhorst, 2006).

SPAIN (THE ESS SCENARIO)

Tomato production methods are more diverse in Spain compared to the Netherlands and Sweden (Möller Nielsen, 2008). Spain produces tomatoes both for fresh consumption and for further processing into canned tomatoes or tomato paste. Tomatoes for fresh consumption are mainly produced in southeast Spain, in the area of Valencia, Murcia and parts of Andalucía. (ESYRCE, 2010 & Tello, 2002) The majority of the production that is sold as fresh tomatoes is produced in greenhouses, although a large part is also grown in irrigated, open fields (ESYRCE, 2010). Although there are greenhouses similar to the highly controlled hydroponic greenhouse systems utilized in the Netherlands and Sweden, the majority of the greenhouses in Spain are characterized by a less controlled and less intensive cropping system (Baille, year unknown). Normally no climate control is used (Tello, 2002). Of the total fresh tomato export from Spain, around 30% comes from Almería, around 23% from Murcia, which are is two neighboring regions in southeast Spain. The remaining export comes mainly from the Canary Islands. (van der Velden et al. 2004) Almería has the highest concentration of plastic greenhouses in Europe (Theurl, 2008). In Almería approximately 80% of the cultivation occurs in soil (Thompson et al., 2007).

SWEDEN (THE SEH SCENARIO)

In Sweden, as in other parts of northern Europe, commercial tomato production occurs in heated greenhouses and only 1.9% of the greenhouse area for tomatoes is unheated producing only 0.4% of the total production (Möller Nielsen, 2008). In 2009 69% of all tomatoes produced in Sweden were produced in Skåne (SJV, 2009b) in southern Sweden. During recent years there has been a shift from fossil fuels to non-fossil fuels for heating in Swedish tomato production. In 2009, 76.7% of the greenhouse area for tomato production was heated with renewable energy sources and woodchips are the dominate energy source. (Möller Nielsen, 2009)

CARROTS

SWEDEN (THE SEC SCENARIO)

The region Skåne has the largest share of total national production of carrots in Sweden (37% of total production in 2008) (SJV, 2009b). More than two thirds of the carrot production occurs in non- humus soils (Ö. Berglund pers. comm., 2011).

IMPORTED CARROTS (THE IC SCENARIO)

Carrot import from the two main import countries, the Netherlands and Italy, were considered. Production techniques were assumed be similar to the techniques used in Sweden in both the Netherlands and Italy, which implies open field production in non-humus soils.

2.3.3 HARVEST SEASONS

TOMATOES

Figure 6 shows the harvest seasons. In the Netherlands tomatoes are harvested from March to December (P. Vermeulen pers. comm., 2011). In southern Spain tomatoes are grown either from August to January (the short growing season) or from August to May and June (the long growing season) (Möller Nilesen, 2008 & Theurl, 2008). In this study the longer growing season was considered and tomatoes are then harvested from October to June (Thompson et al. 2007). In heated greenhouses in Sweden the first tomatoes can be harvested in April and the harvest season continues to mid-November (Möller Nielsen, 2008; Informant 1; 2 pers. comm., 2011). In an unheated greenhouse in Sweden tomatoes can be harvested from late July to mid-October (Informant 3 pers. comm., 2011).

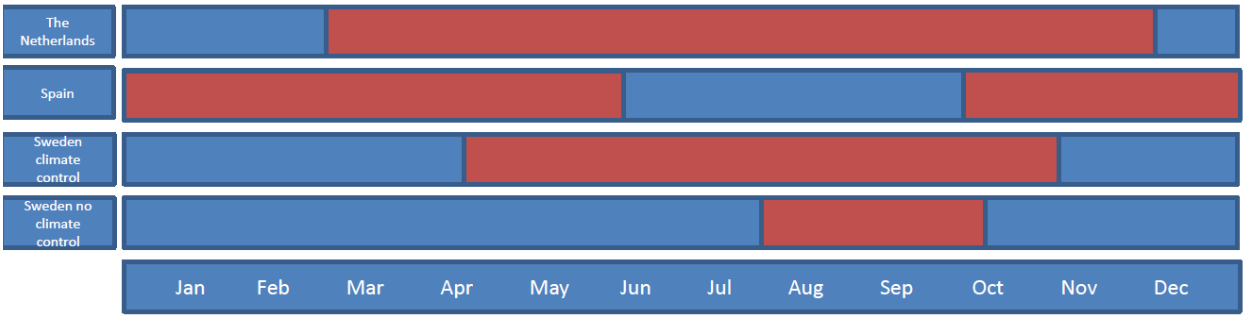

Figure 6. Harvest seasons for tomatoes in the Netherlands, Spain and Sweden

CARROTS

Swedish carrots are sown in March to mid-June and harvested from early July to late October. During autumn and winter the carrots are stored either at the farm or at a wholesaler. (Fuentes & Carlsson-Kanyama, (Eds.) 2006; P-O Nilsson, pers. comm., 2011) In the Netherlands carrots are harvested from mid-June until November (Fuentes & Carlsson-Kanyama, (Eds.) 2006). In southern Italy carrots are harvested from March to April, although the harvest season starts later in north Italy and goes on until late winter. (Terra SLR, 2011)

2.3.4 DATA COLLECTION FOR TOMATOES

ENERGY FOR HEATING AND ELECTRICITY USE

Natural gas and CHP were assumed to be used in the NLH scenario. Divided by square meter greenhouse area the CHP furnace generates 767 MJ and the greenhouse consumes 36 MJ per square meter, leaving approximately 730 MJ which is delivered to the electrical grid (P. Vermeulen, pers. comm., 2011). Woodchips were chosen as the main energy source in the SEH scenario. Many producers use natural gas or oil during the peak demand seasons, such as, the coldest period of the year (Informant 1; 2, pers. comm., 2011); therefore, a small amount of natural gas was used in the SEH scenario. The electricity use in the ESS scenario is primarily for irrigation management (van der Velden et al. 2004) and the same electricity use was assumed in the SEU scenario.

Table 9. Energy use per square meter in the Dutch, Spanish and Swedish tomato production. CHP is assumed to be used in the Netherlands which explains the Dutch negative electricity consumption.

Country and production scenario	Woodchips	Natural gas	Electricity (national mix)
The Netherlands (NLH)		**2500 MJ***	**-730 MJ***
Spain (ESS)			**3.6 MJ°**
Sweden (SEH)	**1400 MJ ˘**	**51 MJ ˘**	**56 MJ ˘**
Sweden unheated (SEU)			**3.6 MJ˜**

*P. Vermeulen, pers. comm. (2011) $71.6m^3$ natural m^{2-} greenhouse area assuming energy content of natural gas to be 35.17 $MJ*m^{-3}$

° van der Velden et al. (2004)

˘ Informant 2, pers. comm. (2011)

˜Assumed to be the same as in Spanish unheated greenhouses

CO$_2$-FERTILIZATION

CO$_2$-fertilization was assumed to be used in the heated greenhouses scenarios NLH and SEH. The natural gas used in these scenarios is partly utilized for producing CO$_2$. It is common practice in intensive tomato production to use CO$_2$ in the greenhouse to compensate for CO$_2$ consumed by the plants during growth. (Möller Nielsen, 2008) Some greenhouses in Spain also use CO$_2$-fertilization, although not in plastic greenhouses such as the Parral (Castilla & Montero, 2008), which was considered in this study.

YIELDS

The yields considered in the tomato production scenarios are shown in *Table 10.* The tomato yields used were based on figures for the common high yielding variety usually called round or globe tomatoes, hereafter referred to as globe tomatoes. Globe tomatoes are higher yielding than smaller varieties, such as, cocktail tomatoes. In northern European heated greenhouses, yields are approximately 50-60 kg per square meter for globe tomatoes and 25 kg for smaller varieties (Möller Nielsen, 2008). Low yielding varieties have substantially higher environmental impact, since the inputs per square meter greenhouse in the form of energy for heating, electricity etc. are nearly independent of the tomato variety grown. National average yields are lower than the yields used in this analysis since average national yields are based on total yields and total greenhouse areas including the low yielding varieties.

Table 10. The tomato yields for globe tomatoes.

Country and production scenario	Yield $kg*m^{-2}$
The Netherlands (NLH)	62*
Spain (ESS)	14°
Sweden (SEH)	57 ˘
Sweden (SEU)	11 ˜

* P. Vermeulen, 2011 pers. comm.

° Castilla & Hernandez (2005)

˘ Informant 2 greenhouse manager, pers. comm. (2011)

˜ Informant 3 greenhouse manager, pers. comm. (2011)

GROWING SUBSTRATE

Rockwool is a common growing substrate in greenhouse horticulture in both Sweden (Jansson, 2010) and the Netherlands (Badgery-Parker, 2001) and was assumed to be used in the scenarios NLH and SEH. The production of growing substrate was included in the analysis. The Rockwool blocks used are 120 cm by 20 cm by 7.5 cm (Informant 2, pers. comm. 2011). Additionally, the tomatoes are grown in 7.5 cm by 7.5 cm by 6.5 cm cubes (Theurl, 2008). Approximately 3937 blocks are used per hectare and 3 cubes per block. The density of the Rockwool blocks and cubes are 48 kg per cubic meter and 73 kg per cubic meter, respectively (Theurl, 2008). This gives a weight of rockwool per greenhouse square meter of 0.37 kg. Rockwool is often recycled after use, for instance, in Sweden Rockwool is recycled in Denmark (Odense) into insulation material and in other countries Rockwool from the horticultural industry may be recycled into house bricks (S. Lambie, pers. comm., 2011). Waste treatment or recycling of growing substrate were not included in this study. In the ESS scenario the tomatoes were assumed to be cultivated in soil, which is the most common practice in Almería (Thompson et al., 2007). Growing substrate in the SEU scenario was assumed to be a perlite, which is a common horticultural growing substrate that allows reuse for several years. A reusable growing substrate was assumed to be suitable for the low productive, unheated greenhouses (Informant 3, pers. comm., 2011). Perlite can be reused for 7 years and 15 liters are required per square meter (assuming a plant density of around 1.6 plants per square meter) (Informant 1, pers. comm. 2011). Perlite has a density of 0.09 kg per liter (Bara mineraler, 2011). This gives (15*0.09)/7= 0.195 kg per square meter per year. The transportation of growing substrate was not included in any of the scenarios. The contribution of transportation of growing substrate to the final results was assumed to be low (see for example: EUPHOROS, 2007).

Fertilizer Use

All the greenhouse scenarios were assumed to use drip irrigation with a nutrient solution called fertigation, which is the dominate method in tomato production in the Netherlands, Spain and Sweden. *Table 11* shows the fertilizer rates considered in the different scenarios. Calculations of fertilizer demand in the SEU scenario were related to yield. Since the yield in the unheated system is only 20% of that in the SEH scenario, the assumption was made that the fertilizer demand is 20% of that in the heated system.

Table 11. Fertilizer use per square meter in the tomato production scenarios.

Country and production scenario	**g N*m^{-2}**	**g P*m^{-2}**	**g K*m^{-2}**
The Netherlands (NLH) *	160	16	140
Spain (ESS)°	75	14	120
Sweden (SEH)˘	170	47	290
Sweden (SEU)˜	34	9.5	57

* P. Vermeulen, pers. comm. (2011)

° Theurl (2008)

˘ Informant 2 greenhouse manager, pers. comm. (2011)

˜ Own calculations (20% of the fertilizer use in the SEH scenario)

Pesticide Use

The pesticide use included in the analyzed scenarios is shown in *Table 12*. Pesticide use is the highest in Spain, mainly due to the lack of both biological protection methods, as well as, climate and humidity control (van der Velden, 2004). The reason why pesticide use is the lowest in Sweden could be that there are no areas in Sweden with a high density of greenhouses (as there are in the Netherlands and Spain). The low density of greenhouses limits the spread of disease between greenhouses. The time period in Swedish greenhouses when the greenhouse is empty of plants is also longer and the climate is colder, when compared to the Netherlands, which could be other explanations for the lower pesticide use. (Informant 2, pers. comm., 2011) It was assumed that the SEU scenario uses the same quantities of pesticides as the SEH scenario. This might underestimate the pesticide use, because unheated systems lack climate control, which increase pest risks and consequently the demand for pesticides. On the other hand, the following factors may decrease the pest risk: production is less intensive, the greenhouse is empty for a long period during winter and biological control is possible. The impacts on toxicity from pesticide use were not included, but the resource and energy use in the production of pesticides were included in the analysis.

Table 12. Pesticide use in the analyzed tomato production scenarios in active substance.

Country and production scenario	**Insecticide g*m^{-2}**	**Fungicide g*m^{-2}**	**Total g*m^{-2}**
The Netherlands (NLH) *	0.3	0.7	1
Spain (ESS)°	0.51	2.1	2.6
Sweden (SEH)˘	0.09	0.14	0.23
Sweden (SEU)˜	0.09	0.14	0.23

* EUPHOROS, 2007

° van der Velden et al. (2004)

˘ Informant 2, pers. comm. (2011)

˜ Assumed to be the same as in the Swedish heated greenhouse

Energy Demand for Tomato Seedlings

The energy demand for producing tomato seedlings in the NLH and SEH scenarios was included. The seedlings were assumed to be produced in the Netherlands for both the NLH and SEH scenarios. However, the greenhouse construction, fertilizer demand, capital goods and transportation of seedlings from the Netherlands to the production sites in the Netherlands and Sweden were not included. The tomato seedlings for the ESS scenarios were assumed to be produced in unheated greenhouses so the environmental impact of these seedlings was not included. Likewise, the seedling impact is disregarded for the SEU scenario.

A tomato producer generally buys tomato seedlings from specialized seedling producers. Tomato seedlings delivered to Swedish and Dutch tomato producers are normally grown for at least six weeks in nurseries before delivery. The plant density in the nursery depends on the age of the plants and varies between 100 plants per square meter the first week and four plants per square meter the eighth week. Consequently, energy demand varies depending on the time spent in the nursery and the plant density. Energy demand also varies with season because energy demand for heating and electricity for artificial lighting varies throughout the year. (J Boeters pers. comm., 2011) The energy demand for heating nursery greenhouses was assumed to be identical to a tomato producing greenhouse without CHP. Thus, the energy demand for heating and electricity are 1260 MJ and 360 MJ (P. Vermulen pers. comm., 2011). The energy and electricity demand for one tomato seedling was based on how many weeks the plant spends in the nursery and average plant density from week one to week six in the nursery. The plant density in the nursery was estimated from the values given by J. Boeters (pers. comm., 2011) and interpolated to obtain the density for each week. *Table 13* shows the plant density in the tomato production greenhouses.

Table 13. Plant density in the greenhouses.

Country and production scenario	Plants*m-^{2}	Number of weeks in nursery
The Netherlands (NLH)	2.5 *	6 ˜
Sweden (SEH)	1.6 ˘	6 ˜

* P. Vermulen pers. comm. 2011
˘ Informant 2 greenhouse manager, pers. comm. 2011
˜ J. Boeters pers. comm. 2011

Greenhouse Structure in the Netherlands and Sweden

The material requirements for the greenhouse structure were assumed to be identical for the scenarios NLH, SEH and SEU. The quantities of materials and material flows considered are shown in *Table 14*. The emissions related to waste treatment and recycling of the greenhouse structure were not included. Other equipment that is used in greenhouses, such as the furnace, additional buildings, sorting equipment, buildings for workers (locker rooms etc.), tanks for irrigation water, irrigation equipment etc. were not included.

Table 14. Materials considered in the greenhouse structure in Sweden and the Netherlands.

Material	kg* ha^{-1}	kg m^{-2}	Annual flow (kg*year^{-1})	Lifetime (years)
Steel*	110,000	11	11/40	40 ˚
Aluminum*	25,000	2.5	2.5/40	40 ˚
Glass*	130,000	13	13/40	40 ˚
Concrete*	504,064	50	50/40	40 ˚

* Theurl (2008)
˚ Informant 2 greenhouse manager, pers. comm. 2011

Greenhouse Structure (Parral) in Spain

The greenhouses type that is most common in Almería is called Parral. It consists of a metal or wooden structure covered with plastic roofs and walls. (Tello, 2002 & Möller Nielsen, 2008) Material use, annual flow and lifetime accounted for in the ESS scenarios are shown in *Table 15*. Other equipment, materials used and waste treatment and recycling in the greenhouse were not considered.

Table 15. Materials used in the construction of Parrals.

Material	kg* ha^{-1}	kg m^{-2}	Annual flow (kg*$year^{-1}$)	Lifetime (years)
Steel*	4,600	0.46	0.46/15	15
Wood*	360,000	36	36/10	10
Plastic film*	2,600	0.26	0.26/1.5	1.5
Concrete*	96,000	9.6	9.6/15	15

*Theurl (2008)

EMISSIONS FROM FERTILIZER APPLICATION

All direct nitrogen losses are presented in *Table 16*. For calculations see: *Appendix E. Nitrogen Balances and Indirect Emissions* for Tomatoes.

THE NLH, SEH AND SEU SCENARIOS

In the Netherlands recycling of drainage water is compulsory although leaching some drainage water is allowed when high concentrations of salts have accumulated in the system (Stanghellini et al., 2005). About 75% of all greenhouses in Sweden are currently recirculating their drainage water (I. Christensen pers. comm, 2011). Therefore no nutrient leaching was accounted for in the NLH, SEH and SEU scenarios since these scenarios were assumed to be closed systems, which means that the drainage water is recirculated. N_2O emissions (to the atmosphere) from N-fertilization in hydroponic closed systems were estimated to be 1% of the applied nitrogen (Mostier et al., 1998). Other nitrogen losses also occur primarily in the form of N_2 (Daum & Schenk, 1996).

THE ESS SCENARIO

For tomato production in soil in the ESS scenario volatilization, denitrification, nitrate leaching and indirect emissions (from deposition of volatilized nitrogen and nitrate leaching) were accounted for. Volatilization and denitrification are estimated in accordance with Brentrup et al. (2000). The sources for all equations and emission factors are Brentrup et al. (2000: Tables 7 and 8) and IPCC (2006). Nitrate leaching was estimated with a nitrogen balance and values from the literature (Thompson et al. 2002 and Va´zquez et al. 2006). In Almería the soil is often soaked before the next cropping season in order to drain salts that have accumulated in the soil during the last cropping season. This, in combination with intensive irrigation, results in high risk of nitrate leaching (Thompson et al., 2007). High concentrations of mineral nitrate below the root zone have been found by Thompson et al., (2002), which indicates high risk of nitrate leaching. Therefore, all remaining nitrogen in the soil after harvest and removal of crops was assumed to be leached.

Indirect emissions (IPCC, 2006) of N_2O was estimated to 1.8 kg N_2O-N*ha^{-1} in the ESS scenario.

Table 16. Direct emissions of nitrogen compounds from fertilizer application.

Country and production scenario	Volatalization kg NH_3-N*ha^{-1}	Denitrification kg N_2O-N*ha^{-1}	Nitrate leaching NO_3-N *ha^{-1}
The Netherlands(NLH)	-	16	-
Spain (ESS)	23	7.3	200
Sweden (SEH)	-	17	-
Sweden (SEU)	-	3.4	-

2.3.5 DATA COLLECTION FOR CARROTS

Inventory analysis on imported carrots was made with the Swedish scenario as a basis. The assumption was that the technology for growing carrots in the countries that export carrots to Sweden is similar to the Swedish cropping system. Imported carrots are mainly imported from the Netherlands and Italy. No other countries exporting carrots to Sweden have a higher share than 5% of the import. (SCB, 2009) Therefore, it was assumed that 100% of the carrot import comes from the Netherlands and Italy, with 72% from the Netherlands and 28% from Italy.

YIELDS

Carrot yields were estimated from the average national carrot yields for 2005-2009 (*Table 17)*. For all the carrot production scenarios, ITC, NLC and SEC yields were assumed to be 46, 61 and 56 tons per hectare.

Table 17. Carrot yields.

Country and production scenario	Carrot yield ton*ha^{-1}
Italy (ITC)	46*
The Netherlands (NLC)	61˚
Sweden (SEC)	56˘

*FAOSTAT (2011)
˚FAOSTAT (2011)
˘SJV (2010)

FIELD OPERATIONS

Field operations were assumed to be the same for the ITC, NLC and SEC scenarios. The number of field operations was assumed to be twelve, including plowing, harrowing, application of fertilizers and plant protection and harvesting, etc. The distance from field to farm was estimated to be two km. (I. Christensen pers. comm., 2011) Total diesel consumption per hectare including transportation from field to storage facilities was estimated to 196.2 kg (approximately 240 liters with a density of 0.81 kg per liter (Lindgren et al., 2002)). Production of agricultural machinery and sheds for the machinery were included.

PESTICIDE USE

Pesticide use in carrot cultivation was taken from the Swedish national average. The data is from a survey considering 1 630 hectares carrot cultivation in Sweden, concerning the cropping season 2005/2006 (SJV, 2008).

Table 18. Pesticide use for carrots.

Country and production scenario	Insecticide kg*ha^{-1}	Herbicides kg*ha^{-1}	Fungicide kg*ha^{-1}	Total kg*ha^{-1}
Sweden (SEC) *	0.21	1.7	0.40	2.3

*SJV, 2008

Pesticide use was assumed to be the same in NLC, ITC and SEC. This assumption is simplified and most likely not correct. It can be made because pesticide production and use are not significant contributors to the impact categories considered in this study. It should be noted, however, that herbicide and pesticide use in vegetable crops like carrots is high, as compared to cereals. If other impact categories were considered, such as toxicity, then any difference between the countries in pesticide use would probably have more significant impact. (see Antón et al. 2005 for impact of pesticide use in Spanish greenhouse horticulture) The impacts on toxicity from pesticide use were not included in the analysis, but the resource and energy use in the production of pesticides was included.

FERTILIZATION AND RELATED EMISSIONS

Nitrogen fertilization rates for carrots in southern Sweden ranges from 100-150 kg nitrogen fertilizer depending on if the carrots are harvested early or late in the season (S. Andersson, pers. comm., 2011). For the SEC scenario, 125 kg nitrogen fertilizers per hectare were assumed to be used. The application rates of phosphorous and potassium were taken from fertilizer recommendations (Hydro, 2003). The amounts of applied fertilizer for the ITC and the NLC scenario were estimated by relating fertilizer rates to national average yields.

Table 19. Fertilizer use for carrots.

Country and production scenario	N kg*ha^{-1}	P kg*ha^{-1}	K kg*ha^{-1}
Italy (ITC) *	100	37	160
The Netherlands (NLC) ˚	140	49	220
Sweden (SEC)	130˘	45˜	200˜

*Assumed to be related to average national yield

˚ Assumed to be related to average national yield

˘ S. Andersson, 2011, pers. comm.

˜Hydro, 2003

Nitrogen Balance for Carrot Production

Volatilization and denitrification were estimated in accordance with Brentrup et al. (2000). All equation and emission factors were taken from Brentrup et al. (2000 Tables 7 and 8) and IPCC (2006). For specific calculations and data sources see: Appendix F. Nitrogen Balances and Indirect Emissions for Carrots.

Nutrient leaching

The rate of nutrients leached from fields depends on multiple factors, such as soil type, precipitation, management and erosion rates, etc. Many of these factors were not known in this study, therefore, nitrate leaching was estimated with a nitrogen balance in combination with values from literature. Nitrate leaching was estimated to be 40.5% of the remaining nitrogen in the soil, based on Breeuwasma et al., (1987) in Audsley et al., (1997). The figure is for Dutch conditions on sandy soil. For nitrogen balances and specific calculations see Appendix F. Nitrogen Balances and Indirect Emissions for Carrots. Leaching of other nutrients such as phosphate was not accounted for in this study.

Table 20. Included volatilization, denitrification and nitrate leaching for all carrot production scenarios.

Country and production scenario	Volatalization kg NH_3-N*ha^{-1}	Direct N_2O kg N_2O-N*ha^{-1}	Nitrate leaching NO_3-N *ha^{-1}
Italy (ITC)	2.0	1.0	13
The Netherlands (NLC)	2.7	1.3	19
Sweden (SEC)	1.3	1.2	16

All indirect emissions were estimated using IPCC (2006) standards. For a more detailed presentation of how the values were calculated see Appendix E.

Table 21. Indirect N_2O emissions for all the carrot production scenarios.

Country and production scenario	Indirect* kg N_2O-N*ha^{-1}	Crop residues kg N*ha^{-1}	N_2O $_{\text{crop residues}}$ kg N_2O-N*ha^{-1}	Total N_2O kg N_2O-N*ha^{-1}
Italy (ITC)	0.12	75	0.75	0.87
The Netherlands (NLC)˚	0.17	88	0.88	1.05
Sweden (SEC)	0.13	84	0.84	0.97

* Indirect emissions from nitrate leaching and volatilization

Harvest and Storage Losses

Harvest and storage losses were calculated as the total harvest loss plus the average storage loss during the storage period. Harvest and storage losses were assumed to be the same for all carrot production scenarios, depending on storage time. The figures on storage losses include the proportion of the harvest that is sold as fodder carrots. Interviews confirm that little of the harvest is thrown away in Sweden. A great proportion of the loss is actually sold as fodder carrots for livestock or horses. The reasons why relatively high proportions of carrots are often sold as fodder carrots are the high quality and the esthetic demands from retailers and consumers (I. Marmolin and P-O. Nilsson pers. comm., 2011). In this study, all harvest and storage losses were handled as actual losses, because of uncertainties when it comes to quantifying lost amounts and amounts that are sold as fodder.

The storage and harvest losses were an important parameter in this study, because it affects the output of the production scenarios. However, as can be seen in *Figure 7*, the effects of storage and harvest losses do not affect the ranking of the results from the production scenarios. For the ITC, NLC and SEC scenarios 11%, 16% and 19% harvest and storage losses were used in the analysis. For ITC and NLC, transportation is an important contributor to global warming potential and transportation is independent of yield. For a further discussion of the affect harvest and storage losses have on other impact categories see Appendix G. The Importance of Harvest and Storage Losses for the Results of the Carrot- LCA.

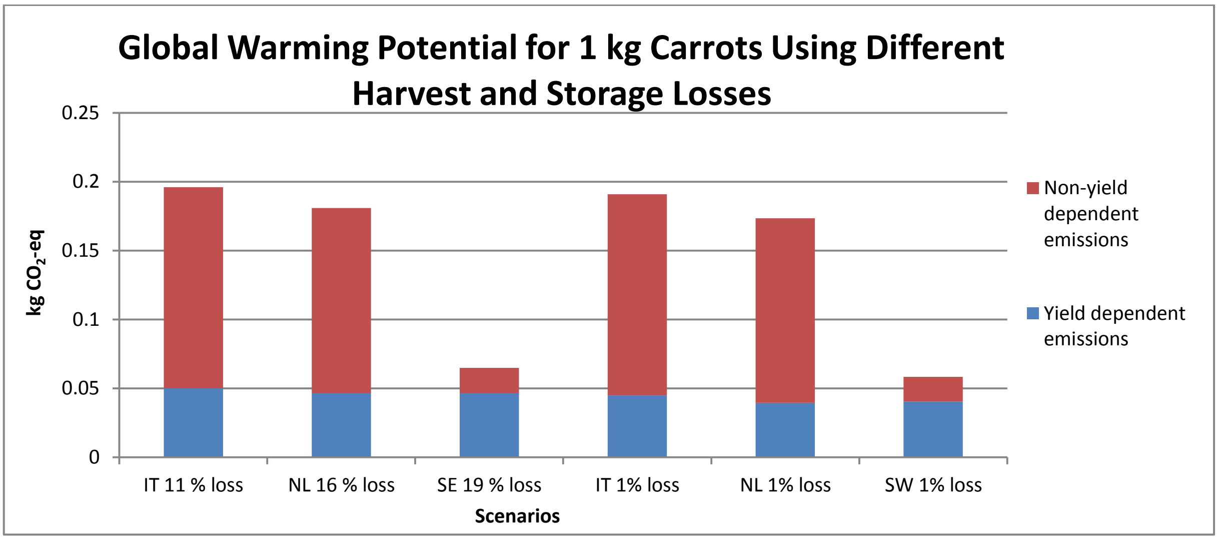

Figure 7. Variation analysis of the impact of harvest and storage losses, global warming potential.

ESTIMATED HARVEST AND STORAGE LOSSES

For the SEC scenario, the losses, including the proportion that is sold as fodder carrots, were assumed to be 11% from July to September. After that the losses were assumed to increase by month until the end of April, (when most carrots are finished in the Swedish storing facilities) with a 30% loss (own estimations based on I. Marmolin and P-O. Nilsson pers. comm., 2011). The average loss from harvest to April was calculated to be 19%, which is similar to the estimated loss in Carlsson-Kanyama (1997), who estimated the losses to be 20% from farm to wholesaler in Swedish conditions. *Figure 8* shows how storage losses in chilled storage are estimated to increase by storage time. In the SEC scenario month 0 is September, month 1 October, etc. The same model was applied to the NLC scenario; although harvest season is expected to end in November (November is month 0).

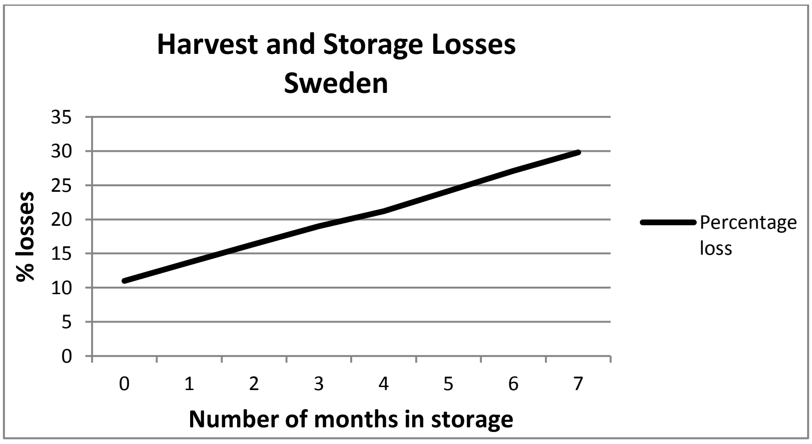

Figure 8. Percentage of harvest that was assumed to be lost or sold as fodder carrots.

In the ITC scenario, 11% was assumed to be lost during harvest, based on the Swedish figures of harvest losses. Carrots from Italy are mainly imported from April to August (99% of the total carrot import from Italy is imported during these months (SCB, 2009)). Since carrots are harvested in Italy from March through April, only a short storage period of ten days was assumed for the ITC scenario. Carrots from the Netherlands are mainly imported from January to April (SCB, 2009). In the Netherlands carrots are harvested until November, therefore, an average storage time of two months was accounted for for the NLC scenario. The average harvest and storage loss was assumed to be 16%, based on figures of harvest and storage losses in Sweden. Swedish carrots are stored from September to October and from March to April, therefore, a storage period of three months was accounted for and the average storage and harvest loss was estimated to be 19% for the SEC scenario.

STORAGE BUILDINGS

Storage buildings were included in this study. To store the yield from one hectare it was assumed that 16 square meters are required (own calculations, based on Röös, 2009). The lifetime of the storage building was assumed to be 50 years.

ENERGY CONSUMPTION FOR COOLING AND STORAGE

In southern Sweden carrots can be stored in the soil on the field or in refrigerated storing facilities. Around one - third of the carrot production in Skåne is stored in the soil. However, this storing technique is not a common practice in the rest of the country due to climatic conditions and soil type. (P-O Nilsson. pers. comm., 2011) Therefore, it was assumed for the SEC scenario that the carrot harvest was stored in refrigerated storing facilities, as it is a more common storage technique in both Skåne and the rest of Sweden. After harvest, the carrots from all carrot production scenarios were assumed to be cooled to at least 4˚C. The average storage time for all the production scenarios was accounted for as explained above: ten days, two months and three months for the ITC, NLC and SEC.

Table 22. Energy requirements for cooling and storage for carrots.

Country of production	Energy requirements for cooling and storage
Italy (ITC)	
Cooling	0.056 MJ*
Storage (10 days, short term storage)	0.16 MJ˚
Total	**0.22 MJ**
The Netherlands (NLC)	
Cooling	0.054*
Storage (two months)	0.21 MJ˘
Total	**0.26 MJ**
Sweden (SEC)	
Cooling	0.057 MJ˜
Storage (three months)	0.31 MJ˜
Total	**0.37 MJ**

*Carlsson-Kanyama (1997)

˚Own calculations based on short term cooled storage Carlsson-Kanyama (1997) (Table 27)

˘Long term storage, assumed to be the same as in Sweden, although average storage time was estimated to be two months

˜Own calculation based on information from I Marmolin, pers. comm. (2011)

2.3.6 TRANSPORTATION OF TOMATOES AND CARROTS FROM PRODUCTION SITE TO WHOLESALER

Most transportation was assumed to be with trucks that load 22 tons. Italian carrots were assumed to be transported to Sweden partly by train and transportation from the Netherlands was assumed to be partly by ferry. All transportation was assumed to be refrigerated. (Nowaste, pers. comm., 2011; Everfresh pers. comm., 2011) Return routes were not considered as transportation networks are complex and within the scope of this study it is not possible to map the transportation routes in detail. The additional fuel consumption during refrigerated transportation, as well as, leakage of refrigerants was included. Energy demand for refrigeration is related to operation time. The extra energy demand was estimated to be 3.1 l diesel per hour and leakage of refrigerants was assed to equal a global warming potential of 0.3 l diesel combustion per hour of operation (Winter et al., 2009). In Winter et al. (2009) the extra energy demand and refrigerant leakage is calculated based on a cooling to 0 degrees Celsius. Tomatoes and carrots require less cooling: around + 1-3˚ C for carrots and 11-14 ˚ C for tomatoes (Nowaste, pers. comm. 2011). The figures from Winter et al. (2009) were used as an indication of the contribution of refrigerated transportation. Tomatoes and carrots from the Netherlands were assumed to be produced in the Westland region and transported from the city Naaldwijk. Tomatoes produced in Almería, Spain were assumed to be transported from the city Almería. Tomatoes and carrots produced in Sweden were assumed to be transported from Höör, which is a town in the middle of Skåne. Carrots from Italy were assumed to be transported from Rome to Sweden (Carlsson-Kanyama, 1997). The carrots travel by truck from Rome to Verona (Italy), by train from Verona to Kolding (Denmark) and from there to Helsingborg (Sweden) by truck. The end station for all products was Helsingborg, where many retailer chains have their national wholesalers.

The transportation distances by truck were estimated with online route calculators www.maps.google.com and www.viamichelin.com. Distance by train was estimated with online route calculator www.ecotransit.org and distance by ferry with http://e-ships.net/dist.htm.

Table 23. Transportation of tomatoes and carrots, from production site to wholesaler in Helsingborg.

Country of Production	To wholesaler in Sweden	Operation time	Vehicle
The Netherlands	911 km (222kmferry, 689km lorry)	24 h *	Truck and ferry
Spain	3,015 km	120 h *	Truck
Sweden	75 km	1 h 8 min	Truck
Italy	2,301 (1,467 km train, 834 km lorry)	48 h* train 9 h 5 min Truck	Train and Truck

* Nowaste, pers. comm. (2011)

3. RESULTS (INTERPRETATION)

3.1 SEASONAL CONSUMER HABITS

Figure 9 shows the results for all consumer habits (A-D). Habit B, Swedish season with unheated greenhouse production and shorter transportation distance, had the lowest impact for the impact categories global warming potential, fossil fuel depletion and acidification potential, but the highest impact on arable land use. Habit C, European season including produce from climate controlled greenhouses, had the highest impact for the impact categories global warming potential, fossil fuel depletion and acidification potential, but the lowest impact for the impact categories arable land use and eutrophication potential. Habit A, Swedish season including tomatoes from climate controlled greenhouses, had the second lowest impact for global warming potential, fossil fuel depletion and arable land use, but the second highest impact on acidification potential and eutrophication potential. Habit D, European season without climate controlled greenhouses but long transportation distance, had the highest eutrophication potential, the second highest global warming potential, fossil fuel depletion and arable land use, and the second lowest impact on acidification potential.

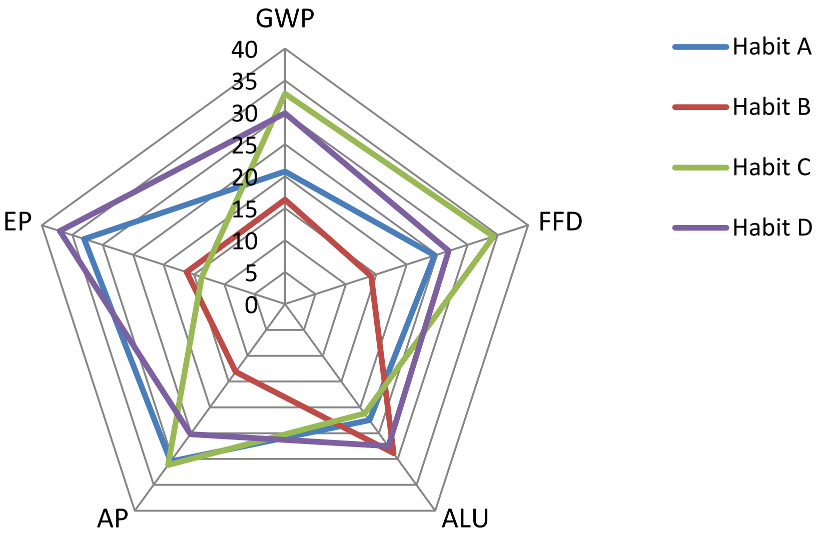

Figure 9. Results for the consumer habits. The consumer habit with the lowest impact is placed closest to the center of the diagram. GWP is Global warming potential, FFD is fossil fuel depletion, ALU is arable land use, AP is acidification potential and EP is eutrophication potential.

The importance of climate control of greenhouses and transportation of produce in percentage of total impact for each habit is shown in *Table 24*. Heating of greenhouses and electricity use in tomato production were the main contributors to the impact of Habit A and C for the impact categories global warming potential (A: 56%, C: 57%), fossil fuel depletion (A: 68%, C: 72%) and acidification potential (A: 75%, C: 63%). The type of energy source that is used for heating was significant for these impact categories. Natural gas with CHP used in the Dutch tomato production included in Habit C affects mostly global warming potential and fossil fuel depletion, however, the use of CHP decreased the impact on acidification potential and eutrophication potential. Combustion of woodchips utilized in the Swedish tomato production included in Habit A and C primarily affected acidification potential. Habit D included the longest transportation distance with 75% of the yearly tomato consumption originating from Spain and carrots were imported two months of the year. Transportation was a significant contributor to the total impact of Habit D for global warming potential (56%), fossil fuel depletion (57%) and acidification potential (45%). For Habit B, with tomatoes produced in unheated greenhouse and short transportation distance, the environmental impact was dominated by emissions from the manufacturing of greenhouse material and fertilizer production and use. Manufacturing of materials for the greenhouse construction dominated the total impact of Habit B for global warming potential (48%), fossil fuel depletion (36%) and acidification potential (51%). Fertilizer production and use was the most important contributor to eutrophication potential, with 42% of the total impact for Habit B.

Table 24. Share of the total impact from transportation of produce or heating and electricity for greenhouse tomato production.

	Habit A				**Habit B**				**Habit C**				**Habit D**			
	GWP	FFD	AP	EP	GWP	FFD	AP	EP	GWP	FFD	AP	EP	GWP	FFD	AP	EP
Transportation	4	3	2	5	6	6	3	3	13	8	12	15	56	57	45	22
Heating and electricity	56	68	75	68	3	12	2	1	57	72	63	2	5	7	18	16
Other	40	29	23	27	91	82	95	96	30	20	25	83	39	36	37	74

GWP is Global warming potential, FFD is fossil fuel depletion, ALU is arable land use, *AP is acidification potential and EP is eutrophication potential.*

The yearly consumption of tomatoes and carrots for each habit was 10.4 kg tomatoes and 9.2 kg carrots. The characterized results for all habits and the impact from tomato and carrot consumption are shown in *Table 25*. The impact from carrot consumption was similar for all habits, although the longer transportation distance of imported carrots included in consumer Habit C and D marginally affected all impact categories except arable land use. Carrot consumption contributed 12-56% (mainly between 12-29%) of the total impact for global warming potential, fossil fuel depletion, acidification potential and eutrophication potential. For the impact category arable land use, on the other hand, carrot production contributed the greatest share of the impact—between 68-92% of the total impact.

Table 25. Characterized results for the consumer habits A-D

	Production Scenario	**GWP (kg CO_2-eq)**	**Fossil fuel depletion (MJ-eq)**	**Arable land use (m^2)**	**Acidification potential (g SO_2- eq)**	**Eutrophication potential (g PO_4-eq)**
Habit A	SHE	3.1	71	0.18	30	9.8
	SEC	0.8	14	2.0	4.1	2.6
	Total	**3.9**	**85**	**2.3**	**34**	**12**
Habit B	SEU	2.3	35	0.9	11	3.5
	SEC	0.8	14	2.0	4.1	2.6
	Total	**3.1**	**49**	**3.0**	**15**	**6.1**
Habit C	SEH	2.1	47	0.1	20	6.6
	NLH	3.2	55	0.1	10	-4.3
	SEC	0.7	12	1.7	3.4	2.2
	CI	0.3	4.8	0.3	1.5	0.7
	Total	**6.2**	**120**	**2.2**	**35**	**5.1**
Habit D	SEU	0.6	8.6	0.2	2.7	0.9
	ESS	4.1	67	0.6	20	10
	SEC	0.7	12	1.7	3.4	2.2
	CI	0.3	4.8	0.3	1.5	0.7
	Total	**5.7**	**93**	**2.8**	**28**	**14**

3.1.1 GLOBAL WARMING POTENTIAL

Habit C had the highest global warming potential of 6.2 kg CO_2-eq. Half of the impact came from Dutch tomatoes where the heating of greenhouses with natural gas is the main contributor. Habit B had the lowest global warming potential of 3.1 kg CO_2-eq. Materials for greenhouse construction in the Swedish unheated greenhouse tomato production had the greatest impact. Habit A had the second lowest global warming potential of 3.4 kg CO_2-eq. Combustion of woodchips in the Swedish tomato production contributed the most. Transportation of Spanish tomatoes was the greatest contributor to Habit D, with the second highest global warming potential of 5.66 kg CO_2-eq.

Habit A and C included tomatoes produced in heated greenhouses and the impact on global warming potential from the heating of greenhouses showed to be significant even when looking at the aggregated yearly global warming potential from tomato and carrot consumption combined. 56% and 57% of the total impact for Habit A and C, was derived from heating and electricity for greenhouse tomato production (*Table 24*). However, for Habit D where 75% of the tomatoes were assumed to be produced in Spain, in unheated greenhouses during winter, the global warming potential impact from transportation distance was assessed to b even larger than the impact from the heating of greenhouses if woodchips are used for heating as in Habit A. Carrot consumption contributed to the total global warming potential with 21%, 26%, 16% and 18% for Habit A, B, C and D, respectively. Imported carrots had a higher global warming potential than Swedish carrots. Habit C and D were assumed to consume imported carrots two months of the year. The imported carrots increased the global warming potential from carrot consumption with 25%, as compared to if only Swedish carrots were consumed as in Habit A and B. Transportation time was the main contributor to the global warming potential of imported carrots with 48% of the impact. For carrots produced in Sweden fertilizer production and use was the main contributor with 54%.

3.1.2 FOSSIL FUEL DEPLETION

The heating of greenhouses and transportation of produce were the largest contributors to fossil fuel depletion. Therefore, Habit C, with natural gas used for heating in Dutch tomato production and relatively long transportation distance, had the highest fossil fuel depletion with 120 MJ-eq. Habit D had the second highest fossil fuel depletion, 93 MJ-eq, mainly due to the long transportation distance of shipping tomatoes from Spain and importing carrots. Habit A had a fossil fuel depletion of 85 MJ-eq, caused by the electricity production in Sweden which is partly based on nuclear power. Habit B had the lowest fossil fuel depletion with 49 MJ-eq because no heating was used and transportations were shorter. Carrot consumption contributed with between 17%, 29%, 14% and 18% of the total fossil fuel depletion for Habit A, B, C and D, respectively. Field operations, electricity use for storage and fertilizer production were the main contributors to the fossil fuel depletion of Swedish carrots, whereas, transportation distance dominated the impact from imported carrots.

3.1.3 ARABLE LAND USE

Carrots are lower yielding per cropped area than tomatoes. Therefore, the consumed amounts of carrots had high arable land use for all scenarios. Carrot consumption contributed to the total arable land use with 91%, 68%, 92% and 71% for Habit A, B, C and D, respectively. Tomatoes from unheated greenhouses have lower yield and consequently higher arable land use. The habits based on tomato production in unheated greenhouses, Habit B and D, had higher arable land use because of the relatively low intensive tomato production. Total arable land use for Habit B was 3.0 m^2 and Habit C had an arable land use of 2.8 m^2. Habit C had the lowest arable land use with 2.2 m^2 which was caused by the high yield in Dutch tomato production.

3.1.4 ACIDIFICATION POTENTIAL

Habit C had the highest total acidification potential with 35 g SO_2-eq, followed by the consumer Habit A with 34 g SO_2-eq. Both these consumer habits included tomatoes from Swedish heated greenhouse production, where the combustion of woodchips for heating was the main contributor to acidification potential. Combustion of fossil fuels also contributed significantly, although the impact from Dutch tomatoes was lowered as electricity production was avoided by the use of CHP. Habit B and D did not include produce from heated greenhouses, which was the main reason for the lower impact of these habits. Longer transportation distance of imported carrots and Spanish tomatoes, as well as, ammonia emissions from high fertilizer rates use on soil in Spanish tomato production were the main reasons to why Habit D (28 g SO_2-eq) had a higher acidification potential than Habit B (15 g SO_2-eq). Consumption of carrots contributed to the total acidification potential with 12%, 28%, 10% and 18% for Habit A, B, C and D, respectively. Transportation was an important factor for imported carrots. Fertilizer use and field operations contributed significantly the acidification potential for Swedish and imported carrots alike.

3.1.5 EUTROPHICATION POTENTIAL

Nitrate and phosphate leaching and emissions of nitrous oxides from combustion of woodchips and fossil fuels were the main contributors to eutrophication potential. Habit D had the highest eutrophication potential with 14 g PO_4-eq, which was mainly caused by tomatoes produced in Spain with a production method with high nitrate losses. Tomatoes produced in heated greenhouses in Sweden were the main contributors to Habit A, which had an eutrophication potential of 12 g PO_4-eq. Nitrogen oxides from combustion of woodchips was the main eutrophying substance for tomatoes produced in Swedish heated greenhouses. Habit B had the second lowest eutrophication potential of 6.1 g PO_4-eq. Fertilizer production and use was the main contributor, as well as, manufacturing of material for greenhouse construction. Habit C had the lowest eutrophication potential due to the negative impact of Dutch tomatoes. Dutch tomato production generates electricity through CHP and results in avoided Dutch electricity production. Dutch electricity production is partly based on brown coal. Waste products from the mining of brown coal cause eutrophication, which is avoided if electricity is produced from natural gas instead. Consumption of carrots contributed to the total eutrophication potential with 21%, 43%, 56% and 21% for Habit A, B, C and D, respectively. Nitrate leaching was an important contributor to the eutrophication potential of carrot production; for imported carrots the impact from transportation was significant.

3.2 CURRENT CONSUMPTION

Adapting a diet following Swedish season with unheated greenhouse production (consumer Habit B) could lower the yearly global warming potential from consumption of tomatoes and carrots from around 8 kg CO_2-eq to around 3 kg CO_2-eq (*Figure 10*). Eating tomatoes and carrots according to the Swedish harvest season with the most common production techniques, similar to Habit A, would decrease the global warming potential from around 8 kg CO_2-eq to around 4 kg CO_2-eq.

All consumer habits (A-D) were assessed to have a lower global warming potential than current consumption of tomatoes and carrots. This is because current consumption of tomatoes is mainly based on imports from the Netherlands and the Dutch tomato production scenario was the one in this study with the highest global warming potential.

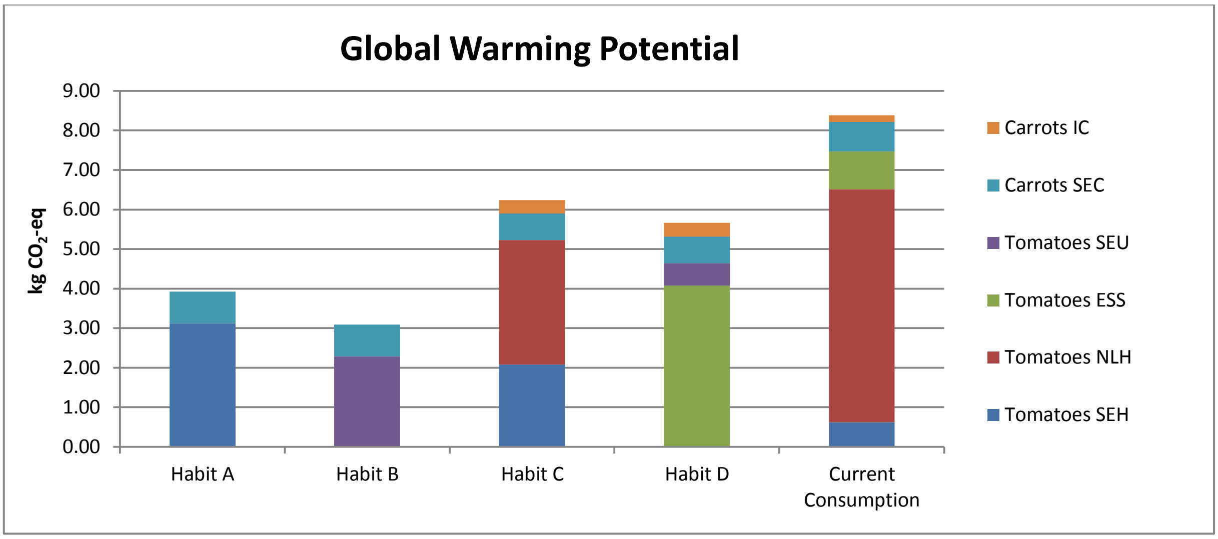

Figure 10. Global warming potential of all consumer habits (A-B) and current consumption.

3.3 PRODUCTION SCENARIOS

Table 26 presents the characterized results for the seven production scenarios and for imported carrots (CI). Carrots (ITC, NLC and SEC) had, with a few exceptions, a lower impact per kg for the impact categories global warming potential, fossil fuel depletion, acidification potential and eutrophication potential than tomatoes (SHE, SEU, NLH, ESS). For the impact category arable land use carrots had a higher impact due to lower yields. For a detailed presentation of the results of the individual production scenarios see *Appendix A. Results from Individual LCA- Tomato* and *Appendix B. Results from Individual LCA- Carrot.*

Table 26. Characterized results for the seven production scenarios and imported carrots (CI) with the functional unit 1 kg tomatoes and 1 kg carrots delivered to a wholesaler in Helsingborg, Sweden.

Production Scenario	**GWP (kg CO_2-eq)**	**Fossil fuel depletion (MJ-eq)**	**Arable land use (m^2)**	**Acidification potential (g SO_2- eq)**	**Eutrophication potential (g PO_4-eq)**
NLH (tomato)	0.9	16	0.02	2.9	-1.2
ESS (tomato)	0.5	8.6	0.08	2.6	1.3
SEH (tomato)	0.3	6.8	0.02	2.9	0.9
SEU (tomato)	0.2	3.3	0.09	1.0	0.3
ITC (carrot)	0.3	4.1	0.2	1.3	0.4
NLC (carrot)	0.2	2.8	0.2	0.9	0.6
SEC (carrot)	0.1	1.5	0.2	0.4	0.3
CI (carrot)	0.2	3.1	0.2	1.0	0.5

3.4 GLOBAL WARMING POTENTIAL FOR ALL SCENARIOS

Global warming potential for all production scenarios employed in the analysis of the habits and a number of other production scenarios with the functional unit 1 kg of tomatoes or carrots delivered to a wholesaler in Helsingborg, Sweden are presented in *Figure 11*. The scenarios included in the analysis of the habits are marked with a * in the diagram. The additional scenarios are scenarios where only one factor has been changed—such as source of heating or soil type. These scenarios are: Tomatoes produced in a greenhouse heated with a mix of energy sources representing share of energy sources used by the tomato producing sector in Sweden 2009 (Möller Nielsen, 2009). Tomatoes SE special is a scenario with special tomato varieties which often have a much lower yield (in this analysis 25 kg*m^{-2} was assumed) than globe tomatoes. The energy source for heating in this case was assumed to be woodchips and all the inputs were the same as in the SEH scenario. Carrot production on peat soils has a higher global warming potential than carrots grown on mineral soils, which can be seen in *Figure 11*.

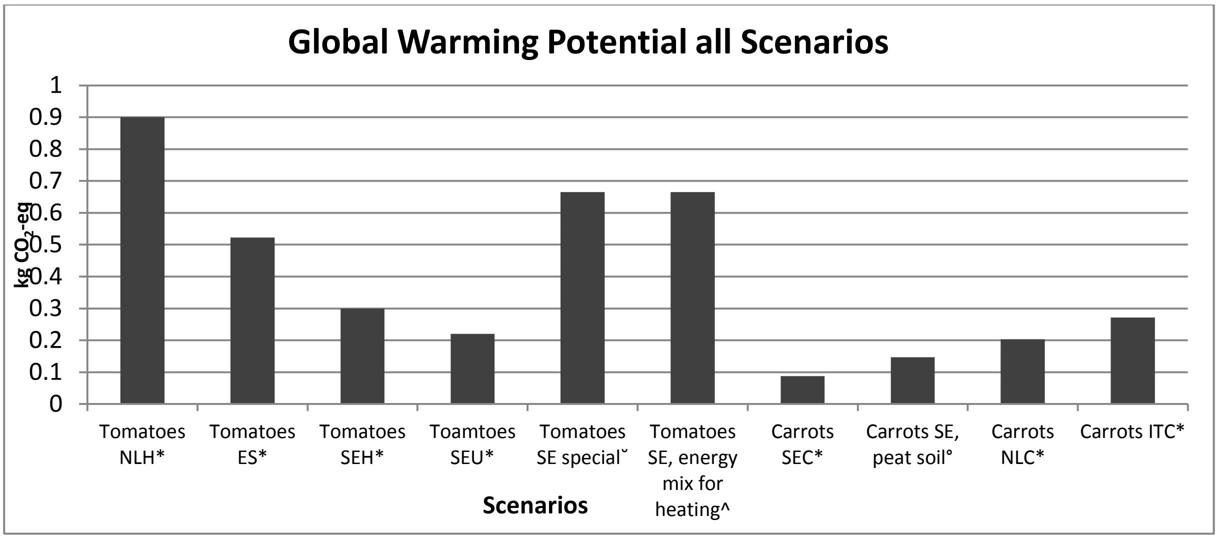

Figure 11. Global warming potential *for all tomato and carrot production scenarios, the functional unit is 1kg produce delivered to wholesaler in Helsingborg.*
**Included in the analysis of the consumer habits*
^Data about energy sources for heating from Möller Nielsen (2009) everything else being the same as for the scenario SEH
°Greenhouse gas emissions from histosols are taken from ICCP (2006)
ˇSpecial tomatoes with lower yields (25kg per square meter) produced in the similar greenhouse as the scenario SEH, (Informant 2 pers. comm. 2011).

4. DISCUSSION

4.1. ROLE OF TRANSPORTATION AND GREENHOUSE CLIMATE CONTROL

The differences in environmental impact between the consumer habits are mainly explained by the different production methods for tomatoes (climate controlled greenhouses or not), but also transportation distance from production site to Helsingborg. Climate control of greenhouses was shown to be significant for the total impact of tomato and carrot consumption for Habit A and C, and transportation was significant for the impact of Habit D. Habit A (Swedish season) and C (European season) both include produce from climate controlled greenhouses, but Habit C had higher global warming potential, fossil fuel depletion and acidification potential. Even if the longer transportation distances for tomatoes and carrots in Habit C had negative environmental impact, this impact was generally lower compared to that from natural gas use in Dutch tomato production. Studies have shown that the contribution of transportation to global warming potential of food products is generally quite low. However, for many fruits and vegetables with a relatively low global warming potential from primary production, the mode of transport and distance comprise a significant portion of the potential (Sonesson et al., 2009, Klimatmärkningen, 2010). For consumer Habit D, which had the longest transportation distance, the contribution of transportation was significant for the impact categories global warming potential, fossil fuel depletion and acidification potential. This supports the theory that transportation can be a large part of the environmental impact of vegetables when they are transported long distances. But, transportation seems to have less impact than the type of climate control. This is illustrated by comparing Habit C and D. For consumer Habit C transportation distance was shorter than for Habit D, but consumer Habit C had a higher impact for categories global warming potential, fossil fuel depletion and acidification potential. This indicates that high energy use, such as for climate control of greenhouses, could be a more important factor than the transportation distance when evaluating the environmental impact of greenhouse produced products on a European scale.

When long transportation distances and climate control of greenhouses were not present, as in Habit B (Swedish season with without climate controlled greenhouses), other factors such as the material use for greenhouses and fertilizer use proved to be more significant. Manufacturing of greenhouse structures proved to be of significant importance for the total impact of Habit B for the tomatoes produced in unheated greenhouses in Sweden. Similarly, Antón et al. (2005) have showed that the manufacture of greenhouse material and auxiliary equipment for recirculating drainage water and irrigation are significant to the environmental impact for greenhouse tomato production in Spain. Even though in the present study auxiliary equipment was not included, the greenhouse material itself proved to be a significant contributor (48% of the total impact of global warming potential) to Habit B. If auxiliary equipment was included, the impact from material use would have been higher. This indicates that for low yielding production systems, the material choice can greatly affect the environmental impact. For example, introducing recirculation of drainage water in low-yielding, unheated greenhouse tomato production could significantly increase the environmental impact from material use. Finding environmentally friendly ways to extend the cropping season would lower the environmental impact of the quantities produced by increasing the yield per square meter (and material use).

4.2 The Method to Assess Environmental Impact From Seasonal Vegetables

The seasonal consumer Habits (A-D) should be viewed as examples of how different definitions of seasonal food could be translated into actual choices made by consumers. The construction of the consumer habits in this study was unproblematic, as will be shown when analyzing Habit B. All the seasonal consumer habits consumed identical amounts of tomatoes and carrots—the amounts were allocated according to the Swedish per capita consumption (2006). This resulted in perhaps an impractical consumption pattern for Habit B, Swedish season without heated greenhouse produce, where it was assumed that neither tomatoes nor carrots was consumed during May and June and the tomato consumption for the whole year was concentrated into the three months during late summer. This concentrated consumption is due to the definition of seasonal food for Habit B where only tomatoes satisfying the definition are of limited quantity and are only available for these three months. It might be more realistic instead replace some tomato consumption with carrot consumption. Consuming more carrots and fewer tomatoes would allow a more evenly distributed vegetable consumption over the year (for Habit B). Increasing the quantity of carrots while decreasing the quantity of tomatoes in the diet would lower the impact for all impact categories except arable land use (which would increase) for all consumer habits.

This study uses representative techniques to represent the production of tomatoes and carrots for the Swedish market. The representative techniques for tomato production in the Netherlands and Sweden also symbolize recent trends within those sectors. More and more Swedish tomato producers are using biofuels (Möller Nielsen, 2008) and in the Netherlands CHP is used by most growers and the use of other techniques such as geometrical heating is small but increasing (P. Vermeulen, pers. comm., 2011). Recirculation of drainage water is also becoming more common in Sweden and is obligatory in the Netherlands. The representative technique chosen for Sweden and the Netherlands resulted in relatively low values for tomatoes produced in heated greenhouses in the scenarios NLH and SEH, which strongly affects the final results for consumer Habit A and C, specifically for the impact categories global warming potential, fossil fuel depletion and eutrophication potential. *Figure 11* displays the global warming potential of all scenarios included in this study and a few additional scenarios. Tomatoes produced in a greenhouse heated with woodchips had almost half as high an impact compared to tomatoes produced in a greenhouse heated with an mix of sources representing Swedish energy use for heating greenhouses in 2009 (Möller Nielsen, 2009). 23.3% of the greenhouse area used for tomato production in Sweden was heated with fossil fuels in 2009 (Möller Nielsen, 2009), still the effect on the global warming potential of the average tomato were assessed to be quite large. The same pattern could appear if a similar analysis was performed on the entire Dutch tomato production, including marginal production without CHP.

Carrots were assumed to be grown in mineral soils. Agricultural use of peat soils results in higher emissions of CO_2 and N_2O compared to cultivation in other soil types (Maljanen et al. 2007). Less than one third of the carrot production in Sweden is in peat soils, but the figure is only a rough approximation (Ö. Berglund pers. comm. 2011). Including the proportion of carrots grown in peat soils would primarily affect the global warming potential of the average Swedish carrot (see the difference between 1kg of carrots that are grown in peat soils and 1kg of carrots grown in mineral soils in *Figure 11*). The use of peat soils for agriculture has decreased since the 1940s (Berglund et al. 2009) and the use of peat soil for agriculture is questioned primarily due to its high greenhouse gas emissions (SJV, 2004).

Marginal techniques were not included in this study because it would be difficult to include all marginal production methods in all import countries. Nevertheless, it should be noted that marginal production methods could potentially influence the average environmental impact.

Previous comparative studies on tomato and carrot production for the Swedish market have primarily focused on the impact category global warming potential. The difference in global warming potential observed in this study where tomatoes have a higher impact than carrots is supported by these studies (Carlsson-Kanyama, 1998b and Sonesson et al. 2009). In previous studies, however, the difference in global warming potential for tomato and carrot production was even larger than found in this study. Notably, the global warming potential of tomatoes was assessed to be lower in the present study than previously assessed. The reason for this discrepancy, as discussed above, is the choice of the representative technique. Wood chips were used as the main energy source in the SEH scenario representing Swedish tomatoes produced in climate controlled greenhouses. This scenario showed a comparatively low global warming potential, which is similar to the results found by Högberg (2010) when he assesses the global warming potential of Swedish tomato production using biofuels. Another reason for the lower global warming potential of the tomatoes in this study could be that the yields used in this study were yields of high yielding tomato varieties, which decreased the total impact of the 1kg tomato functional unit. The present study, in contrast to other comparative studies on tomato and carrot production, assessed more impact categories than global warming potential. This study shows that carrots generally are environmentally preferable for all of the assessed impact categories, except arable land use, as compared to tomatoes. With the exception that tomatoes produced in unheated greenhouses in Sweden (SEU) were assessed to have an impact similar to imported carrots (IC).

The Swedish tomato production without climate control, scenario SEU, used for consumer Habit B was a hypothetical scenario that would be difficult to implement on a large scale—meaning that a transition to consumer habits more like Habit B would be problematic. Currently, greenhouses for tomato production in Sweden are often heated year-round even though there is approximately two months during winter when there are not any plants in the greenhouses. Heating greenhouses decreases the risk of cold induced damages, such as cracked glass panes and frozen pipes (Informant 1; Informant 2. pers. comm. 2011). Reducing the heating would pose other challenges beyond the material damages, such as low productivity and increased risk of disease threats. The current stock of heated greenhouses is a large investment, so it can be assumed that the economic returns are more or less required for commercial tomato production. Thus, transitioning to unheated greenhouses, which have lower yields, may not be commercially tenable. In other words, producing tomatoes in unheated greenhouses in Sweden on a large scale would involve challenges—technical and potentially economic.

4.2 LCA METHODOLOGY AND SYSTEM BOUNDARIES

The choice of system boundaries could be important for the results and conclusions found in this study. For example, the retailer and user phase of tomatoes and carrots were excluded. This study also chose to focus only five impact categories, which affected the results and final conclusion. The possible effects of expanding the system boundaries, as well as, the choice of impact categories are discussed below.

All activities after delivery to a wholesaler in Helsingborg were excluded including storage at the wholesaler, transportation to retailers, storage at retailers, transportation to consumers, cooking, etc. Very few studies on carrot and tomato production have included the shopping and user phases. One study conducted on processed tomatoes (ketchup) showed that the contribution from transportation to the consumer could be important (Andersson et al., 1998). Including the shopping phase in this study would result in higher environmental impact, specifically for global warming potential, fossil fuel depletion and acidification potential. The significance of the contribution depends on distances between the retailer and the consumer, means of transport and amounts of groceries bought per visit. However, it can be expected that this additional impact would be similar for all consumer habits (as all consumer habits are assumed to consume the same amounts of tomatoes and carrots, which would require transportation from retailer). Furthermore, the additional impact would be independent of the production methods and produce origin. Retailer waste differs between tomatoes and carrots. In a study by Gustavsson (2010) the effects of retailer waste on the global warming potential of a number of products was studied, including tomatoes and carrots. It was concluded that approximately 2.2% of tomatoes and 1.3% of carrots are lost at the retailer (Gustavsson, 2010). If the retailer phase and losses during this period were included in this study, the potential impact for all impact categories for both tomatoes and carrots would be slightly higher. The effect would be higher for tomatoes since the losses for tomatoes are greater.

The functional units of this study were chosen to be 10.4 kg tomatoes and 9.2 kg carrots delivered to a wholesaler in Helsingborg. For agricultural systems, the function of the system analyzed and the functional unit can be defined in many ways (Andersson, 2000a). When considering the function of tomato and carrot consumption, nutrient or fiber content, and taste or durability could have been the functional unit of the production systems. Choosing another functional unit than the quantitative (kilogram) one chosen would probably significantly alter the results. Bearing in mind that this study assesses the environmental impact of a part of the diet, other functional units such as nutrient content could prove to be an interesting alternative functional unit to investigate.

Within LCA methodology some impact categories and how their environmental impact should be assessed are disputed. Impact categories that are difficult to assess, and thus often disputed, are highly relevant for assessing the environmental impact of agricultural systems. The discussion mainly concerns the impact categories that are not caused by emissions or where the effects of emissions are complex, i.e. resource use, such as the use and decrease of topsoil, the use of phosphorous in fertilizers, impacts on biodiversity, effects from land use, as well as, toxicity (Baumann & Tillman, 2004). Hayashi et al. (2007) evaluate LCA methodology and the methodological improvements needed to sufficiently assess the environmental impacts of agriculture. They stress that the important impact categories—soil quality, biodiversity and impacts from pesticide use—are either omitted or not sufficiently covered by the LCA methodology (Hayashi et al., 2007). Alternatives for assessing toxicity and effects of land use are discussed below.

Pesticide production was included in this study, but the environmental impact from pesticide use—spreading of pesticides in the environment—was not included. Assessing the impact category toxicity is complicated because many different toxic substances have many, often overlapping, toxic effects (Baumann & Tillman, 2004). For example, a study on Spanish tomatoes concluded that pesticide use had the greatest impact on the toxicity impact category and that the impact of pesticides is complex because the type of substances may vary from year to year and consequently affect the magnitude of the impact (Antón et al, 2005). In the present study, pesticides were included as the amount of active ingredient per square meter. While the amount of active ingredients per functional unit could be used as an indicator of the environmental impact, this method would have drawbacks since different active ingredients are not commensurable. Another alternative for assessing toxicity is to use a so called red-flag system—sampling noting or flagging chemical use with serious negative effects on the environment or humans (Lagerberg Fogelberg & Carlsson-Kanyama, 2006). However the red-flag system requires knowledge about the chemicals that are used; and this was not known in this study.

Land use and its consequences are important when assessing the environmental impact of agricultural production. The consequences of land use are not sufficiently covered in LCA methodology (Andersson, 2000a; Brentrup et al., 2002; Kløverpris et al., 2008). Even if readymade impact assessment methods often have an impact category called land use, there is no agreement on how it should be assessed. Land use has different impacts depending on the type of land use and where it occurs. This is discussed in Haas et al. (2000), where it is suggested that the land use impact category should be specified more precisely and take the agricultural landscape into account. Another method to assess land use impact in LCA studies was suggested by Brentrup et al. (2002). In short, the method applies the Hemeroby concept which measures human influence on ecosystems and includes land use, the magnitude of human influence and regional differences. This method assumes that there is a natural condition with no human influence and all land uses are related to this natural state. (Brentrup et al., 2002) In the present study, arable land use was assessed as the occupation of arable land. This method of assessing merely the occupation of land is not sufficient to describe the environmental impacts from land use—it can simply indicate possible impacts. It should be noted that the tomato production in this study involves a more intense land use when compared to carrot production in general, although this is not reflected in the results. Tomato production involves covering land with buildings and removing topsoil, i.e. in the case of Almería where soil is sometimes removed and replaced by sand. Greenhouses can also result in large visual impacts as they do in Almeria, Spain and in Westland in the Netherlands (*Figure 12).* This visual impact, as well as other impact of land use were not expressed in the results of this study.

Figure 12. Picture of greenhouses in the Westland region of the Netherlands (to the left) and "El mar de plástico" (the sea of plastic) from southern Spain, in Almería (to the right). Greenhouses have a large visual impact in both areas. Sources: www.greenopia.com and: http://alpujarrasostenible.wordpress.com

The LCA methodology is better suited for assessing global environmental effects than assessing local effects. Rarely LCA studies account for the locality of emissions or activities (such as land use) (Baumann & Tillman, 2004). The location of an emission or activity can be very important for the actual effect. For example, emissions of acidifying compounds may do more harm in one local environment that is sensitive to acidification, such as parts of Sweden, whereas areas with a lot of lime in the soil are not damaged to the same extent. In in Almería, Spain, where the Spanish tomato production was assumed to be located in this study, large concentrations of greenhouses for horticultural production cause local effects on the environment such as high concentrations of nitrate in the groundwater (Thompson et al. 2007).

The exampled mentioned above underlines the fact that LCA results are problematic to interpret. Knowledge of the study and the background situation is definitely an advantage for interpreting the results.

4.3 SEASONAL FOOD

"It's the changing of the seasons

He says I need them

I guess I'm too Scandinavian"

(Lyrics by Ane Brun (2008), the song is called "Changing of seasons")

Proponents of seasonal food state that it is "something to long for", "fun" and could actually be something worth throwing a party for. These are qualities of food that cannot be quantified or objectively compared. Conversely, this study focused only on the quantifiable environmental impact of seasonal vegetable consumption. This study also recognized that contradictory advice is given to consumers regarding how to eat seasonally. The contradictory advice is even further complicated by the fact that the environmental importance of production methods, such as greenhouse production or transportation, is not always clear for the consumer who wants to do right by eating seasonal food.

This study indicates that when discussing and relating seasonal vegetables and environmental impact, one has to distinguish between different types of vegetables, production methods and properties of the vegetables. In a way products produced in climate controlled greenhouses challenge the concept of seasonality in that these products come from an artificially created microclimate, which is created by the means of energy use. As mentioned above Swedish greenhouses are heated in the winter even when there are no plants in the greenhouse to maintain the glass panels and the equipment (informant 1 and 2 pers. comm., 2011). Energy demand for heating during the summer is low; still it can be argued that all production the whole year around from the greenhouse should be ascribed with the same environmental load. This because the high productivity from the greenhouse, during the extended cropping season, is a result of the high energy use during the colder periods of the year. Therefore, from an environmental perspective, it does not matter when the tomatoes are consumed. They have the same environmental impact during the whole harvest season—in Sweden from April to November. The environmental impact is almost entirely attributed to heating and energy sources for heating. This means that it is more relevant to focus on production technologies than on seasonality for greenhouse produced products.

For open field crops that can be stored such as carrots, seasonality becomes relevant since the environmental impact from carrots is lowest right after harvest, but increases during storage due to electricity use and increasing losses. For Swedish carrots electricity use and amount of losses during storage are equally important for the increased global warming potential, which were assessed to increase by around 30% from end of harvest season in September to March (*Figure 11*). Despite the increase of global warming potential during storage of Swedish carrots, imported carrots were assessed to have a higher global warming potential than Swedish carrots at the end of storage time in March. This was due to the significantly longer transportation distance of imported carrots compared to domestic carrots. It should be noted however that despite the increase in global warming potential for Swedish carrots during storage, the global warming potential was still low in comparison with tomatoes, because the initial impact from primary production of carrots was assessed to be so low.

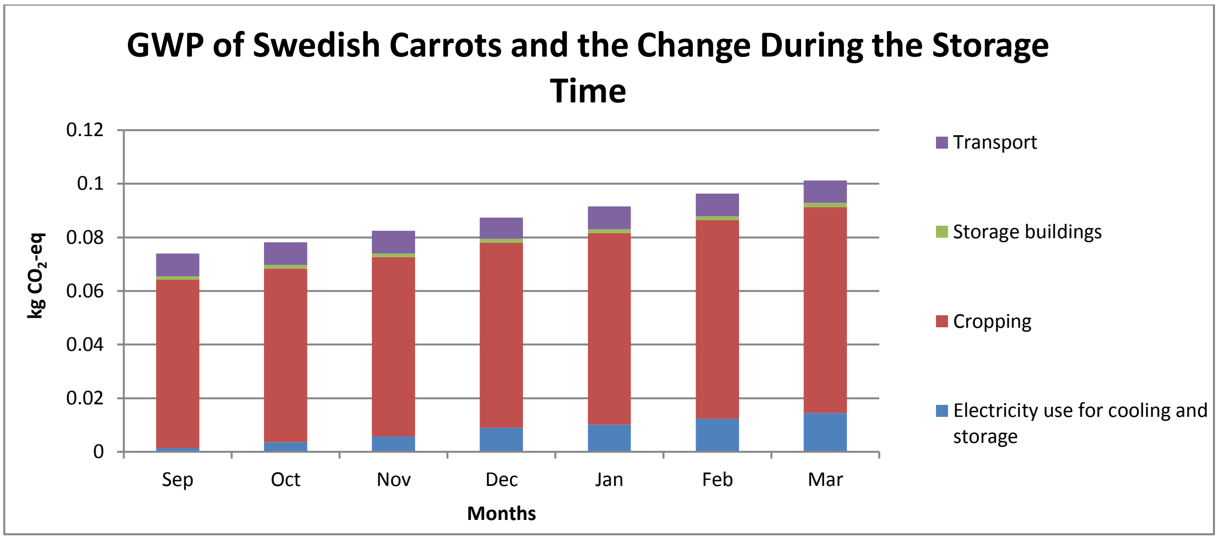

Figure 13. Global warming potential of Swedish carrots and the change from the end of harvest season in September to the end of storage time in March.

5. CONCLUSION

What is the difference in environmental impact from the yearly consumption of tomatoes and carrots depending on how seasonal food is defined?

The results showed a significant difference in environmental impact from the yearly consumption of fresh tomatoes and carrots depending on how seasonal food was defined. If tomatoes from climate controlled greenhouses or produce that has been transported long distances were included, the environmental impact for the impact categories assessed increases significantly. The exception was arable land use, which was lowest when produce from high yielding production systems, such as climate controlled greenhouses, were included.

This study showed that choosing to consume according to the definition of seasonal foods—Swedish season without climate controlled greenhouses (represented in this study by Habit B), can decrease the environmental impact for at least three of five impact categories compared to the other definitions of seasonal foods analyzed. Consuming tomatoes and carrots according to this definition had the lowest potential environmental impact for three (global warming potential, fossil fuel depletion and acidification potential) out of five considered impact categories, the second lowest for eutrophication potential, but the highest impact for arable land use. However, adjusting the consumption patterns according to domestic season without climate controlled greenhouses would entail large changes from current consumption patterns of tomatoes; the consumption of tomatoes would have to be concentrated to late summer/early autumn. It would also necessitate challenging changes for the tomato producing sector in Sweden where today only approximately 2% of the greenhouse area for tomato production does not use climate control.

What is the global warming potential from the current tomato and carrot consumption? Could the global warming potential of current tomato and carrot consumption be decreased if tomatoes and carrots were consumed as seasonal food?

Global warming potential from tomato and carrot production can be decreased from current consumption level from ca. 8 kg CO2-eq to ca. 3 kg CO2-eq if consumption patterns changed in accordance with Habit B, Swedish season that excluded tomatoes from climate controlled greenhouses. However, the global warming potential would decrease if tomatoes and carrots were consumed in accordance with all the four assessed definitions of seasonal food. The reason for this is that current consumption consists of a greater share of tomatoes from the greenhouses heated with fossil fuels then any of the other assessed definitions.

What are the most important features of low environmental impact seasonal food?

Climate control of greenhouses and the transportation of produce were the most important contributors to the environmental impact. Furthermore, the results indicate that energy use, specifically energy source for climate control of greenhouses, is more significant than transportation distances in a European context. Tomatoes had a higher impact compared to carrots for all impact categories, except arable land use, independent of the production system.

The environmental impact of consuming tomatoes from climate controlled greenhouses included in Swedish season with produce from climate controlled greenhouses (Habit A) and European season with produce from climate controlled greenhouses (Habit C) were probably underestimated by the choice to assess merely representative technique for tomato production in the LCA analysis. Nevertheless, the results indicated that the energy source for climate control in tomato production is the most important factor for the aggregated impact from the consumption of tomatoes and carrots.

Crops produced in climate controlled greenhouses are difficult to incorporate into the concept of seasonal food. Since it can be argued that these products have the same environmental impact, independent of when they are consumed during the year. For open field vegetables that can be stored fresh, such as carrots, energy use during storage does contribute to the environmental impact and even more so if the product has high losses during the storage time. For these products season matters in the sense that the environmental impact increases if the product is consumed “out of season”. It is important to note, however, that energy use and losses during storage of Swedish carrots does not contribute as much to the global warming potential as transportation does for imported carrots.

This indicates that for tomatoes, and probably also other climate controlled greenhouse grown produce in the Swedish market, seasonality is less applicable advice when encouraging environmentally friendly consumption. Instead it is more relevant to emphasize production methods (energy use and energy source). For carrots there is an environmental gain when they are consumed during harvest season, because energy for storage and storage losses are avoided. However, at the end of the storage time when carrots have the highest impact, it is still lower than greenhouse produced tomatoes.

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PERSONAL REFERENCES

Andersson Stina, Extension service, Kristianstad, Sweden

Berglund Örjan, Department of Soil and Environment Swedish University of Agricultural Sciences, Uppsala, Sweden

Boeters Jos, Hollandplant, Bergschenhoek, the Netherlands

Christensen Inger, Grön kompetens, Alnarp, Sweden

Gullstrand My, Nowaste logistics AB, Helsingborg Sweden

Informant 1, greenhouse manager, Sweden

Informant 2, greenhouse manager, Sweden

Informant 3, greenhouse manager, Sweden

Lambie Stuart, Grodan Rockwool B.V.

Luedtke Paulina, Everfresh, Helsingborg, Sweden

Marmolin Christina, HS, Skara, Sweden

Nilsson P-O, Carrot farm manager, Skåne, Sweden

Vermulen Peter, Wageningen UR Greenhouse Horticultur, Bleiswijk, the Netherlands

APPENDIX A. RESULTS FROM INDIVIDUAL LCA- TOMATO

All results presented here are the characterization results for the functional unit 1 kg tomatoes delivered to a wholesaler in Helsingborg.

GLOBAL WARMING POTENTIAL

Dutch tomatoes (NLH) have the highest global potential of 0.91 kg CO_2-eq per kg tomatoes. Heating of greenhouses with associated combustion of natural gas is the main contributor with 75% of the total global warming potential. Spanish tomatoes (ESS) have a global warming potential of 0.52 kg CO_2-eq per kg tomatoes. Transportation is the main contributor with 71% of the total global warming potential. Tomatoes produced in heated greenhouses in Sweden (SEH) were assessed to have a global warming potential of 0.3 kg CO_2-eq per kg tomatoes. Electricity and heating for greenhouses are the greatest contributors with 67% of the total global warming potential. Tomatoes produced in the unheated greenhouse in Sweden (SEU) had a global warming potential of 0.21 kg CO_2-eq per kg tomatoes. The greenhouse structure is the main contributor to global warming potential; this is mainly because the yields to which the emissions are related are much lower than other scenarios using the same structure (SEH and NLH).

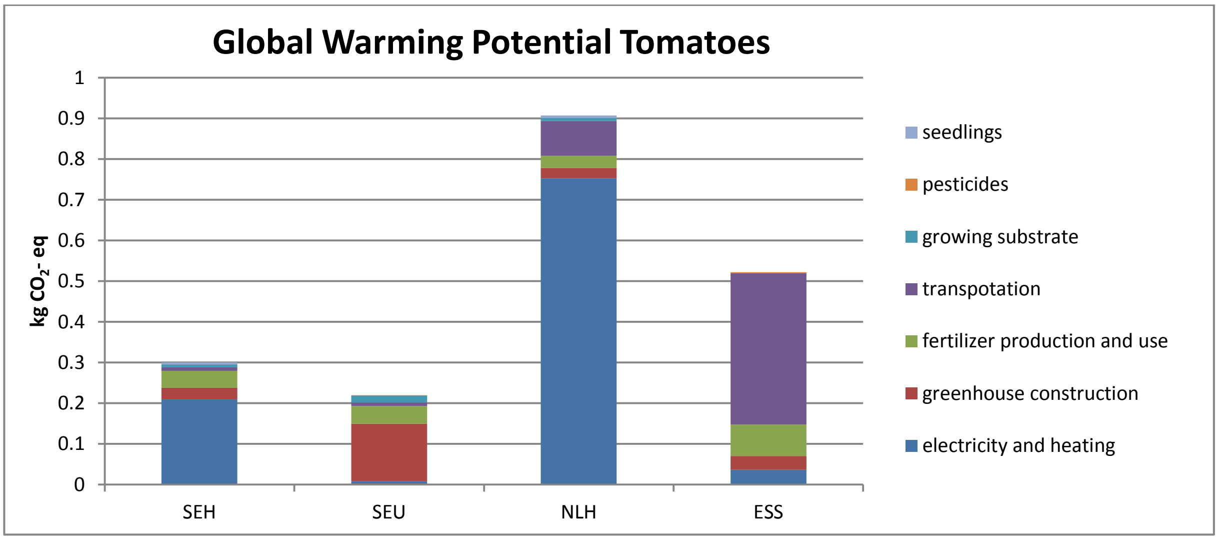

Figure 14. GWP for all tomato production scenarios, functional unit 1 kg tomatoes delivered to wholesaler in Sweden.

FOSSIL FUEL DEPLETION

Dutch tomato production (NLH) uses natural gas for heating which is the reason for the high fossil fuel depletion of 16.8 MJ-eq per kg tomatoes. The long transportation distance of importing tomatoes from Spain to Sweden fueled with diesel is the main reason why the ESS scenario has a fossil fuel depletion of 8.6 MJ-eq per kg tomatoes. Tomatoes produced in Swedish heated greenhouses (SEH), have a fossil fuel depletion of 6.8 MJ-eq per kg tomatoes. The main reason for this is the use of electricity, which in Sweden includes electricity produced by nuclear power. For unheated greenhouses in Sweden (SEU) manufacturing of material for greenhouse construction contributes 51% of the total fossil fuel depletion--3.6 MJ-eq per kg tomatoes.

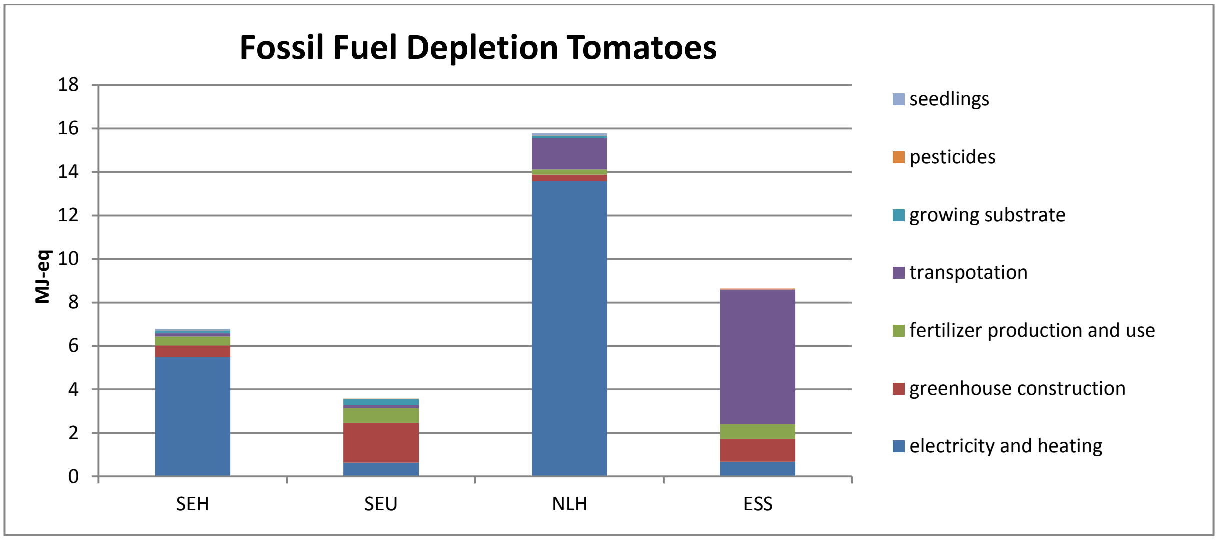

Figure 15. Fossil fuel depletion for all tomato production scenarios, functional unit 1 kg tomatoes delivered to wholesaler in Sweden.

ARABLE LAND USE

The tomato production scenarios with the highest yields, SEH and NLH, have the lowest arable land use, whereas the scenarios with lower yields, SEU and ESS, have a higher arable land use.

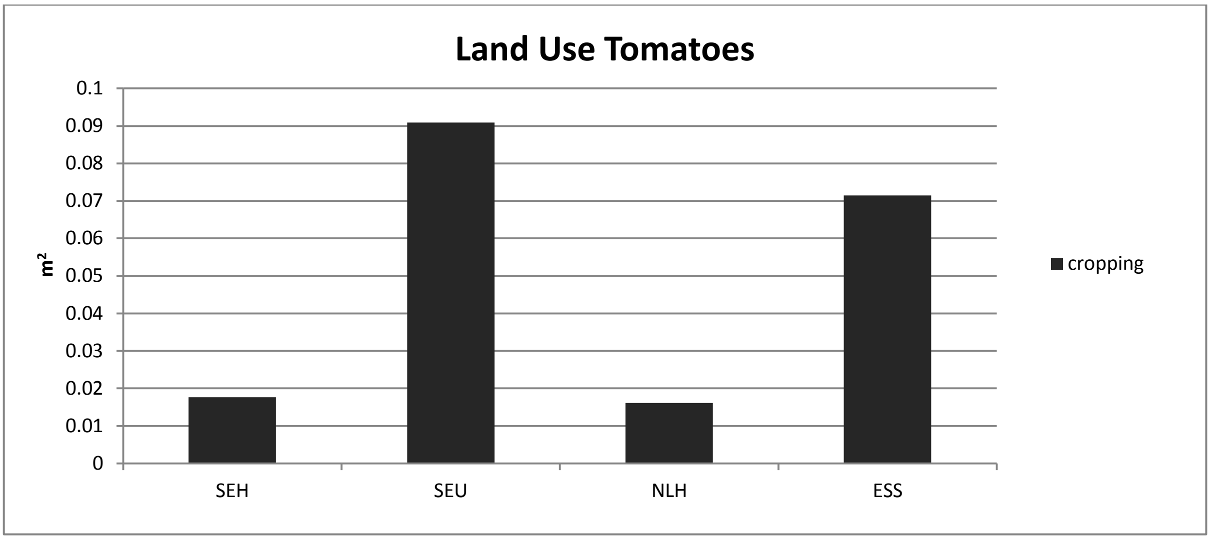

Figure 16. Land use for all tomato production scenarios, functional unit 1 kg tomatoes delivered to wholesaler in Sweden.

ACIDIFICATION POTENTIAL

The Swedish heated greenhouse scenario (SEH) has the highest acidification potential with 2.9 g SO_2-eq per kg tomatoes. Heating and electricity is the main contributor with 86% of the total potential. This is primarily due to the combustion of woodchips and emissions of sulfur dioxide and nitrous oxides. Spanish tomatoes have an acidification potential of 2.6 g SO_2-eq per kg tomatoes, which is mainly due to emissions from transportation (56% of the total impact), but also from emissions from fertilizer use and associated emissions of ammonia. Dutch tomatoes (NLH) have an acidification potential of 1.35 g SO_2-eq per kg tomatoes. Nitrogen oxides from combustion of natural gas and transportation are the most important acidification substance. The avoided electricity production in the NLH scenario results in negative emissions of both sulfur dioxide and ammonia, which lowers the acidification potential significantly. Unheated greenhouses in Sweden (SEU) have an acidification potential of 1.0 g

SO_2-eq per kg tomatoes. Manufacturing of materials for greenhouse construction is the most important contributor. Sulfur dioxide is the most important acidifying compound for this scenario with 70% of the impact.

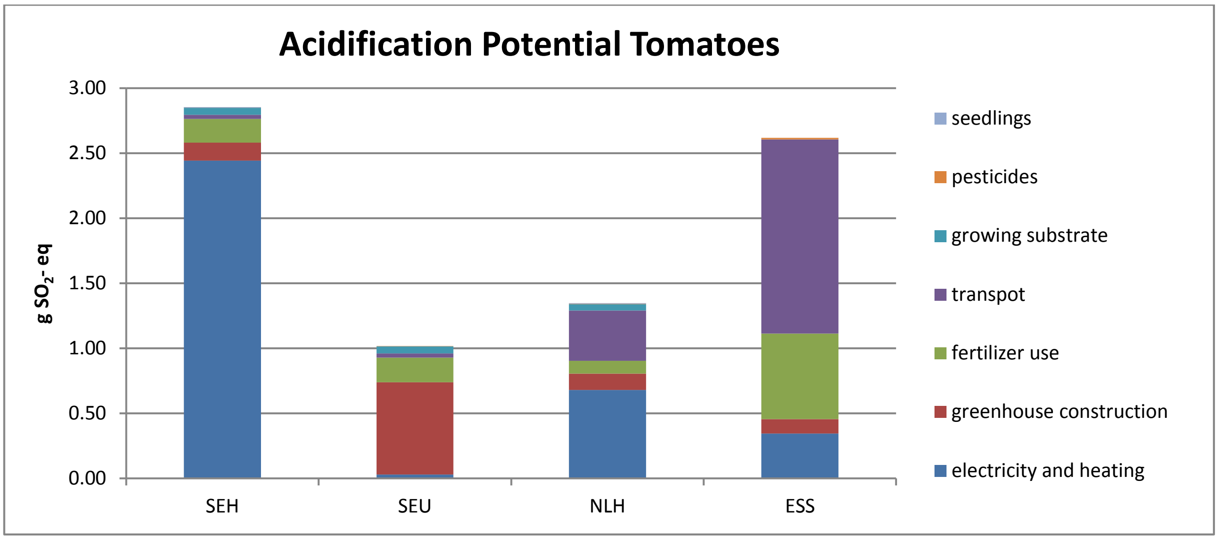

Figure 17. Acidification potential all tomato production scenarios, functional unit 1 kg tomatoes delivered to wholesaler in Sweden.

EUTROPHICATION POTENTIAL

Spanish tomatoes (ESS) have the highest eutrophication potential with 1.3 g PO_4-eq per kg tomatoes. Nitrate leached into water due to fertilization is the most important eutrophying substance. The contribution from transportation and the resulting emission of nitrogen oxides is also significant. The Swedish heated greenhouse scenario (SEH) has an eutrophication potential of 0.9 g PO_4-eq per kg tomatoes. Nitrogen oxides, mainly from the combustion of woodchips, are the main eutrophying substances. The unheated greenhouse scenario in Sweden (SEU) has an eutrophication potential of 0.3 g PO_4-eq per kg tomatoes. Phosphate leeching into water from the manufacturing of materials for the greenhouse construction is the main eutrophying substance. Dutch tomatoes (NLH) have an eutrophication potential of 1.2 g PO_4-eq per kg tomatoes. The negative potential is a result of the avoided Dutch electricity production, where mining of brown coal causes leeching of mainly phosphate, but also other eutrophying compounds, an activity which is avoided when electricity is produced from natural gas, as in the Dutch tomato production (NLH).

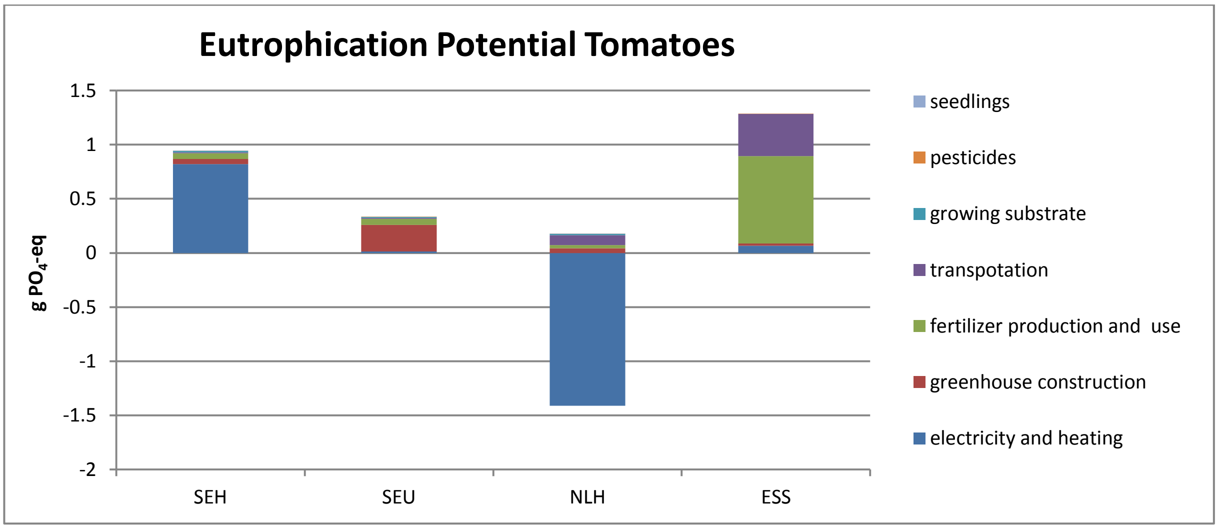

Figure 18. Eutrophication potential for all tomato production scenarios, functional unit 1 kg tomatoes delivered to wholesaler in Sweden.

APPENDIX B. RESULTS FROM INDIVIDUAL LCA- CARROT

All results presented here are the characterization results, based on the functional unit 1 kg carrots delivered to a wholesaler in Helsingborg.

Since production methods were assumed to be similar, the main differences between Swedish, Dutch and Italian carrots are the lengths of the transportation distances. For Italian and Dutch carrots transport distances are longer but also take a longer time, which contributes to the higher emissions (diesel consumption to refrigeration and leaching of refrigerants). The electricity use is almost the same for all of the scenarios (see *Table 22*), but the national electricity production affects the results. Dutch electricity production is based mainly on fossil fuels (natural gas 49% and hard coal 19%) and Italian electricity production is also dominated by fossil fuels (natural gas 37%, hard coal 12% and oil 13%). Swedish electricity production is mainly from nuclear power (46%) and hydropower (36%) (Ecoinvent, 2007).

GLOBAL WARMING POTENTIAL

Italian carrots have the highest global warming potential of 0.27 kg CO_2-eq per kg carrots. Transportation from Italian to Sweden by truck and rail contributes 62% of the total impact. Carbon dioxide from transportation is the most important substance and dinitrogen monoxide the second most important substance. Transportation distance has a significant impact on the global warming potential for Italian carrots (ITC) even though carrots from Italy are partly transported by train. Approximately 64% of the distance is rail transport and 36% by truck. Of the total impact from transportation, 41% originates from the rail transport and 59% from the truck transport. This Indicates that rail transportation has a lower global warming potential, but the magnitude of the environmental gain will be variable depending on how the electricity for the rail transportation is produced. The field operations were assumed to be the same for all analyzed scenarios; therefore, the yield is of significant importance. It can be seen in the diagram that the impact from field operations is slightly larger for the scenario with the lowest yield (ITC). Dutch carrots (NLC) have a global warming potential of 0.20 kg CO_2-eq per kg carrots. Transportation contributes 42% of the total impact. Swedish carrots (SEC) have the lowest global warming potential of 0.09 kg CO_2-eq per kg carrots. This is due to shorter transportation distances and lower impact from electricity consumption during washing, cooling and storage. Fertilizer production and emissions related to fertilizer use is the greatest contributor, with 53% of total global warming potential. For all carrot production scenarios (SEC, NLC and ITC) the main climate change gases are carbon dioxide followed by dinitrogen monoxide.

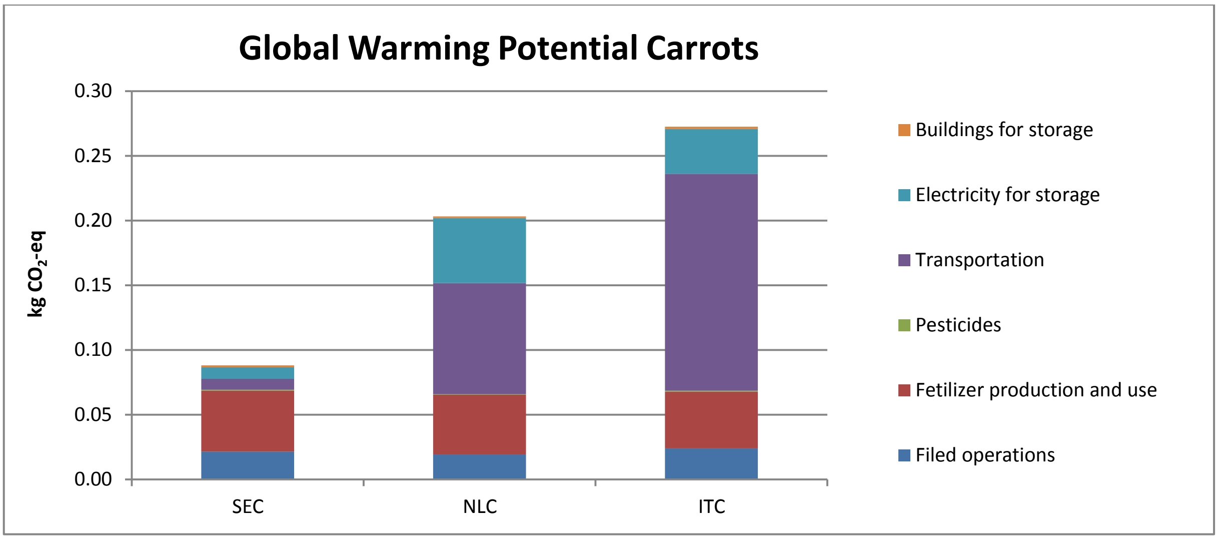

Figure 19. Global warming potential all carrot production scenarios, functional unit is 1 kg carrots delivered to wholesaler in Sweden.

FOSSIL FUEL DEPLETION

Transportation and electricity use are significant contributors to fossil fuel depletion for the Dutch (NLC) and Italian (ITC) carrots. Italian carrots (ITC) have a fossil fuel depletion of 4.1 MJ-eq per kg carrots and Dutch carrots (NLC) have 2.8 MJ-eq per kg carrots. For Italian carrots transportation contributes 70% and electricity 13% of the total. Oil used for electricity production for rail transportation is the main fossil source. Transportation contributes 50%

and electricity 28% of the total impact from Dutch carrots (NLC). Diesel used in field operations and gas used for electricity production are the main fossil sources. Swedish carrots (SEC) have a fossil fuel depletion of 1.5 MJ-eq per kg carrots. Electricity use, fertilizer use and field operations are the activities contributing the most to fossil fuel depletion, with 47%, 20% and 22% of the total impact. The main fossil source used in Swedish electricity production is uranium.

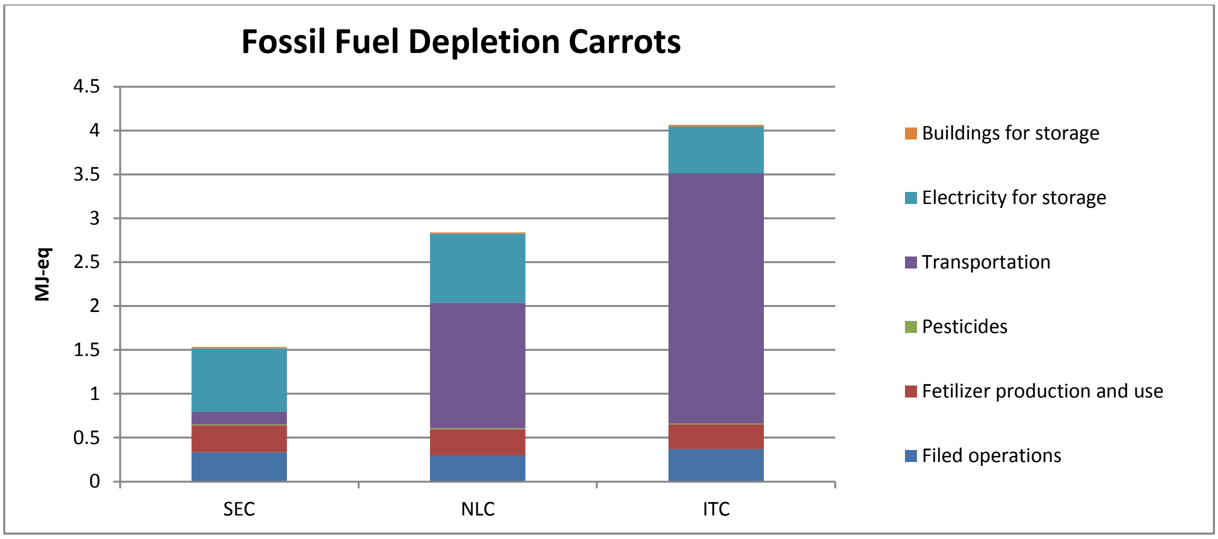

Figure 20. Fossil fuel depletion for all carrot scenarios, functional unit is 1 kg carrots delivered to wholesaler in Sweden.

ARABLE LAND USE

Arable land use is yield dependent, therefore, Dutch carrots (NLC) have the lowest impact because of the higher yield.

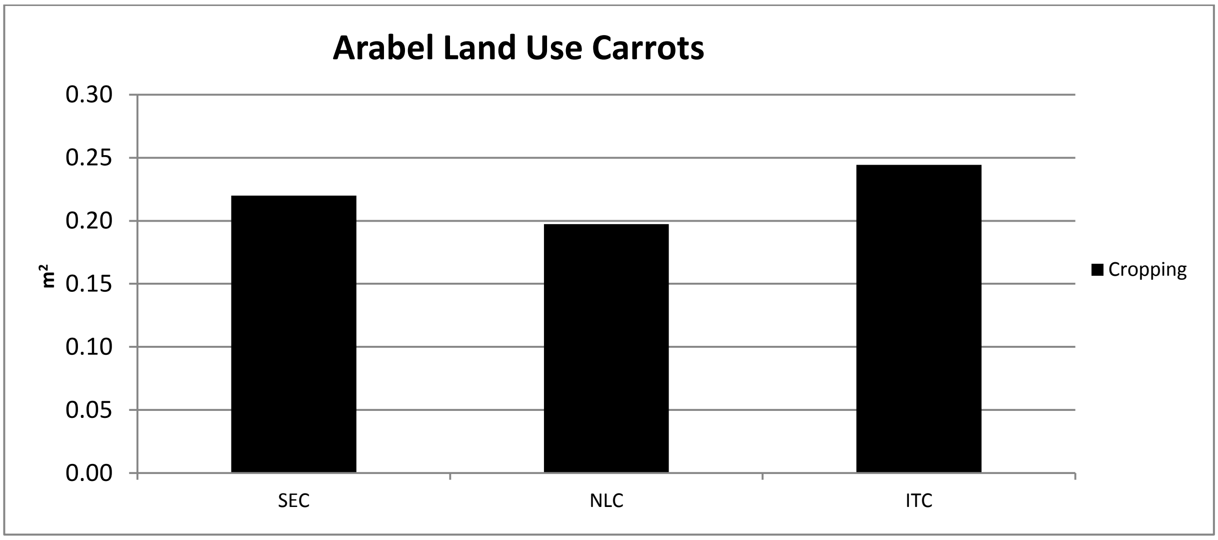

Figure 21. Arable land use for all carrot production scenarios, functional unit is 1 kg carrots delivered to wholesaler in Sweden.

ACIDIFICATION POTENTIAL

Combustion of fossil fuels and emissions of nitrogen oxides and sulfur oxide are the greatest contributors to acidification potential. It can be seen from the figure below that electricity, transportation and field operations are great contributors to acidification due to fossil fuel combustion. Ammonia from fertilizer application is also significant. Italian carrots (ITC) have an acidification potential of 1.3 g SO_2-eq. Transportation contributes 56% of total acidification potential and fertilizer application contributes 19%. Dutch carrots (NLC) have an acidification potential of 0.9 g SO_2-eq per kg carrots. Transportation contributes 46%, fertilizer use 32% and field operations

14%. Swedish carrots have an acidification potential of 0.44 g SO_2-eq per kg carrots. Fertilizer production and use is the greatest contributor with 52 % of the total.

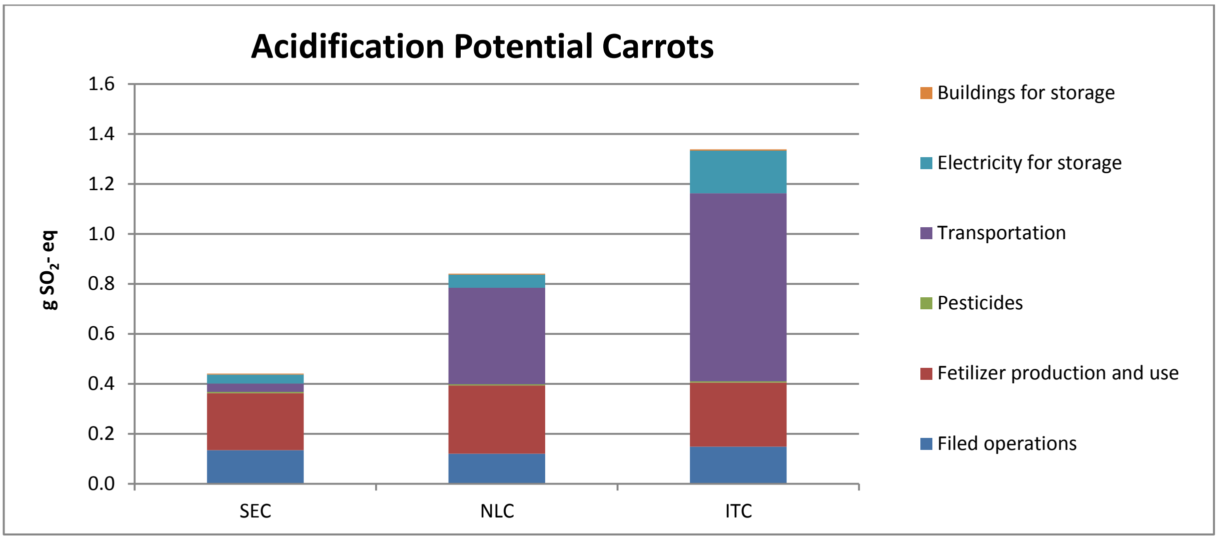

Figure 22. Acidification potential all carrot production scenarios, functional unit is 1 kg carrots delivered to wholesaler in Sweden.

EUTROPHICATION POTENTIAL

Nitrate leaching from the field, emission of nitrogen oxides from diesel combustion and leaching of phosphate during coal mining for electricity production are the main substances for eutrophication potential of carrot production.

For Italian carrots (ITC) rail transportation and the electricity production (with associated phosphate leaching into water) for this transportation is the main reason for the high eutrophication potential, which was assessed to be 0.55 g PO_4-eq per kg carrots. Transportation contributes with 48% of the total eutrophication potential and nitrate leaching 37%. For Dutch carrots (NLC) nitrate from fertilizer use is the greatest contributor to eutrophication potential. Swedish carrots (SEC) have an eutrophication potential of 0.28 g PO_4-eq per kg carrots. Fertilizer use is the greatest contributor with 77% of the total eutrophication potential and nitrates leeching into water is the main substance that causes eutrophication.

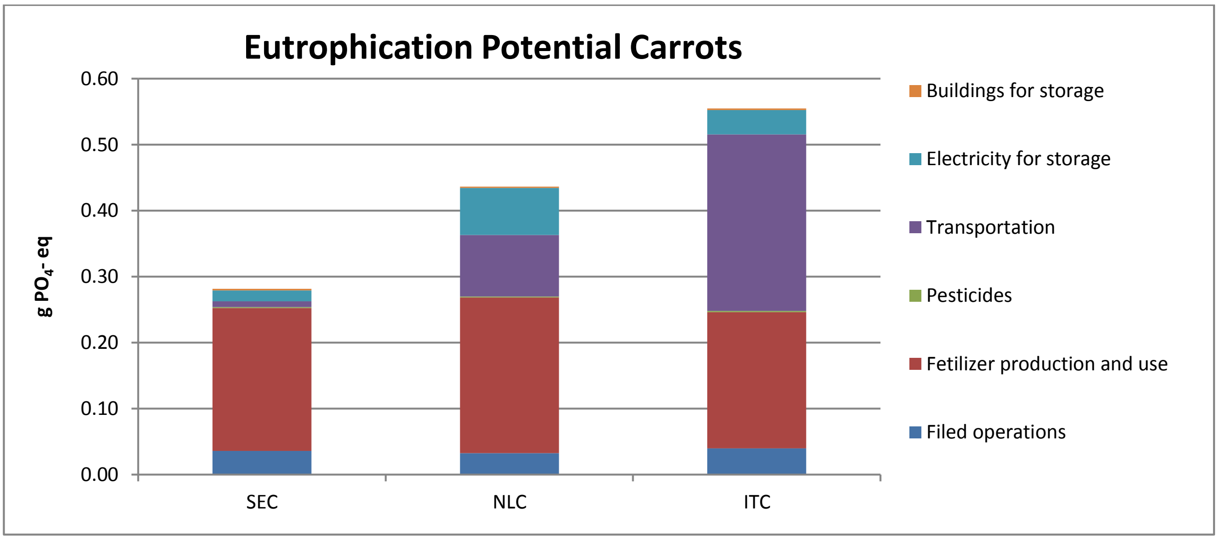

Figure 23. Eutrophication potential for all the carrot production scenarios, functional unit is 1 kg carrots delivered to wholesaler in Sweden.

APPENDIX C. DETAILED RESULTS OF THE ANALYSIS OF CONSUMER HABITS

GLOBAL WARMING POTENTIAL

The global warming potential of the yearly consumption of tomatoes and carrots for the four consumer habits is shown in *Figure 24*. Tomato consumption has a greater impact on the global warming potential than carrot consumption. Habit B, with no extra energy used for heating of greenhouses and shorter transportation distances, has the lowest global warming potential. Habit A, where tomatoes are produced in greenhouses heated with woodchips, has the second lowest total global warming potential. Habit C has the highest global warming potential, which is mainly due to tomatoes imported from the Netherlands where the heating of greenhouses is the greatest contributor to the global warming potential. Tomatoes from Spain are the greatest contributor to Habit D with the second largest global warming potential. Spanish tomatoes have the second largest global warming potential of all four tomato scenarios, even though no energy heating of greenhouses is used. The main reason for this is the long transportation distance from Spain to Sweden. Consumption of carrots contributes to the total global warming potential with 21% for Habit A, 26% for Habit B, 16% for Habit C and 18% for Habit D. The share of total global warming potential for carrots is highest for the habit with the lowest global warming potential--Habit B. However the sum of the total global warming potential from carrots is highest when carrots are imported--for Habit C and D--due to the longer transportation distance of imported carrots.

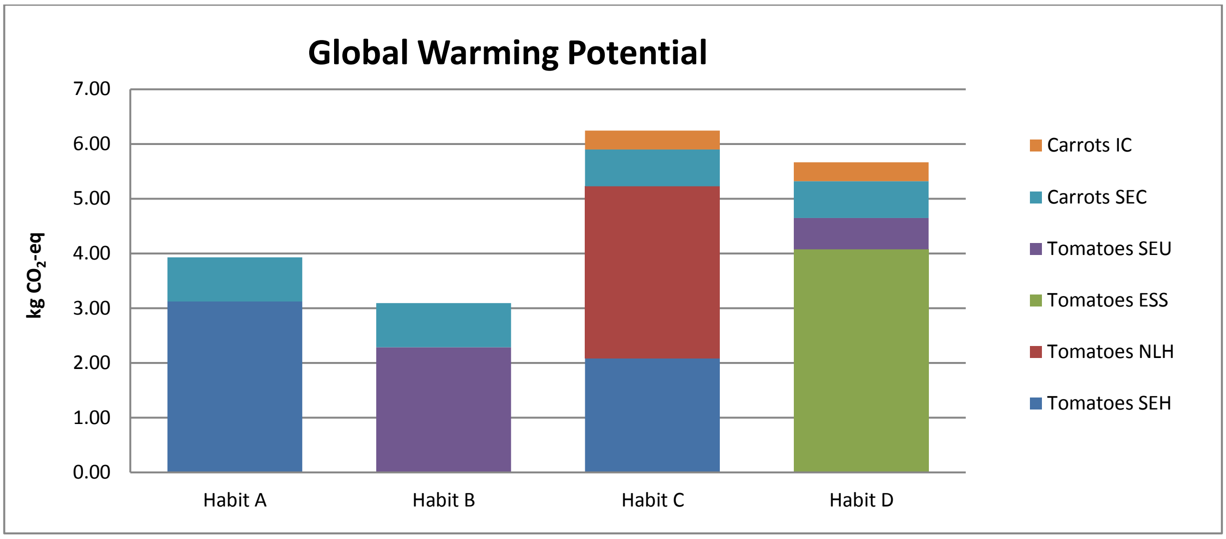

Figure 24. Global warming potential for the consumer habits. Where Habit A is National season with no restrictions on production system, Habit B is Local season with no extra energy, Habit C is European season no restrictions on production systems, and Habit D is European season with no extra energy.

Figure 25 shows the importance of different activities, such as heating of greenhouses, fertilizer production and use, transportation etc., for each consumer habit. Habit A and D include tomatoes produced in heated greenhouses and the impact on global warming potential from this activity is significant even when looking at the aggregated yearly global warming potential from tomato and carrot consumption combined. More than half of the impact is derived from the heating of greenhouses for both Habit A and D. However, if tomatoes are produced in unheated greenhouses during winter, as in Habit D, production is located far away from the consumer, which involves long transport distances from the production site to Sweden. The impact on global warming potential of this transportation distance is even larger than the impact from the heating of greenhouses if greenhouses are fueled with woodchips, as in Habit A. Results for consumer Habit B show that materials for greenhouse construction will have a significant importance for the aggregated global warming potential when production systems which are low yielding are employed in material rich greenhouses. Generally, storage of carrots and field operations for carrot production has a relatively small importance for the aggregated global warming potential of the consumer habits. Fertilizer production and use is one activity where carrot consumption contributes as much as tomato consumption, mainly due to emissions of dinitrogen monoxide from fertilization use on soil.

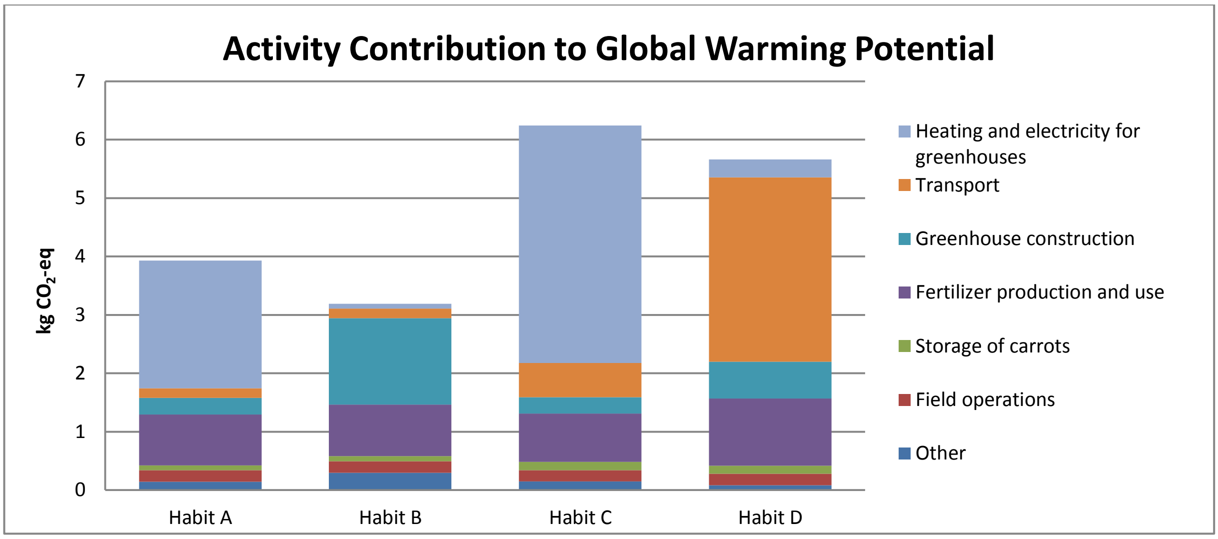

Figure 25. Activity contribution to global warming potential. Where Habit A is National season with no restrictions on production system, Habit B is Local season with no extra energy, Habit C is European season no restrictions on production systems, and Habit D is European season with no extra energy.

FOSSIL FUEL DEPLETION

The transportation of produce and heating of greenhouses contributes the most to fossil fuel depletion. Therefore, Habit C, with fossil fuels used for heating in Dutch tomato production and longer transportation distances, has the highest fossil fuel depletion. Habit C includes tomatoes produced in greenhouse heated with woodchips in Sweden and transportation distances are short, but tomatoes from heated greenhouses in Sweden have relatively high fossil fuel depletion. This is mainly due to electricity production in Sweden, which is partly based on nuclear power and uranium. Habit B, with no heating and shorter transportation distances, has lower fossil fuel depletion. For Habit C, with imported carrots and tomatoes part of the year, transportations of produce is the most important contributor. Carrot consumption contributes 17% for Habit A, 29% for Habit B, 14% for Habit C and 18% for Habit D of the total fossil fuel depletion.

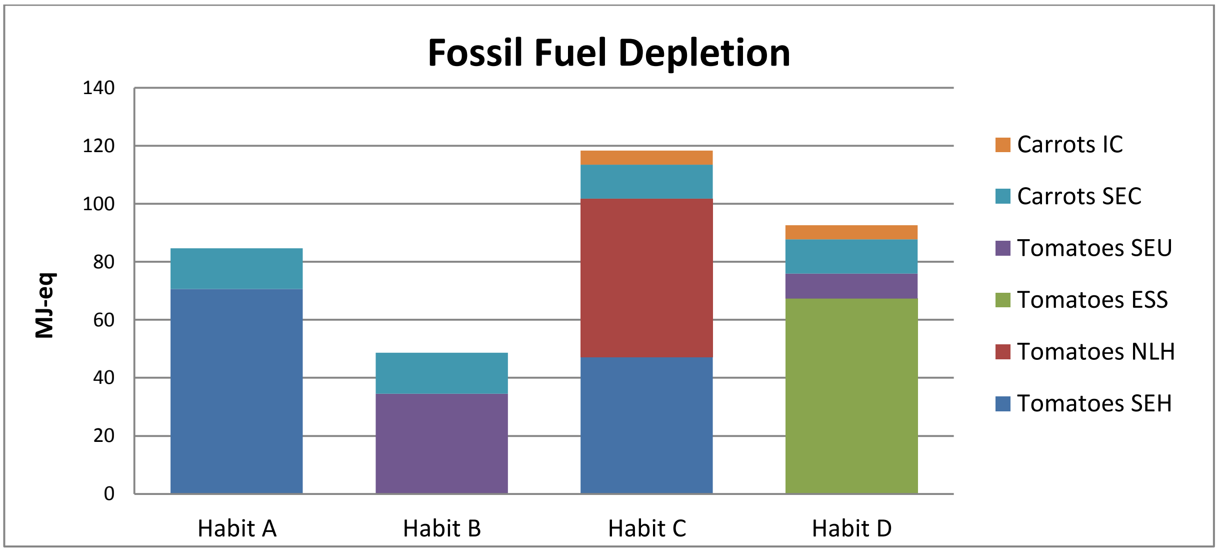

Figure 26. Fossil Fuel depletion for all consumer habits. Where Habit A is National season with no restrictions on production system, Habit B is Local season with no extra energy, Habit C is European season no restrictions on production systems, and Habit D is European season with no extra energy.

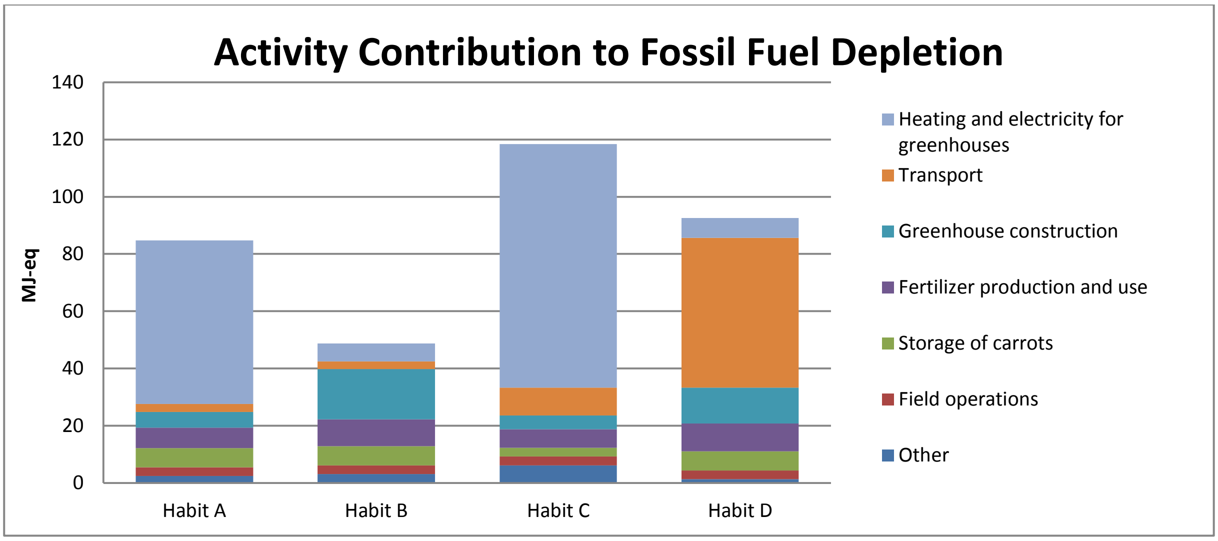

Figure 27. Activity contribution to Fossil fuel depletion. Where Habit A is National season with no restrictions on production system, Habit B is Local season with no extra energy, Habit C is European season no restrictions on production systems, and Habit D is European season with no extra energy.

ARABLE LAND USE

Carrots are lower yielding than tomatoes. Therefore, the consumed amounts of carrots have a high impact on arable land use for all habits. It can also be noted that tomatoes from production systems with significantly lower yields have a higher land use. The habits including tomatoes produced in unheated greenhouses (Habit B and D) have a higher arable land use because of the relatively low intensive tomato production included in these consumer habits. The aggregated arable land use for carrot production is similar for all consumer habits. Carrots contribute to the total arable land use with 92%, 69%, 92% and 71% for Habit A, B, C and D, respectively.

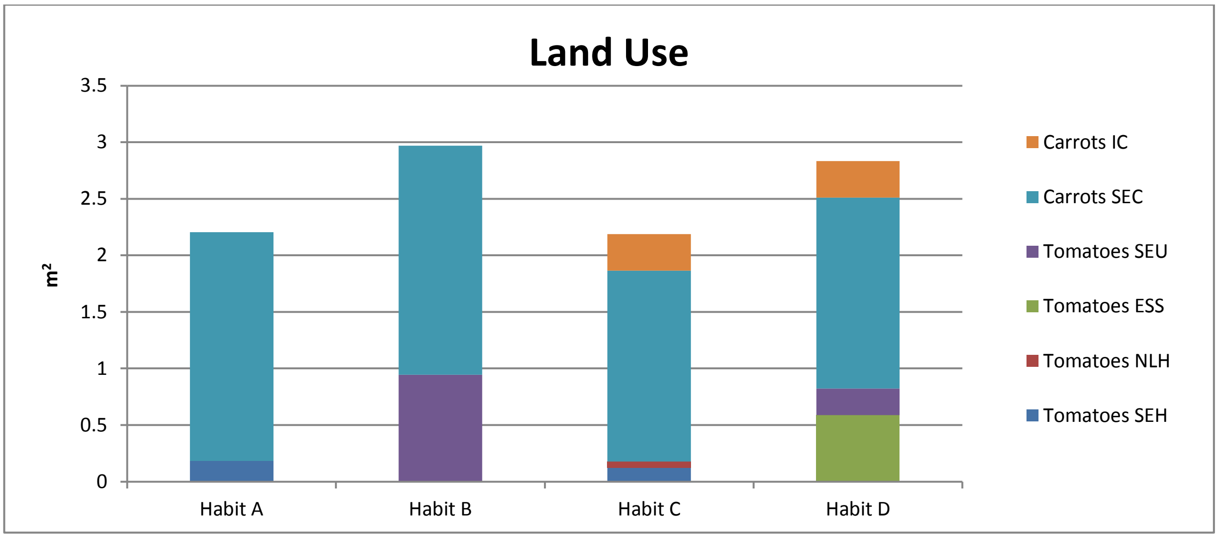

Figure 28. Land use for all hypothetical consumer habits. Where Habit A is National season with no restrictions on production system, Habit B is Local season with no extra energy, Habit C is European season no restrictions on production systems, and Habit D is European season with no extra energy.

ACIDIFICATION POTENTIAL

Habit C has the largest acidification potential, followed by Habit A. Both of these habits include tomatoes from the Swedish heated greenhouse scenario, where the combustion of wood chips for heating is the main contributor to acidification potential. Combustion of fossil fuels is another significant contributor to the acidification potential, as mainly nitrous oxides and sulfur dioxides are emitted. The acidification potential from Dutch tomatoes is lowered, however, as electricity production is avoided by the use of CHP. Habit B and D does not include produce from heated greenhouses, which is the main reason for the lower impact from these habits. The longer transportation distances of imported carrots and Spanish tomatoes, as well as, ammonia emissions from high fertilizer use on soil in Spanish tomato production, are the main reasons why Habit D has a higher acidification potential than Habit B. Consumption of carrots contributes to the total acidification potential with 13%, 29%, 10%, 18% for Habit A, B, C and D. Transportation is an important factor for imported carrots. Fertilizer use and field operations are also significant contributors to acidification potential for Swedish and imported carrots alike.

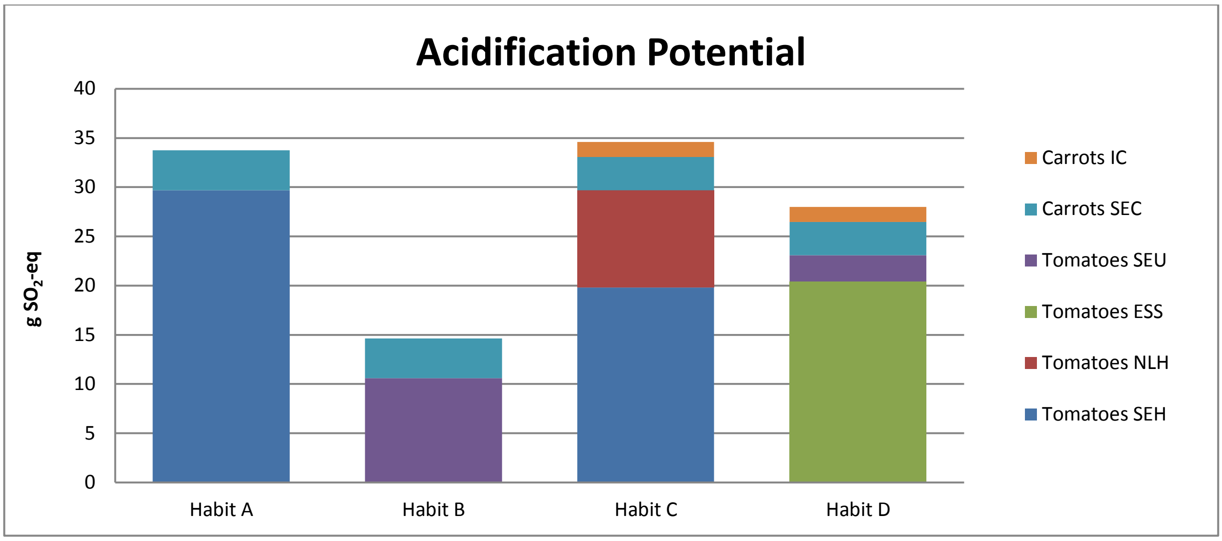

Figure 29. Acidification potential for the consumer habits. Where Habit A is National season with no restrictions on production system, Habit B is Local season with no extra energy, Habit C is European season no restrictions on production systems, and Habit D is European season with no extra energy.

It can be seen that the heating of greenhouses is a great contributor to acidification potential for consumer Habit A and C, whereas the impact from transportation is significant for consumer Habit D.

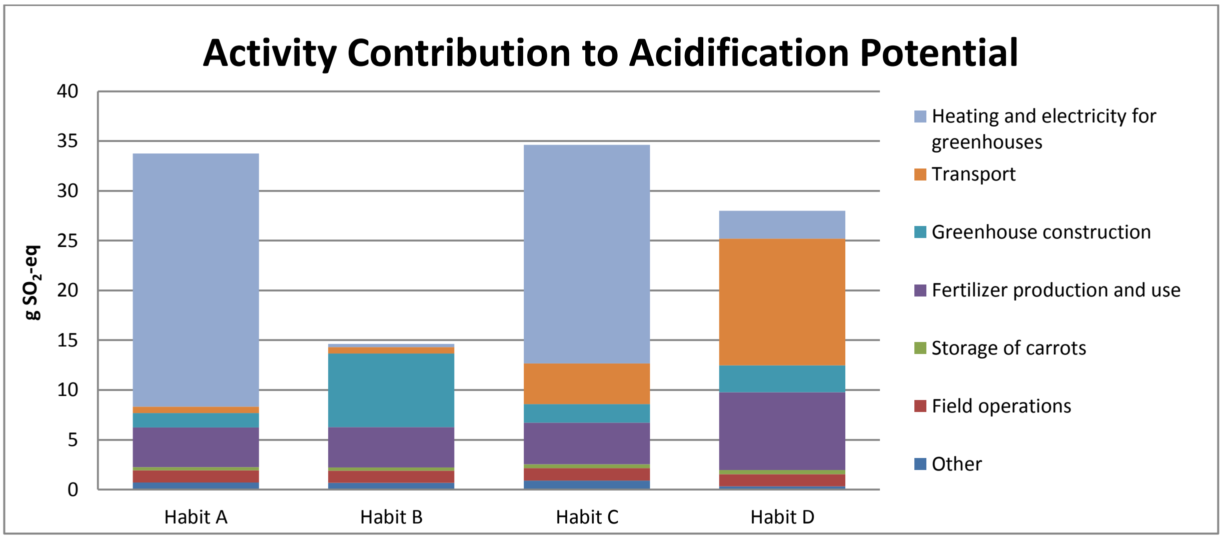

Figure 30. Activity contribution to acidification potential. Where Habit A is National season with no restrictions on production system, Habit B is Local season with no extra energy, Habit C is European season no restrictions on production systems, and Habit D is European season with no extra energy.

EUTROPHICATION POTENTIAL

Nitrate leaching and emissions of nitrous oxides from combustion of woodchips and fossil fuels are the main factors for eutrophication potential. Habit D has the highest eutrophication potential because it includes tomatoes produced in Spain--a production method with high nitrate losses. Tomatoes produced in heated greenhouse in Sweden are the main contributors to consumer Habit A. Consumer Habit B has the lowest eutrophication potential due to the low eutrophication potential of tomatoes from Swedish unheated greenhouse production. Consumer Habit C, with tomatoes from the Netherlands, has a negative eutrophication potential due to the avoided Dutch electricity production. Consumption of carrots contributes to the total eutrophication potential with 22%, 44%, 68% and 21% for Habit A, B, C and D. Nitrate leaching is an important contributor for the eutrophication potential of carrot production, and for imported carrots the impact from transportation is significant.

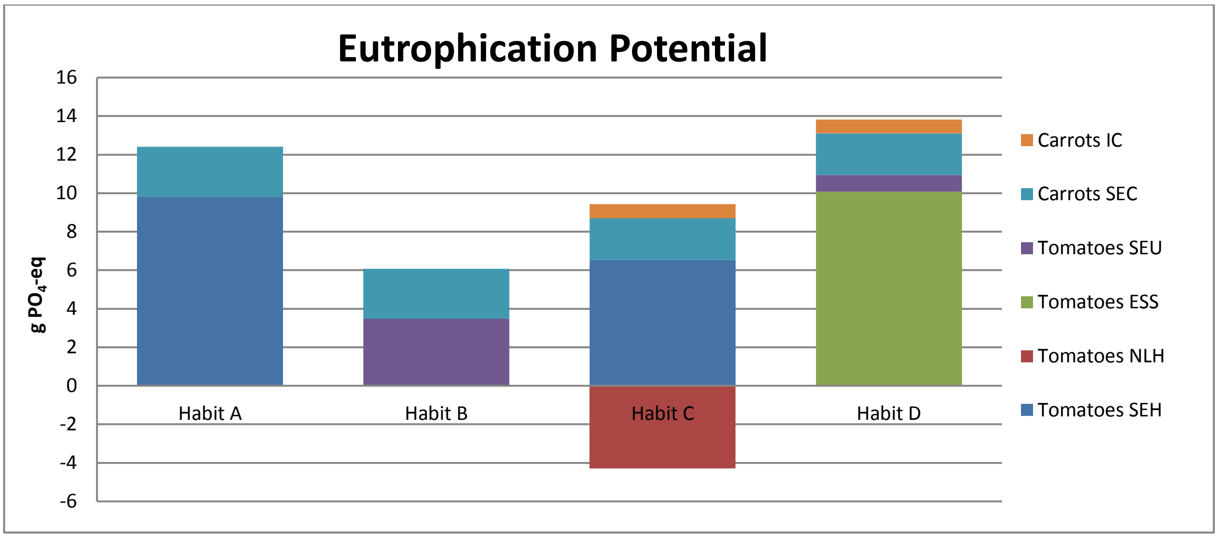

Figure 31. Eutrophication potential of the consumer habits. Where Habit A is National season with no restrictions on production system, Habit B is Local season with no extra energy, Habit C is European season no restrictions on production systems, and Habit D is European season with no extra energy.

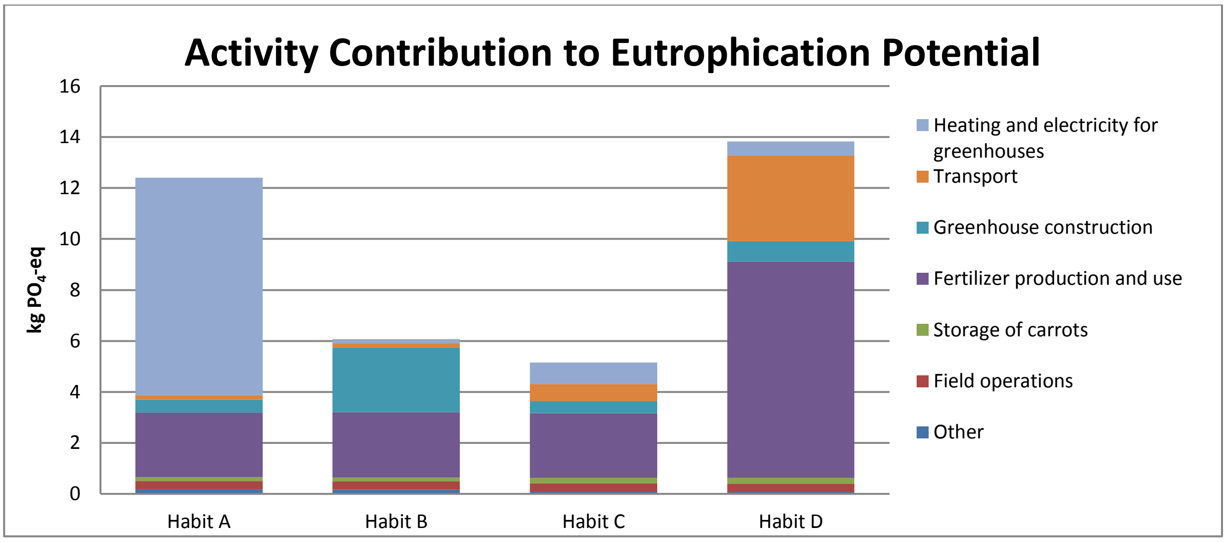

Figure 32. Eutrophication potential.
Where Habit A is National season with no restrictions on production system, Habit B is Local season with no extra energy, Habit C is European season no restrictions on production systems, and Habit D is European season with no extra energy.

APPENDIX D. PROCESSES USED IN THE INVENTORY ANALYSIS- SIMAPRO

Production Scenario	**Activity /Material**	**Process in Ecoinvent**
All scenarios	N-fertilizer[4]	Calcium nitrate, as N, at regional storehouse/RER U and
		Potassium nitrate, as N, at regional storehouse/RER U
	P-fertilizer	Single superphosphate, as P2O5, at regional storehouse/RER U
	K-fertilizer	Potassium sulphate, as K2O, at regional storehouse/RER U
	Electricity (NL)	Electricity, medium voltage, at grid/NL U
	Electricity (ES)	Electricity, medium voltage, at grid/ES U
	Electricity (SE)	Electricity, medium voltage, at grid/SE U
	Electricity (IT)	Electricity, medium voltage, at grid/IT U
	Insecticides	Insecticides, at regional storehouse/RER U
	Fungicides	Fungicides, at regional storehouse/RER U
	Transportation	Transport, lorry >32t, EURO4/RER U
	Extra energy use for refrigeration	Diesel, at regional storage/RER U
Tomato production		
	Heating woodchips	Heat, mixed chips from industry, at furnace 300kW/CH U
	Heating natural gas	Heat, natural gas, at boiler modulating <100kW/RER U
	Rockwool	Rockwool, packed, at plant/CH U
	Perlite	Expanded perlite, at plant/CH U
	Heating- natural gas CHP	
	Electricity saved NL	Electricity, production mix NL/NL U
Greenhouse construction (NL, SE)		
	Concrete	Concrete block, at plant/DE U
	Steel	Chromium steel 18/8, at plant/RER U

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[4] Greenhouse gas emission from N- fertilizer production was adjusted so that is corresponds to current production techniques in Scandinavia, meaning that one kilogram of nitrogen fertilizer as ammonium nitrate has a global warming potential of 3.1 kg CO2-eq.

	Glass	Flat glass, uncoated, at plant/RER U
	Aluminum	Aluminium, production mix, at plant/RER U
Greenhouse construction ES		
	Concrete	Concrete block, at plant/DE U
	Steel	Steel, converter, low-alloyed, at plant/RER U
	Plastic film	Polyethylene, HDPE, granulate, at plant/RER U
	Wood	Sawn timber, hardwood, raw, air dried, u=20%, at plant/RER S
Carrot production		
	Herbicides	Herbicides, at regional storehouse/RER U
Field operations		
	Pesticide application*3	Application of plant protection products, by field sprayer/CH U
	Harrowing*2	Tillage, harrowing, by rotary harrow/CH U
	Rotary cultivator*1	Tillage, rotary cultivator/CH U
	Harrowing spring*1	Tillage, harrowing, by spring tine harrow/CH U
	Plowing*1	Tillage, ploughing/CH U
	Fertilizer app. *1	Fertilising, by broadcaster/CH U
	Planting*1	Potato planting/CH U
	Harvesting*1	Harvesting, by complete harvester, beets/CH U
	Earthing up*1	Tillage, hoeing and earthing-up, potatoes/CH U
	Transp. from field	Transport, tractor and trailer/CH U

APPENDIX E. NITROGEN BALANCES AND INDIRECT EMISSIONS FOR TOMATOES

NITROGEN LOSSES IN HYDROPONIC SYSTEMS- THE NETHERLANDS AND SWEDEN

No nutrient losses to water were accounted for, since the Dutch and the Swedish greenhouse scenarios were assumed to be closed systems; meaning that the drainage water is recycled. N_2O emissions from N-fertilization in hydroponic closed systems were estimated to be 1% of applied nitrogen in accordance with Mostier et al. (1998). Other nitrogen losses also occur primarily in the form of N_2 (Daum & Schenk, 1996).

The N2O losses were estimated to be 16.3 and 17.1 kg $N_2O\text{-}N*ha^{-1}$ for the Dutch and Swedish scenario respectively.

The N_2O-N [kg $N_2O\text{-}N*ha^{-1}$] losses were estimated according to the formula

$$N_2O\text{–}N_{loss} = Ef_1 \times N_a$$

where Ef_1 is the emission factor 0.01 and N_a annual amount of nitrogen applied to the soil [kg $N*ha^{-1}$].

NITROGEN BALANCE TOMATO CULTIVATION IN SOIL- GREENHOUSE IN ALMERÍA, SPAIN

In this study volatilization and denitrification was estimated in accordance with Brentrup et al. (2000). Nitrate leaching was estimated with a nitrogen balance in combination with values from literature. All equations and emission factors were taken from Brentrup et al. (2000 Tables 7 and 8) and IPCC (2006).

NH_3-N VOLATILIZATION

NH_3 volatilization is generally low when mineral fertilizers are used, especially when mineral nitrogen is primarily applied as nitrate (Brentrup et al. 2000). In the survey made by Thompson et al (2007) around 75% of mineral nitrogen application was in the form of nitrate. Therefore, the NH_3 volatilization was estimated to be 3% of applied mineral nitrogen according to Brentrup et al (2000, Tables 7 and 8).

The NH_3-N volatilization related to fertilizer application was estimated to be 22.5 kg $NH_3\text{-}N*ha^{-1}$.

The NH_3-N [kg $NH_3\text{-}N*ha^{-1}$] losses were estimated according to the formula

$$NH_3\text{–}N_{loss} = Ef_2 \times N_a$$

where Ef_2 is the emission factor 0.03 (Brentrup et al. 2000) and N_a annual amount of nitrogen applied to the soil 750 [kg $N*ha^{-1}$].

DENITRIFICATION

N_2-N and N_2O-N losses related to fertilizer application were estimated to be, respectively, 65.5 kg $N_2\text{-}N*ha^{-1}$ and 7.275 kg $N_2O\text{-}N*ha^{-1}$.

The N_2-N [kg $N_2\text{-}N*ha^{-1}$] losses were estimated according to the formula

$$N_2\text{–}N_{loss} = Ef_3 \times N_a$$

where Ef_3 is the emission factor 0.09 (Brentrup et al. 2000) and N_a annual amount of nitrogen applied to the soil 727.5 [kg $N*ha^{-1}$].

The N_2O-N [kg $N_2O\text{-}N*ha^{-1}$] losses were estimated according to the formula

$$N_2O\text{–}N_{loss} = Ef_4 \times N_a$$

(IPCC, 2006 equation 11.2)

where Ef_4 is the emission factor 0.01 (IPCC, 2006) and N_a annual amount of nitrogen applied to the soil 727.5 [kg $N*ha^{-1}$].

Note that N- application is adjusted for volatilization as NH_3 losses most often occur before N_2 and N_2O losses. (Kroeze, 1994)

Nitrogen deposition was not taken into account. The greenhouses are protected systems which are irrigated and protected by a roof.

NITRATE LEACHING

Nitrate leaching [kg NO_3^- -N $*ha^{-1}$] was estimated using a nitrogen balance. The amount of nitrogen that was left in the soil after harvest was estimated to be 202.93 kg N $*ha^{-1}$.

Remaining nitrogen N_{rem} in the soil after harvest was estimated according to the formula

$$N_{rem} = N_a - (N_{crop} + (NH_3\text{–} N_{loss}) + (N_2\text{–} N_{loss}) + (N_2O\text{–} N_{loss}))$$

where N_a is applied amounts of nitrogen, N_{crop} is crop nitrogen uptake which was estimated to be 450 kg N*ha-1 (Vázquez et al. 2005)

The remaining amount of nitrogen in the soil after harvest was assumed to be leached in the form of nitrate. The calculated figure (202.93 kg NO_3^- -N $*ha^{-1}$) is comparable with a study of nitrate leaching from tomato cultivation in Spain (Vázquez et al. 2005). Annual drainage rate and soil capacities were not accounted for when nitrate leaching was estimated.

All above ground biomass is assumed to be removed from the greenhouse after the harvest season. Waste treatment of the biomass was not accounted for.

INDIRECT N_2O EMISSIONS

Indirect emissions of N_2O emissions from nitrate leaching and volatilization were estimated using IPCC standards (2006). Indirect N_2O emission was estimated to be 1.52 and 0.23 kg N_2O-N$*ha^{-1}$ form nitrate leaching and deposition respectively.

Indirect N_2O-N [kg N_2O-N$*ha^{-1}$] emissions from nitrogen leaching was estimated according to the formula

$$N_2O\text{–} N_{indirect} = Ef_5 \times N_{leac}$$

(IPCC, 2006 equation 11.10)

where N_2O-$N_{indirect}$ is the indirect emission from nitrate leaching, Ef_5 is the emission factor 0.0075 (IPCC, 2006) and N_{leac} is the nitrate leaching [kg NO_3^- -N $*ha^{-1}$]

Indirect emissions of N_2O due to deposition of volatile nitrogen was estimated according to the formula

$$N_2O\text{–} N_{indirect} = Ef_6 \times N_{vol}$$

(IPCC, 2006 equation 11.11)

where N_2O-$N_{indirect}$ is the indirect emission from volatilized nitrogen, Ef_6 is the emission factor 0.01 (IPCC 2006) and N_{vol} is the fraction that volatilizes [kg NH_3-N$*ha^{-1}$]

APPENDIX F. NITROGEN BALANCES AND INDIRECT EMISSIONS FOR CARROTS

THE NETHERLANDS AND SWEDEN FERTILIZER APPLICATION RELATED EMISSIONS

NITROGEN DEPOSITION

Atmospheric deposition of nitrogen was estimated to be 20 kg for the Dutch scenario (Brentrup et al. 2000), 16.2 kg N*ha^{-1} for the Swedish scenario (Falkengren- Grerup & Diekmann, 2002) and 10 kg N* ha^{-1} for the Italian scenario (Brentrup et al. 2000).

NH_3-N VOLATILIZATION

NH_3 volatilization was estimated to be 2.0, 2.7 and 1.25 kg NH_3-N*ha^{-1} for the Italian, Dutch and Swedish Scenarios. Mineral fertilizers were assumed to be applied primarily as nitrate, therefore, the 1% (Sweden) and 2% (Italy and the Netherlands) were assumed to volatilize (Brentrup et al. 2000).

$$NH_3 - N_{loss} = Ef_2 \times N_a$$

where Ef_2 is the emission and N_a is annual amount of nitrogen applied to the soil [kg N*ha^{-1}].

DENITRIFICATION

N_2-N and N_2O losses related to fertilizer application was estimated to be 12.0 kg N_2-N*ha^{-1} and 1.34 kg N_2O-N*ha^{-1} for the Dutch scenario and 11.1 kg N_2-N*ha^{-1} and 1.24 kg N_2O-N*ha^{-1}, for the Swedish scenario and 9.09 kg N_2-N*ha^{-1} and 1.01 kg N_2O-N*ha^{-1} for the Italian scenario. Emission factors were taken from Brentrup et al. 2000 and IPCC (2006).

N_2-N losses were estimated according to the formula

$$N_2 - N_{loss} = Ef_3 \times N_a$$

where Ef_3 is the emission factor 0.09 (Brentrup et al. 2000) and N_a annual amount of nitrogen applied to the soil [kg N*ha^{-1}].

The N_2O-N [kg N_2O-N*ha^{-1}] losses were estimated according to the formula

$$N_2O - N_{loss} = Ef_4 \times N_a$$

(IPCC, 2006 Equation 11.)

where Ef_4 is the emission factor 0.01 (IPCC, 2006) and N_a annual amount of nitrogen applied to the soil [kg N*ha^{-1}].

Note that nitrogen application is correlated for volatilization as NH_3 losses most often occur before N_2 and N_2O emissions. (Kroeze, 1994)

NITROGEN BALANCE

The amount of nitrogen that was left in the soil after harvest was estimated to be 47.5, 38.6 and 31.9 kg N *ha^{-1} for the Dutch, Swedish and Italian scenarios respectively.

Remaining nitrogen N_{rem} in the soil after harvest was estimated according to the formula

$$N_{rem} = (N_a + N_{dep}) - (N_{crop} + (NH_3 - N_{loss}) + (N_2 - N_{loss}) + (N_2O - N_{loss}))$$

where N_a is applied amounts of nitrogen, N_{dep} is deposition and N_{crop} is crop nitrogen uptake which was estimated to be 89kg N*ha-^{1} (Rahn, 2000) [5] for the Swedish and Dutch scenario and 69 kg N*ha-^{1} (Rahn, 2000)[6] for the Italian scenario.

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[5] Crop nitrogen uptake is based on a marketable yield of 60-68 tons*ha^{-1} (Rahn (2000))

NITRATE LEACHING

Nitrate leaching was estimated with a nitrogen balance in combination with values from literature. For now nitrate leaching was estimated to be 40.5% of the remaining nitrogen in the soil, based on Breeuwasma et al., 1987 in Audsley et al., 1997.The figure is for Dutch conditions on sandy soil. Nitrate leaching was estimated to be 13, 19 and 16 kg NO_3-N $*ha^{-1}$ for the Italian, Dutch and Swedish scenarios.

NITROGEN CONTENT IN CROP RESIDUES AND RELATED N_2O EMISSIONS

All non-yield biomass was assumed to be left on the carrot field. The amount of nitrogen in crop residues depends on yield and was calculated to be 88 kg $N*ha^{-1}$ assuming a yield of 61 $tons*ha^{-1}$, 85 kg $N*ha^{-1}$ assuming a yield of 56 tons and 75 $N*ha^{-1}$ assuming a yield of 46 $N*ha^{-1}$; all was calculated using the IPCC standards (2006 equation 11.6). 1% of this nitrogen was assumed to denitrify to N_2O (0.88 kg N2O-$N*ha^{-1}$). Indirect N_2O emissions from crop residues was, therefore, estimated to be 0.88, 0.85 and 0.75 kg N_2O-$N*ha^{-1}$ for the Dutch, Italian and Swedish scenario respectively.

INDIRECT N_2O EMISSIONS

Indirect emissions of N_2O emissions from nitrate leaching were estimated using IPCC standards (2006). Indirect N_2O emission was estimated to be 0.10, 0.14 and 0.12 kg N_2O-$N*ha^{-1}$ from nitrate leaching for the Italian, Dutch and Swedish scenarios.

Indirect N_2O-N [kg N_2O-$N*ha^{-1}$] emissions from nitrogen leaching was estimated according to the formula

$$N_2O\text{–}\,N_{indirect} = Ef_5 \times N_{leac}$$

(IPCC, 2006 equation 11.10)

where $N_2O\text{-}N_{\ indirect}$ is the indirect emission from nitrate leaching, Ef_5 is the emission factor 0.0075 (IPCC, 2006) and N_{leac} is the nitrate leaching [kg NO_3^- -N $*ha^{-1}$]

Indirect emissions of N_2O due to deposition of volatile nitrogen was estimated according to the IPCC (2006) and were estimated to be 0.02, 0.03 and 0.01 kg N_2O-$N*ha^{-1}$ for the Italian, Dutch and Swedish scenarios.

Indirect emissions of N_2O due to deposition of volatile nitrogen was estimated according to the formula

$$N_2O\text{–}\,N_{indirect} = Ef_6 \times N_{vol}$$

(IPCC, 2006 equation 11.11)

where $N_2O\text{-}N_{\ indirect}$ is the indirect emission from volatilized nitrogen, Ef_6 is the emission factor 0.01 (IPCC 2006) and N_{vol} is the fraction that volatilizes[kg NH_3-$N*ha^{-1}$]

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[6] Crop nitrogen removal was estimated from Rahn (2000) and is based on a marketable yield of 60-68 $tons*ha^{-1}$. Crop nitrogen removal was correlated for the lower yield.

APPENDIX G. THE IMPORTANCE OF HARVEST AND STORAGE LOSSES FOR THE RESULTS OF THE CARROT- LCA

Changing the harvest and storage losses to 1% does not change the ranking of the results for arable land use and acidification potential.

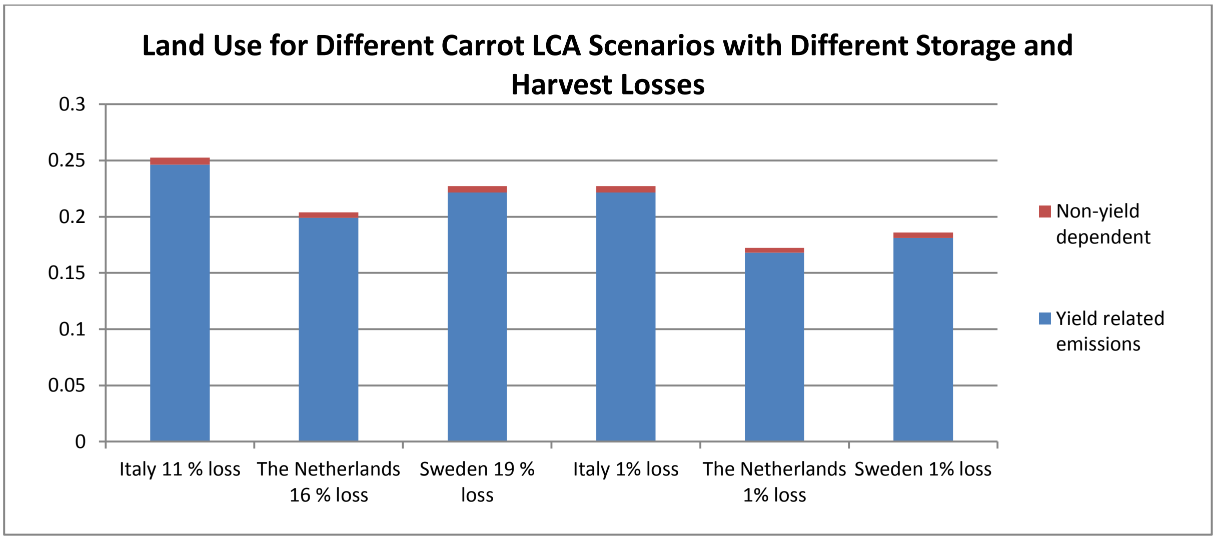

Figure 33. Land use and the effects of changed harvest and storage losses.

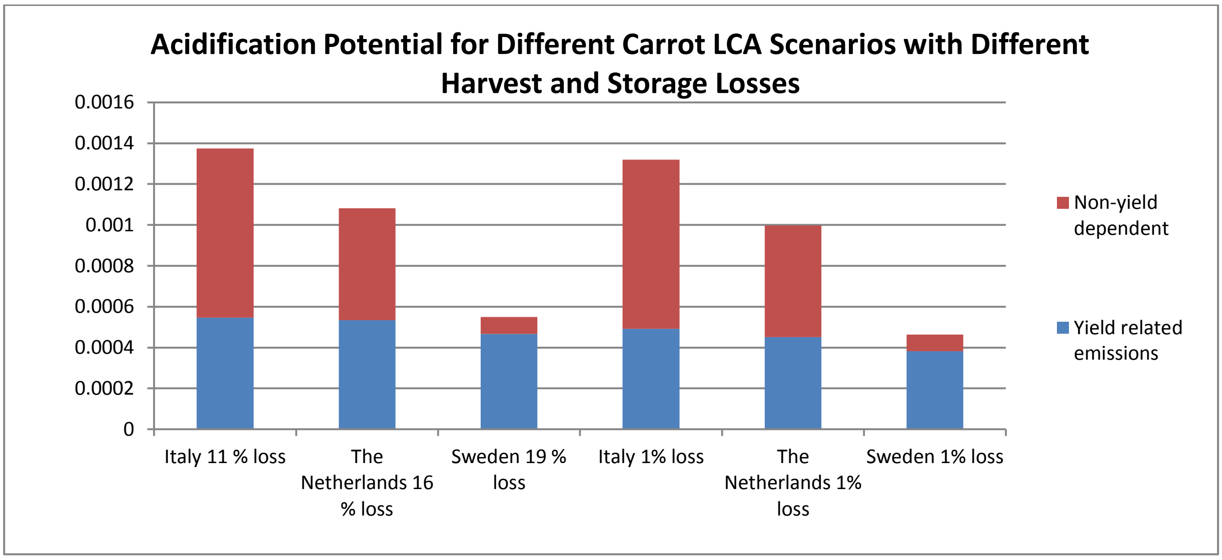

Figure 34. Acidification potential and the effects of harvest and storage losses.

APPENDIX H. LIST OF FIGURES AND TABLES

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