Lappeenranta University of Technology
Faculty of Technology
Master's Degree Programme in Energy Technology

Raghu KC

COMPARATIVE LIFECYCLE ASSESSMENT ON ORGANIC AND CONVENTIONAL CARROTS – CASE: CARROTS FROM SOUTH-SAVO AND IMPORTED CARROTS FROM ITALY

Examiner: Prof. Tapio Ranta
Supervisor: Dr. Eero Jäppinen
Lappeenranta, September 3, 2014

ABSTRACT

Lappeenranta University of Technology
Faculty of Technology
Master's Degree Programme in Energy Technology

Raghu KC

Comparative Lifecycle Assessment of Organic and Conventional Carrots - Case: Carrots from South-Savo and Imported Carrots from Italy

2014

49 Pages, 13 appendices

Examiners: Professor Tapio Ranta
Dr. Eero Jäppinen

Key words: lifecycle assessment, greenhouse gas, energy demand, organic farming, carrots

Organic farming is perceived to be an environmental friendly method of food production, thus assumed to be an alternative means of minimizing food-based environmental footprints. However, lower yield and unproductive years in organic crop rotation raise questions of whether it is really an environmentally friendly farming practice. Thus, the aim of this thesis was to examine the carbon footprint and energy demands of organic carrots cultivated and sold in South-Savo, Finland and compare them with those of local and imported conventional carrots using lifecycle assessment (LCA) as a method.

From the investigation, it was found that organic carrots produced in South-Savo have the lowest GHG emissions and energy demand. The GHG emissions of local organic, local conventional and imported conventional carrots were found to be 4g CO_2 eq. $kg_{carrots}^{-1}$, 142g CO_2 eq. $kg_{carrots}^{-1}$ and 280 g CO_2 eq. $kg_{carrots}^{-1}$, respectively. On the other hand, energy demand for those carrots was found to be 1,33 MJ, 1,88 MJ and 3,68 MJ $kg_{carrots}^{-1}$. Furthermore, it was also found that local organic carrots would have approximately similar GHG emissions as conventional counterpart if soil carbon stock change was excluded from the study.

ACKNOWLEDGEMENTS

This work was carried out in the Department of Energy Technology, Lappeenranta University of Technology, in Lappeenranta. This thesis is funded by LUT foundation.

I would like to thank my supervisors Dr. Eero Jäppinen and Prof. Tapio Ranta for their unprecedented support throughout the work. I would also like to thank Sari Iivonen from Ruralia Institute for valuable information regarding local farming. A big thanks to good friend Michael Child for his support on language issues.

Last but not least, this work would not have been completed without the unconditional support from my lovely wife, Laxmi Ranabhat.

Raghu KC

Lappeenranta, September 3, 2014

TABLE OF CONTENTS

LIST OF ABBREVIATIONS **4**
LIST OF TABLES **9**
LIST OF FIGURES **9**
1 INTRODUCTION **10**
1.1 Background 10
1.2 Objective 11
2 LITERATURE REVIEW **13**
2.1 Main Features 13
2.2 Analysis 17
2.2.1 Product System and System Boundaries 17
2.2.2 Co-product Allocation 17
2.2.3 Energy Demand 18
2.2.4 GHG Emission 18
2.2.5 Crop Rotation in Organic Farming 20
3 MATERIALS AND METHODS **21**
3.1 Farm Model 21
3.1.1 Organic Crop Rotation Farm Model 21
3.1.2 Conventional Carrots 22
3.2 LCA as a Method 23
3.3 Goal and Scope Definition 24
3.3.1 Functional Unit 24
3.3.2 System Boundary and Delimitation 25
3.3.3 Allocation and System Expansion 27
3.4 Life Cycle Inventory Analysis (LCI) 27
3.4.1 Soil Emissions and Soil Carbon Stock Change 28
4 RESULTS **30**
4.1 Life Cycle Impact Assessment (LCIA) 30
4.2 Interpretation 36
4.2.1 Sensitivity Analysis 36
4.2.2 Comparison with Previous Studies 40
5 DISCUSSION **42**

5.1 Implications 42
5.2 Role of N-fixing Ley Cultivation and its Explicitness 42
5.3 Importance of Allocation Method 43
5.4 Role of Packaging... 43
5.5 Role of Transportation.. 43
5.6 Need for Further Research... 44
REFERENCE **45**
APPENDICES **50**

LIST OF ABBREVIATIONS

DM	Dry matter
EF	Emission factor
GHG	Greenhouse gas
GWP	Global warming potential
HDPE	High density polyethylene
IFOAM	International federation of organic agriculture movements
IPCC	International panel on climate change
ISO	International organization for standardization
LCA	Lifecycle assessment
LCIA	Lifecycle impact assessment
LCI	Lifecycle inventory
PELD	Low density polyethylene
PP	Polypropylene
SNF	Symbiotic nitrogen fixation

Units

g	gram
ha	hectare
MJ	mega joules
kg	kilogram
t	tonne

LIST OF TABLES

Table 1. Classification of reviewed studies. 14

Table 2. Organic crop rotation for carrot as a main crop.. 22

Table 3. Data used for calculation of carbon footprint and energy demand.............. 29

Table 4. Lifecycle phases of all three types carrots and their environmental impacts. 31

LIST OF FIGURES

Figure 1. Map of carrots farms 12

Figure 2. Schematic map of carrots supply chain 23

Figure 3. Stages of an LCA. 24

Figure 4. System boundaries for organic crop rotation.. 26

Figure 5. System boundaries for conventional carrot. 26

Figure 6. GWP_{100} of carrots of all three scenarios.. 32

Figure 7. Contribution analysis regarding GHG emission from lifecycle phases of carrots production and supply chain presented in g CO_2 eq. kg_{carrot}^{-1}. 33

Figure 8. Energy consumption per kg carrot for all three types of carrots with relative contribution. 34

Figure 9. Impacts of soil emission factor uncertainty on total GHG emission.......... 35

Figure 10. Sensitivity analysis regarding GHG emissions from waste management. 37

Figure 11. Sensitivity analysis regarding energy production from waste incineration. 37

Figure 12. Sensitivity analysis regarding GHG emissions from carrots available in different packages. 39

Figure 13. Sensitivity analysis regarding energy demand of carrots available in different packages. 39

1 INTRODUCTION

1.1 Background

Agriculture has been a major source of global greenhouse gas (GHG) emissions, which contribute to climate change. According to Niggli *et al.* (2008), agriculture causes 10-12% of global GHG emissions through energy use, livestock, fertilizer production, pesticide production, machineries, land use change and soil degradation. Yet, agriculture has been considered as an opportunity to mitigate GHG gas emissions by building soil fertility and avoiding industrial fertilizers and pesticides (Niggli *et al.* 2008; FAO 2011). Such practice is defined as organic agriculture by the International Federation of Organic Agriculture Movements (IFOAM) (Luttikholt 2007).

According to IFOAM organic agriculture is defined as:

> *Organic Agriculture is a production system that sustains the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic Agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved.* (IFOAM 2014)

Furthermore, organic agriculture has four principles, namely, health, ecology, fairness and care. Organic agriculture should comply with the production of high quality food without using mineral fertilizers, synthetic pesticides and other chemicals that are believed to have adverse effects on health and environment. In addition, it should not distort natural systems and cycles while keeping fair and respectful relationships between living beings. Finally, organic agriculture demands precautionary and responsible management, development and selection of technology while respecting indigenous knowledge. (Luttikholt 2007)

Organic farming is often perceived to be an environmentally-friendly production method because it eliminates the use of mineral fertilizers and synthetic chemicals (Grönroos *et al*. 2006; Meisterling *et al.* 2009). In order to replace synthetic fertilizers, N-fixing crops such as leguminous crops are grown. Leguminous crops belong to the

Fabaceae family, which includes plants such as alfalfa, clover and pea. The root nodules of these plants contain symbiotic bacteria called *Rhizobium* and they are able to fix atmospheric nitrogen (N_2) into a usable form such as ammonia (NH_3) (Wagner 2011).

Furthermore, organically produced food products are often believed to be tastier and healthier than traditionally produced products (Gracia *et al.* 2008). Such perceptions may have led to the growing consumption of organic food products (Rigby *et al.* 2001). The growing consumption of organically grown food may result in growing concern about its environmental impacts specifically on climate change.

However, cultivation of leguminous crops along with organic crop rotation results in lack of food production during that time, which means a low production rate. **S**tudies such as Tuomisto *et al.* (2012) and Nemecek *et al.* (2011) have reported that climate change effects may be counterbalanced by the reported lower yield from organic farming compared to conventional farming. On the other hand, Knudsen *et al.* (2010) argue that soaring global demand for organic products and consequently increased imports has led to longer distances travelled by the products, which may result in increased environmental loadings.

1.2 Objective

The objective of this thesis is to compare the GHG emissions and energy demands from organic and conventional carrots available in Finnish supermarkets and identify the environmental hot spots along the supply chain. Finnish organic carrots are grown in five-year crop rotations whereas conventional carrots are grown using synthetic fertilizers and crop protection chemicals. In addition, conventional carrots imported from Italy are also compared with locally produced counterparts.

Lifecycle assessment (LCA) is used as a tool to calculate environmental impacts. In this study, the environmental impact refers to impact categories, namely, global warming potential (GWP) and energy consumption. GWP and energy demands are calculated in gram CO_2 equivalent (g-CO_2 eq.) in a 100-year time horizon and mega joules (MJ), respectively. The purpose of calculating energy demands is to provide insights from a consumption point of view as energy is a significant issue in the agriculture sector.

Figure 1. Map of carrot farms. (Google Map 2014)

2 LITERATURE REVIEW

Generally, LCA is primarily focused on industrial products and processes. However, growing concern about sustainable food production and human food consumption habits has motivated the need for research on the environmental impacts of agriculture (Roy *et al*. 2009). In this section, a number of studies investigating LCA on field grown products is investigated.

2.1 Main Features

Fifteen peer-reviewed journal articles (published 2006 or later) performing LCAs of one or more agricultural products were reviewed in order to gain insight into energy use and GHG emissions from agriculture. The details of LCAs are illustrated in Table 1. The impact categories listed in Table 1 are further illustrated in Appendix 8.

Table 1. Classification of reviewed studies. GWP100 = global warming potential with 100-year time frame, POCP= photochemical ozone creation potential, EP= eutrophication potential, AP= acidification potential, AEP= aquatic ecotoxicity potential, TETP= terrestrial ecotoxicity potential, HTP= human toxicity potential, DM= dry matter, LU= land use, ODP= ozone depletion potential, NRE= non-renewable energy, CED= cumulative energy demand, GWP500 = global warming potential with 500 year time frame, t= tonne, ha= hectare, kg= kilogram, g = gram, y= year

Product(s)	**Studied product system**	**Impact categories**	**Functional Unit**	**System boundaries**	**Location**	**Authors**
Spring barley, fava bean, potatoes, wheat	Comparative LCA of organic and conventional arable crop rotations on their carbon footprints	GWP_{100}	1 kg DM	Cradle-to-farm gate	Denmark Germany	(Knudsen *et al.* 2013)
Potato, winter wheat, beetroot, winter barley and grass clover	Comparative LCA of organic and integrated farming systems	Energy, GWP_{100}, POCP, EP, AP, AEP, TETP and HTP	1 ha and y and 1 kg DM	Cradle-to-gate	Switzerland	(Nemecek *et al.* 2011)
Winter wheat, potato, winter barley, spring beans, cabbages, grass clover	Comparative LCA of organic and conventional food production systems	GWP_{100}	1 ha and y and 1 GJ human food energy	Cradle-to-farm gate and cradle-to-societal gate	UK	(Cooper *et al.* 2011)
Leek	Comparative LCA of organic and conventional leek production	GWP_{100}, ADP, HTP, TETP, POCP, AP and EP	1 kg product and 1 m^2 area	Cradle-to-farm gate	Belgium	(De Backer *et al.* 2009)
Rye bread	Energy demand study on organic and conventional rye production	Energy	1 t rye bread	Cradle-to-bakery gate	Finland	(Grönroos et al. 2006)
Wheat	Comparative LCA on organic and conventional wheat bread production	Energy and GWP_{100}	1 kg bread	Cradle-to-bakery gate	USA	(Meisterling *et al.* 2009)
Winter wheat	Comparative LCA on organic, conventional and integrated winter wheat production	Energy and GWP_{100}	1 t wheat with 86% DM and 1 ha farm	Cradle-to-farm gate	UK	(Tuomisto *et al.* 2012)

Table 1. Continued. GWP100 = global warming potential with 100 year time frame, POCP= photochemical ozone creation potential, EP= eutrophication potential, AP= acidification potential, AEP= aquatic ecotoxicity potential, TETP= terrestrial ecotoxitciy potential, HTP= human toxicity potential, DM= dry matter, LU= land use, ODP= ozone depletion potential, NRE= non-renewable energy, CED= cumulative energy demand, GWP500 = global warming potential with 500 year time frame, t= tonne, ha= hectare, kg= kilogram, g = gram

Product(s)	**Studied product system**	**Impact categories**	**Functional Unit**	**System boundaries**	**Locations**	**Author(s)**
Wheat	Environmental analysis of intensity level in wheat production	Energy LU, GWP_{500}, POCP, AP, EP, AEP, TETP and HTP	1 t product 1 ha and 1 t (protein corrected product)	Unspecified	Switzerland	(Charles *et al.* 2006)
Pepper, Tomato, Cherry tomato, Melon, Zucchini	LCA on various protected crops grown in greenhouse	Energy, GWP_{100}, ODP, POCP, AP and EP	1 t packaged vegetables	Cradle-to-grave	Italy	(Cellura *et al.* 2012a)
Pepper, Tomato, Cherry tomato, Melon, Zucchini	LCA on various protected crops grown in greenhouse in southern Italy	Energy, GWP_{100}, ODP, POCP, AP and EP	1 t packaged vegetables	Cradle-to-grave	Italy	(Cellura *et al.* 2012b)
Potato	Lifecycle GHG emissions and energy consumption during potato production	NRE and GWP_{100}	1 ha	Cradle-to-farm gate	Iran	(Pishgar-Komleh *et al*. 2012)
Blueberry and raspberry	Lifecycle GHG emissions and energy consumption from blueberry and rasp berry production	Energy and GWP_{100}	125g flow pack	Cradle-to-grave	Italy	(Girgenti *et al*. 2013)

Table 1. Continued. GWP100 = global warming potential with 100 year time frame, POCP= photochemical ozone creation potential, EP= eutrophication potential, AP= acidification potential, AEP= aquatic ecotoxicity potential, TETP= terrestrial ecotoxicity potential, HTP= human toxicity potential, DM= dry matter, LU= land use, ODP= ozone depletion potential, NRE= non-renewable energy, CED= cumulative energy demand, GWP500 = global warming potential with 500 year time frame, t= tonne, ha= hectare, kg= kilogram, g = gram

Product(s)	**Studied product system**	**Impact categories**	**Functional Unit (FU)**	**System boundaries**	**Locations**	**Author(s)**
Soybean	Comparative LCA on organic and conventional soybean delivered to Denmark from China	NRE, LU, GWP_{100}, AP and EP	1 t soybean delivered to Denmark	Cradle-to-farm gate	Denmark China	(Knudsen *et al.* 2010)
Tomato	LCA of tomatoes in a multi-tunnel greenhouse in Almeria	CED, AD, EP, GWP_{100}, POPC and AP	1 t loose classic tomatoes	Cradle-to-farm gate	Spain	(Torrellas *et al.* 2012)
Grass clover, cereals, row crops and permanent grass	Comparative assessment of fossil energy use in organic and conventional agricultural systems	Energy	1 kg soybean meal delivered to Rotterdam from Argentina	Cradle-to-gate	Denmark Argentina	(Dalgaard *et al.* 2008)

2.2 Analysis

2.2.1 Product System and System Boundaries

Ideally, LCA should start as the natural system ends and technological system starts. However, in agriculture, integration of a biological system as a part of the production phase makes it complicated to isolate the technological sphere (Schau *et al.* 2008). Many of the reviewed studies have set initial boundaries at input production and end at the farm gate. Such system is known as cradle-to-farm gate. Among the reviewed studies, the majority of them have set their system boundaries at the farm gate, except for Meisterling *et al.* (2009), who have extended their research further by including post-harvest transportation from China to Denmark in order to determine the impacts of long haul transportation. In contrast, studies by Girgenti *et al.* (2013), Cellura *et al*. (2012a) and Cellura *et al.* (2012b) have included waste management in their study, referred to as cradle-to-grave.

2.2.2 Co-product Allocation

According to ISO 14040 (2006), allocation is: "Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems". ISO 14040 (2006) suggests that allocation should primarily be avoided by expanding the product system. However, in situations where system expansion is not possible, the inputs and outputs should be allocated to respective products based on the underlying physical relationships or economic values.

Dalgaard *et al.* (2008) have avoided allocation through system expansion in their study. The main product of their product system is soybean meal whereas soybean oil, as a co-product, replaces traditional vegetable oil. The product system is expanded in such a way that soybean oil compensates the environmental loadings which would have occurred from vegetable oil production. In contrast, Grönroos *et al.* (2006) have allocated potential burden from set-aside land and cultivated land by their physical properties such as area. Similarly, Nemecek *et al.* (2011) have allocated grain and straw by their economic value, in which 90-93% of environmental loadings are allocated to grain and the rest to straw.

Knudsen *et al.* (2013) have allocated environmental loadings of green manure and catch crops cultivation in crop rotation based on the area (ha) where cash crops were cultivated. In contrast, Tuomisto *et al.* (2012) have allocated impacts from cultivation of ley to other crops based on their N- content.

2.2.3 Energy Demands

In agricultural LCAs, some of the elements such as infrastructure, seeds, human energy, and manure uses are considered to be crucial for the energy demands study. Most of the studies on energy consumption are performed in two phases: direct and indirect. The direct energy demands refers to direct use of energy sources such as fuel needed for machine operation as well as electricity and heat uses for drying and other purposes. Indirect energy demands refers to energy consumed during indirect processes such as the manufacture of machineries, fertilizers and other inputs.

2.2.4 GHG Emissions

The majority of studies have calculated GHG emissions from organic and conventional farming. The emissions from various lifecycle stages such as background and foreground are well attributed in the study. The emissions from those phases which are not directly involved in farming activities such as fertilizer, pesticides and machinery production fall under background emissions. On the other hand, foreground emissions refer to emissions from farm activities such as tractor mechanization, grain drying, washing, packaging and transport.

Manure

In organic farming, manure is often applied as an additional source of N. Due to its complicated production process and it has its own lifecycle phases itself, it could be considered as waste product from livestock production. However, manure handling and application could fall within the system boundary as done by Knudsen *et al.* (2010) and De Backer *et al*. (2009).

Seed

In food LCAs, environmental loadings from seed production have been a subject of consideration. Nemecek *et al.* (2011) have included seed production and its environmental burden in their studies whereas Tuomisto *et al.* (2012) and Knudsen *et al.* (2010) have accounted N inputs from seed sown. In contrast, Knudsen *et al.* (2010), Cellura *et al*. (2012a), Meisterling *et al.* (2009) and Cellura *et al.* (2012b) have excluded seed production from their study.

Soil Carbon Stock Change

Atmospheric CO_2 can be transferred into long-lived sinks such as soil by implementing suitable farming practices (Lal 2004). Such a phenomenon is known as carbon sequestration. However, the role of carbon sequestration in agricultural LCAs has been the subject of consideration because net sequestration occurs only when a certain soil management practice is adopted and until it reaches equilibrium (Tuomisto *et al.* 2012; Lal 2004).

All of the studies except Knudsen *et al.* (2013) have opted to exclude soil carbon change and its impact on climate change. However, Knudsen *et al.* (2013) have highlighted the importance of soil carbon stock change in organic farming and thus opted to include carbon sequestration in organic crop rotation assuming conventional rotation as a baseline scenario.

Soil Emissions

In-field emissions of GHG are attributed in the reviewed food LCAs. In-field emissions refer to nitrous oxide (N_2O) emissions due to anthropogenic N incorporated into the soil and CO_2 emissions due to lime application. According to the Intergovernmental Panel on Climate Change (IPCC) (2006), emissions of N_2O from managed soils are divided into two: direct and indirect emission. Direct emissions of N_2O occur when anthropogenic N is applied to the soil via synthetic N fertilizer, manure, crop residues and symbiotic nitrogen fixation (SNF). In addition, cultivation of organic soil also contributes to direct emissions. On the other hand, indirect emissions of N_2O occur due to leached and atmospherically deposited N.

The majority of the reviewed studies have calculated soil emissions according to the guideline set by the 2006 edition of IPCC while Nemecek *et al.* (2011) and Dalgaard *et al.* (2008) have followed older editions of the guidelines such as IPCC 2001 and IPCC 2000, respectively.

2.2.5 Crop Rotation in Organic Farming

Among the reviewed articles, Cooper *et al.* (2011) and Knudsen *et al*. (2013) have conducted LCAs based on crop rotation where the latter have also analyzed impacts from individual crops. The authors believe that crops in organic farming are interlinked, as cash crops depend on N fixed by green manure crops. Thus, the impacts and benefits from these green manure crops should be allocated to the crops that have financial benefits. The idea of allocating impacts of non-cash crops to cash crops is also documented elsewhere as Tuomisto *et al.* (2011) have allocated impacts of ley cultivation based on the N-content of cash crops. In contrast, Grönroos *et al*. (2006) have allocated energy related impacts during ley cultivation to cash crops based on their respective masses.

3 MATERIALS AND METHODS

The study presents comparative LCA of organic carrots with conventional carrots grown in the South-Savo region of Finland. Mikkeli, the biggest city in the region (61.7° N, 27.3° E), is considered as a place of consumption for the agricultural products. In addition, the study also compares results from conventional carrots grown in Sicily (37.5° N, 14° E), Italy and brought to Mikkeli. A geographical illustration of location is presented in Figure 1.

3.1 Farm Model

3.1.1 Organic Crop Rotation Farm Model

A realistic five-year crop rotation has two cash crops: organic rye (*Secale cereale*) and carrot *(Daucus carota)* that are grown in the third and fifth year, respectively. A mixture of N-fixing clover grasses such as red clover (*Trifolium pretense)* and timothy (*Phleum pratense)* are grown during the first and second year whereas a mixture of catch crops such as oat (*Avena sativa*), pea (*Pisum sativum*) and vetch (*Vicia sativa*) is grown during the fourth year. The residues from the first year are incorporated into the soil as a green manure. Furthermore, the first cut of the second year green manure is used as fodder that replaces feed barley whereas the second cut is incorporated into the soil as a green manure. Similarly, residues from a mixture of grass are also incorporated into the soil. The crop rotation and DM yield is further illustrated in Table 2.

Table 2. Organic crop rotation for carrot as a main crop. Note that total DM yield of cash crops from crop rotation is 5,79 t ha^{-1} in which rye and carrots contribute by 33% and 67%, respectively.

Year	**Crops**	**Purpose**	**Residues incorporated into the soil (t DM ha^{-1})**	**Yield (t DM ha^{-1})**	**Comment**
1	Red Clover (25%) + Timothy (75%)	Green manure	7 [a]		Two cuts incorporated into soil
2	Red Clover (25%) + Timothy (75%)	Forage + Green manure	10 [a]	4 [a]	First cut for forage, second cut incorporated into soil
3	Rye	For sale	3,6 [c]	1,89[b]	
4	Pea-oat-vetch	Catch crop	9,5 [a]		Incorporated into soil
5	Carrot	For sale (main crop)	0,9 [c]	3,9 [d]	Fresh yield of 30 t ha^{-1} that contains 87% moisture

[a] (Leinonen 2014)
[b] (Grönroos *et al.* 2006)
[c] NIR (2013), calculated from IPCC default values
[d] (Iivonen 2013)

3.1.2 Conventional Carrots

Conventional carrots are grown using crop protection chemicals and synthetic fertilizers. The distance from Finnish farms to sales points is assumed to be the same as for organic farms. The post-harvest activities for conventional carrots are the same as for organic carrots but as per the Sicilian carrots, they are first washed and packaged in the farmyard and transported by trucks to Travemunde, Germany to be shipped to Helsinki by ocean-going bulk commodity carrier. From Helsinki carrots are transported to Mikkeli by truck. In addition, both truck and ship are refrigerated all the way from Sicily to Mikkeli. The schematic supply chains of organic and conventional carrots are illustrated in Figure 2.

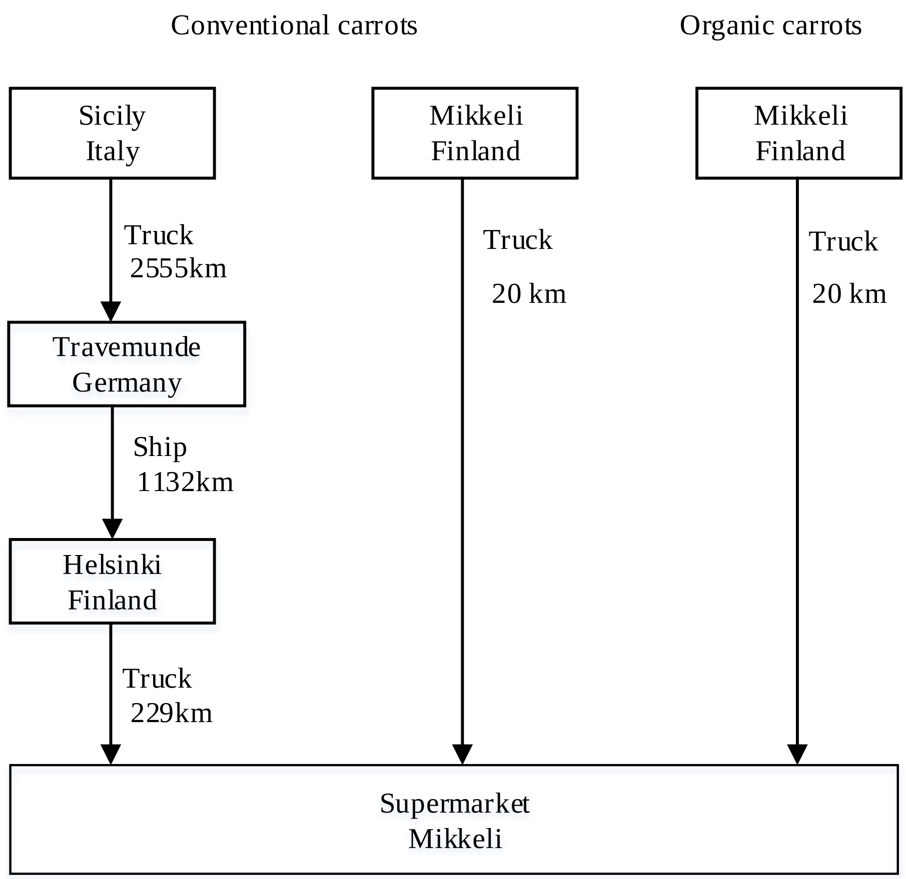


Figure 2. Schematic map of carrots supply chain.

3.2 LCA as a Method

The LCA is a tool to assess potential environmental impacts of a product throughout its lifecycle starting from raw material acquisition to final disposal. It is generally guided internationally by ISO. According to the standard ISO 14040 (2006), LCA has four major phases: goal and scope definition, inventory analysis, impact assessment and interpretation. These four phases are iterative processes where results from individual phases may be used in other phases. The LCA stages and framework is illustrated in Figure 3. (ISO 14040 2006)

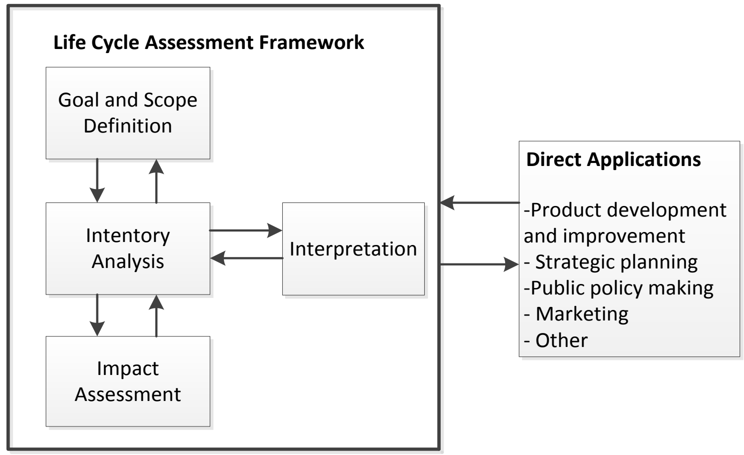


Figure 3. Stages of an LCA. (ISO 14040 2006)

3.3 Goal and Scope Definition

Goal and the scope definition is one of the most important phases in LCA. The purpose of the study, intended applications, system boundary and functional unit of the study are defined in this phase. The purpose of the functional unit is to provide the reference unit related to the input and output flows. (ISO 14040 2006) The goal of this study is already described in Section 1.2.

3.3.1 Functional Unit

The functional unit of the study is a package of one kg carrots delivered to a supermarket in Mikkeli quantified as 'kg_{carrot}' in this study. A package refers to a low-density polyethylene (PELD) bag. In addition, as a sensitivity analysis, carrots available in Finnish supermarkets in different forms, such as those sold in open corrugated boxes (both washed and unwashed), are compared in order to identify the best packaging solution in terms of GHG emissions and energy demands.

3.3.2 System Boundary and Delimitation

This study covers cultivation of crops and transportation to the supermarket, thus, could be defined as cradle-to-gate, meaning storage in supermarkets and transportation to the consumers' households are not taken into account. The pre-farm activities include electricity, fuels and packaging material production. Since the cattle manure is assumed to be waste from a livestock farm, the environmental cost of manure production has been excluded from this study. However, fuel consumption during manure loading and spreading is taken into account. Furthermore, farm waste management, seeds and machinery production as well as farm buildings are excluded from the study. In addition, carbon sequestration is included only in organic carrots calculations, assuming conventional carrot farming as a baseline scenario.

However, packaging waste incineration after the consumption of carrots and its impacts are investigated in a sensitivity analysis. The energy production from waste incineration is accounted as negative energy demand. Furthermore, the energy produced from waste incineration replaces traditional fossil-based energy, thus fossil-based emissions that would have occurred in the absence of waste incineration is accounted as avoided emissions.

A separate LCA on avoided organic feed barley is conducted according to a cradle-to-gate system. Further information on inputs and avoided emissions are illustrated in Table 3 and Appendix 7. The system boundary regarding organic crop rotation and conventional carrot cultivation are presented in Figures 4 and 5.

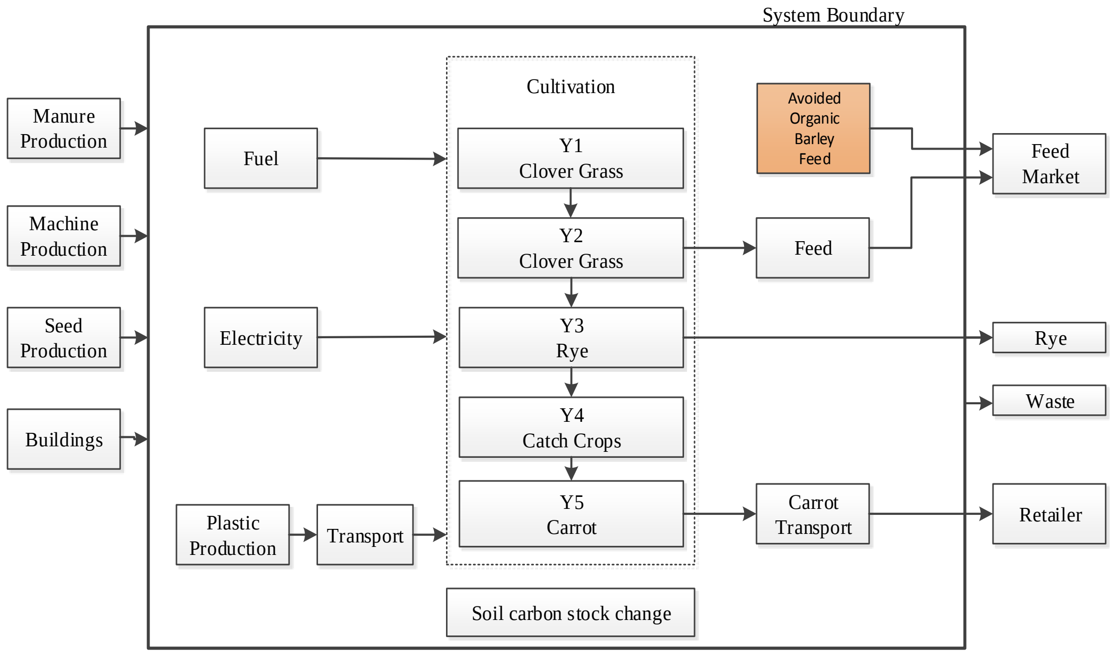


Figure 4. System boundaries for organic crop rotation. Note that orange box represents expanded product system with negative emissions.

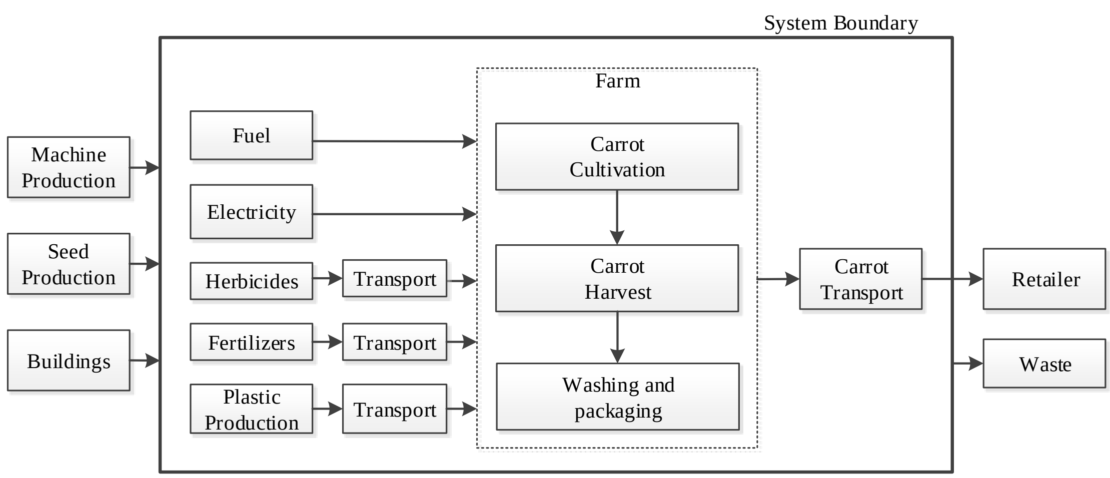


Figure 5. System boundaries for conventional carrot. Note that soil carbon stock change has not been included in this system boundary because conventional carrot farm is assumed to be the baseline scenario.

3.3.3 Allocation and System Expansion

In the case of organic farming, a full crop rotation is assessed as a collective unit and environmental loadings of all N-fixing crop cultivation are allocated based on the DM yield of the cash crops. The corresponding yields of cash crops are presented in Table 2. Similarly, the carbon sequestered in organic crop rotation is also allocated based on the DM yield of cash crops.

The grass silage produced in the second year of organic crop rotation replaces organic barley feed. The reason behind assuming barley as a replaced feed is that barley is one of the main sources of feed in Finland and covers approximately 60% of the nation's cereal feed (Tike 2013). The amount of barley feed that is replaced by 4t of grass silage is calculated based on their respective metabolizable energy content applicable to ruminants. In this study, it is assumed that mixed clover grass feed has energy content of 9,59 MJ per kg DM whereas barley feed contains 13,8 MJ per kg DM (MTT 2014). Thus, 4t DM of grass silage is equivalent to 2,78t DM of barley feed.

3.4 Life Cycle Inventory Analysis (LCI)

In this phase, the input and output data of all unit processes that are defined in the goal and scoping phase are collected. Furthermore, the collected data are validated and assigned to respective unit processes and the functional unit. Finally, in case of multiple outputs, the flows and releases are allocated to the studied output (ISO 14040 2006).

Fuel consumption during field activities is acquired from scientific literature and databases. The N-content of crop residues are IPCC default values whereas N-content of above and below ground biomass of N-fixing leys is based on an expert's judgment (Leinonen 2014). Further details on inputs and outputs are illustrated in Table 3.

3.4.1 Soil Emissions and Soil Carbon Stock Change

Soil N_2O emissions due to anthropogenic N inputs and CO_2 emissions due to liming are calculated based on IPCC (2006). However, differences between IPCC (2006) and IPCC (1996) are shown shortly in result section.

Furthermore, it is assumed that 10% of carbon added to soil is sequestered over a 100-year perspective (Knudsen e*t al.* 2013). That means after 100 years of addition, 10% of the carbon added is sequestered as carbon stock, while 90% of the carbon goes back to the atmosphere as CO_2.

Table 3. Data used for calculation of carbon footprint and energy demand. HFO= heavy fuel oil, LPG= liquefied petroleum gas, DWT= deadweight tonnage, OC-FI= organic carrots produced in Finland, CC-FI= conventional carrots produced in Finland and CC-IT= conventional carrots produced in Italy.

Categories	**Scenarios**		
	OC-FI	**CC-FI**	**CC-IT**
Crop residues ploughed into soil (t DM ha^{-1})	See Table 2	1,2 [i]	1,32 [i]
Fresh yield (t ha^{-1}) [k]	30 [a]	40 [b]	44 [b]
Fuels			
Diesel (ml kg_{carrot}^{-1})	4,31 [j]	4,25	46,75
HFO (ml kg_{carrot}^{-1})			1,17 [g]
LPG (g kg_{carrot}^{-1})	1,67 [a]		
Synthetic Fertilizers (g kg_{carrot}^{-1}) [c]			
N		2,25	2,05
P		1	0,9
K		4	3,6
Lime (Dolomite)		50	45,45
Manure nitrogen (g kg_{carrot}^{-1}) [a]	4,9		
Pesticide (g kg_{carrot}^{-1}) [f, c]		0,23	0,2
Plastic (g kg_{carrot}^{-1})			
Mulching (PP) [d]	2,83	2,12	1,93
Packaging, PELD [h]	6,1	6,1	6,1
Baling, PELD [e]	0,29		
Transport (km)			
Truck (27 t payload)	20	20	2784 [e, g]
Ship (160000 DWT)			1132 [e, g]

[a] Iivonen (2013) and, [b] Average yield from 2004-2011, (Eurostat. 2014),

[c] Kajalo (2013), Assumed to be same (in hectare basis) for both Finnish and Italian carrots, method of assumption is documented elsewhere in Carlsson (1997)

[d] Data covers for one season, in reality mulching plastic could be used for two seasons

[e] Refrigeration for 26,5h and 28h for truck and ship respectively, (Carlsson 1997)

[f] Includes glyphosate (5 kg), fenix (3 kg) and afalon (1 kg) for one hectare

[g] Google Map (2014)

[h] Jokinen (2014)

[i] NIR (2013), calculated from IPCC default values

[j] Includes allocation from ley cultivation years 1, 2 and 4

[k] Contain 87% moisture and applicable for scenarios, Bastin *et al.* (1997)

4 RESULTS

4.1 Life Cycle Impact Assessment (LCIA)

The potential environmental impacts based on the LCI results are expressed within the boundary of goal and scope definition. Generally, LCI data are associated with the specific environmental impact categories and category indicators in order to better understand the actual impacts on the environment. The element which associates selected impact categories and category indicators with the LCI results is called classification whereas calculation of category indicator is known as characterization. The potential impacts of a single impact category are compared through normalization (ISO 14040 2006).

In this study, characterization and classification in LCIA is conducted according to the CML2001, November 2010 edition. CML2001 is an impact assessment method developed by the Institute of Environmental Sciences, Leiden University, and The Netherlands. Two impact categories, namely, GWP with a 100-year time horizon (in g CO_2 eq.) and energy demand (in MJ) are studied in this study.

Table 4. Lifecycle phases of all three types of carrots and their environmental impacts. Unit processes and their description and references are illustrated in respective appendices.

Carrots	**Lifecycle phases**	**Unit processes and Descriptions**	**GWP gCO_2 eq. kg_{carrot}^{-1}**	**Energy Demand MJ kg_{carrot}^{-1}**
OC-FI	Crop Protection	Appendix 1	6	0,09
	Fertilizer production			
	Field activities		25	0,43
	Washing and packaging		27	0,81
	Transportation		1	0,01
	Field emissions		35	
	Allocation from ley cultivation (year 1, 2 and 4)		57	-0,01
	Sum (after allocation)	Appendix 4	152	
	Soil carbon change [1]	Appendix 6	-148	
	Sum		**4**	**1,33**
CC-FI	Crop Protection	Appendix 2	3	0,05
	Fertilizer production		53	0,69
	Field activities		19	0,32
	Washing and packaging		27	0,81
	Transportation		1	0,01
	Field emissions		40	
	Sum		**142**	**1,88**
CC-IT	Crop Protection	Appendix 3	2	0,05
	Fertilizer production		48	0,63
	Field activities		17	0,29
	Washing and packaging		32	0,82
	Transportation		144	1,89
	Field emissions		37	
	Sum		**280**	**3,68**

[1] Includes allocation of carbon sequestered from year 1, 2 and 4

GWP

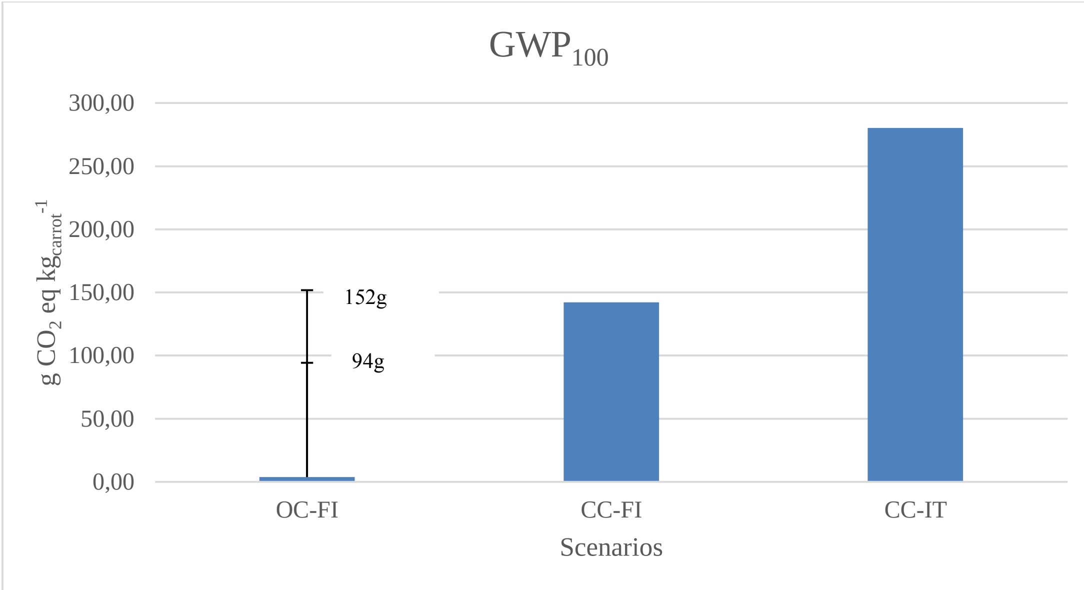


Figure 6. GWP_{100} of carrots of all three scenarios. The upper uncertainty bar on OC-FI indicates GHG emissions of organic carrots without carbon sequestration and the lower bar indicates GHG emissions of carrots without the contribution of carbon sequestration and ley cultivation.

As illustrated in Figure 6, imported conventional carrots have the highest GHG emissions with about 280 g CO_2 eq. kg_{carrot}^{-1}. On the other hand, organic carrots produced in the South-Savo region have the lowest, with about 4g CO_2 eq. kg_{carrot}^{-1} thanks to the major contribution of carbon sequestration. Furthermore, conventional carrots produced in the South-Savo region have GHG emissions of 142 g CO_2 eq. kg_{carrot}^{-1}

It should be noted that without carbon sequestration, GHG emissions of organic carrots would increase to 152g CO_2 eq. kg_{carrot}^{-1}. Furthermore, the carbon emissions of carrots without carbon sequestration and allocation from ley cultivation would be 94g CO_2 eq. kg_{carrot}^{-1}.

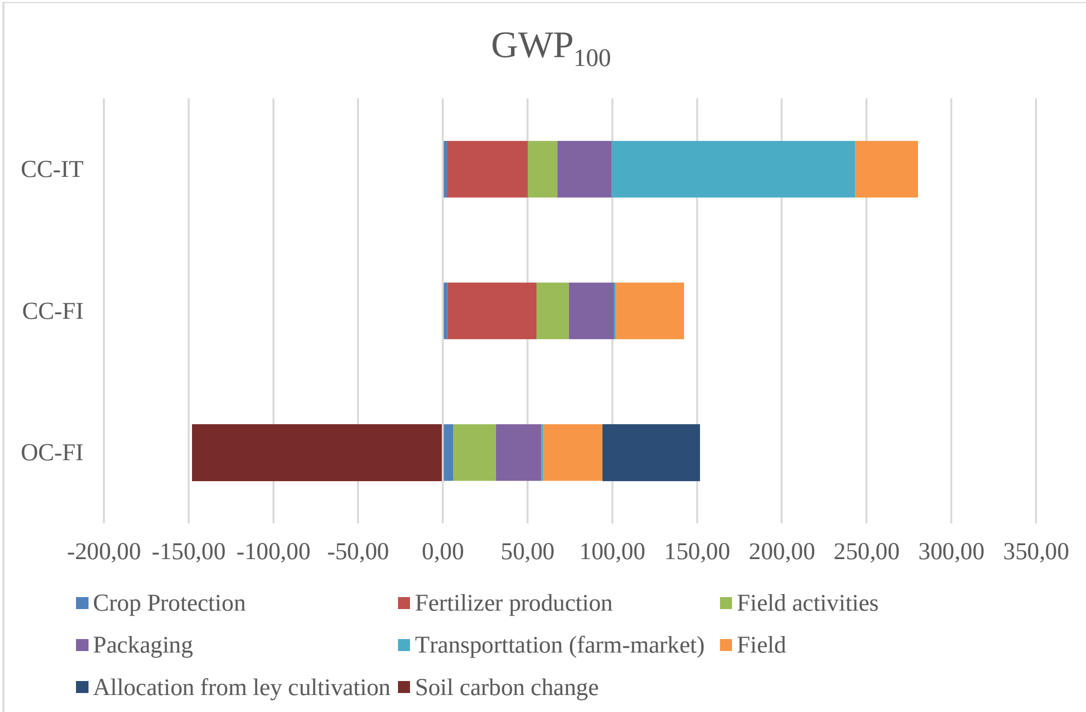


Figure 7. Contribution analysis regarding GHG emission from lifecycle phases of carrot production and supply chain presented in g CO_2 eq. kg_{carrot}^{-1}. Note that soil carbon change compensates the positive emissions in OC-FI scenario.

As illustrated in Figure 7, long haul transportation is a major contributor for imported carrots (CC-IT) with approximately 51%, compared to negligible contribution for Finnish carrots. Synthetic fertilizer related emissions and soil emissions are other major contributors for Italian carrots, with approximately 17% and 13%, respectively. It should be noted that the emissions from washing and packaging of CC-IT is comparatively higher than CC-FI because the electricity grid mix in Italy is more carbon intensive than in Finland (Gabi Database 2011).

Carbon sequestration and N-fixing ley husbandry are major issues in organic farming. Approximately 97% of GHG emissions are compensated by carbon sequestration whereas ley cultivation, which is a source of N in organic farming contributed approximately 37% of total GHG emissions.

Energy Consumption

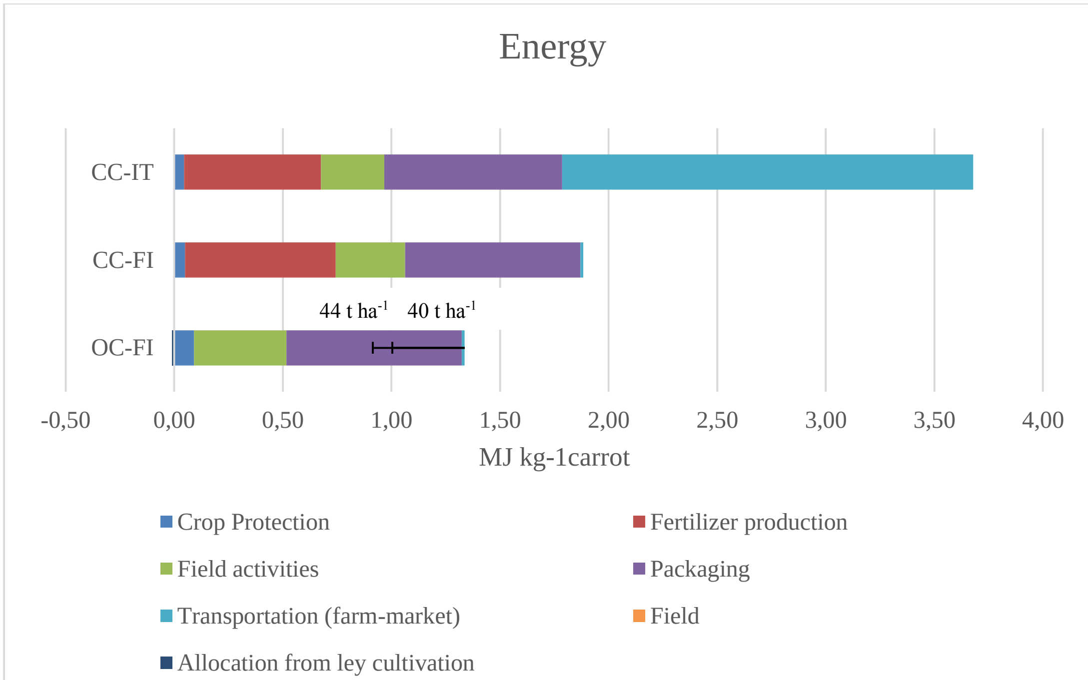


Figure 8. Energy consumption per kg carrot for all three types of carrots with relative contribution. The uncertainty bars in OC-FI represent the energy demand if the yields of organic carrots were similar to conventional farms: 40 and 44 t ha^{-1}. Note that the negative number that is negligible in OC-FI refers to the allocated energy demand from ley cultivation.

As illustrated in Figure 8, imported carrots have the highest energy demand followed by local conventional and organic carrots, respectively. Long haul transportation is a major contributor for imported carrots, with approximately 51% compared to a negligible contribution for local, conventional carrots. It should be noted that without the contribution from long haul transportation, CC-IT would have less energy demand than CC-FI because of the higher yield of CC-IT.

Furthermore, the uncertainty bars for OC-FI indicate that increasing the yield of organic farms from 30t ha^{-1} to 40t ha^{-1} and 44 t ha^{-1} would decrease the energy demand by 25% and 32%, respectively.

Uncertainty Related to Soil Emissions

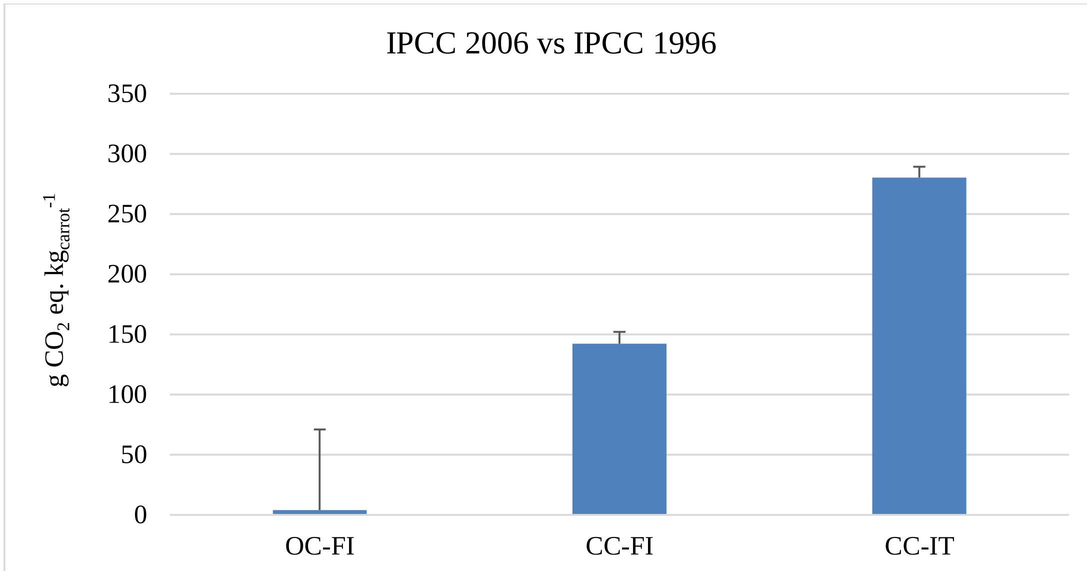


Figure 9. Impacts of soil emission factor uncertainty on total GHG emission. The uncertainty bars represent results based on emission factors (EF) reported by IPCC (1996). One of the major differences between IPCC guidelines from 1996 and 2006 is that the older version of guideline assumes 1,25% total N input is directly lost to the atmosphere as N_2O whereas 2006 version assumes 1%. Note that the larger difference for OC-FI compared to rest of the scenarios is because soil emissions are dominant in emissions from ley cultivation.

As presented in Figure 9, the total GHG emissions from organic carrots would increase to 71g if the IPCC (1996) guideline is adopted for the soil emissions calculation. On the other hand, the difference in carbon emissions for conventional carrots is comparatively lower than organic carrots. The reason behind the higher difference for OC-FI is because of the domination of soil emissions in ley cultivation.

4.2 Interpretation

In this section, the results from the LCI and LCIA that are consistent with the goal and scope are expressed. In addition, conclusions and recommendations are made in order to identify, quantify and evaluate the results from the LCI and LCIA as well as provide information to decision makers (Roy *et al.* 2009;ISO 14040 2006).

In this study, environmental impacts regarding different packaging possibilities are compared under sensitivity analysis. The results are further compared with similar studies available in scientific literature before presenting concluding remarks.

4.2.1 Sensitivity Analysis

Cradle-to-Grave Approach

The main results in Section 4 do not include lifecycle phases beyond retailers' gates. Thus, waste management after use phases was not included. However, in this section, management of packaging material is studied. In Finland, dry wastes are often used for energy recovery, thus this chapter investigates incineration of PELD bags. Information regarding the transportation of waste is not included in the study as it is assumed to be negligible. The produced energy from PELD waste replaces traditional sources of energy such as energy from natural gas. Assuming energy from PELD waste replaces fossil-based energy, such as that produced from natural gas combustion, a corresponding quantity of fossil-based emissions can be avoided. The breakdown of GHG emissions and energy production from PELD incineration is presented in Appendix 11.

Approximately 19,2g of GHGs are emitted from the incineration of a single PELD bag, which produces 0,12 MJ of energy. To produce the same amount of energy from natural gas, approximately 9,5g of GHG emissions would have occurred. Thus, after accounting for avoided emissions, approximately 9,6g of net GHG emissions is additional to each package of carrots sold. Furthermore, the energy demand for a single package of carrots decreases by 0,12 MJ after waste incineration.

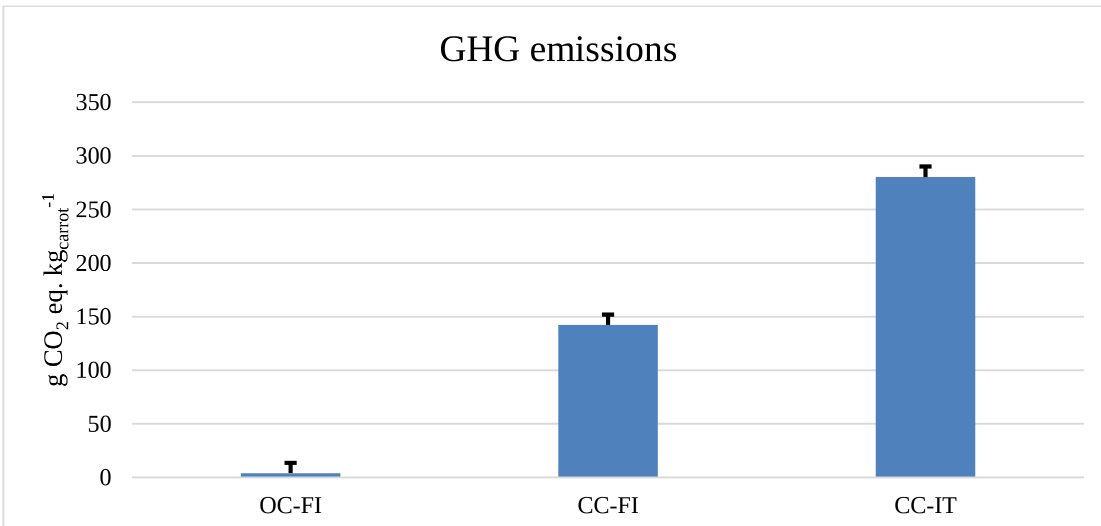


Figure 10. Sensitivity analysis regarding GHG emissions from waste management. (See Appendix 13 for further details)

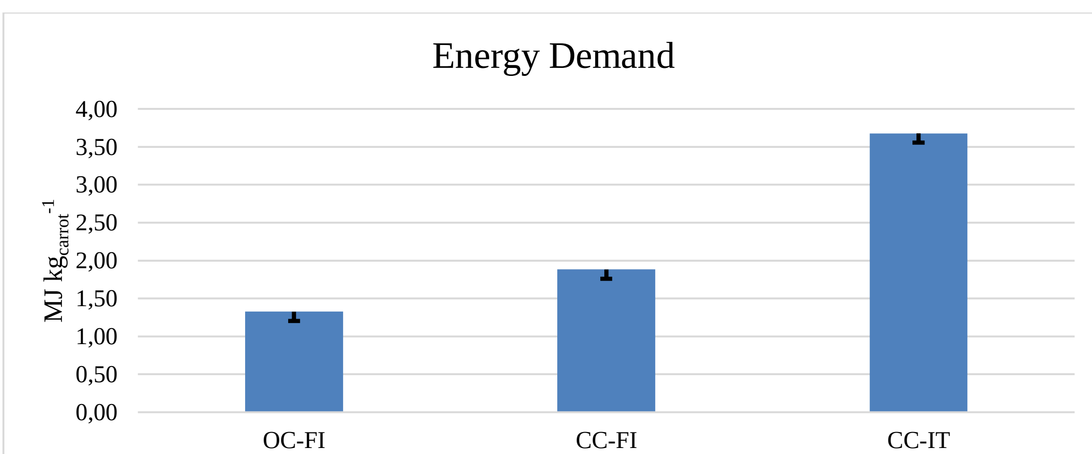


Figure 11. Sensitivity analysis regarding energy production from waste incineration. (See Appendix 12 for further details)

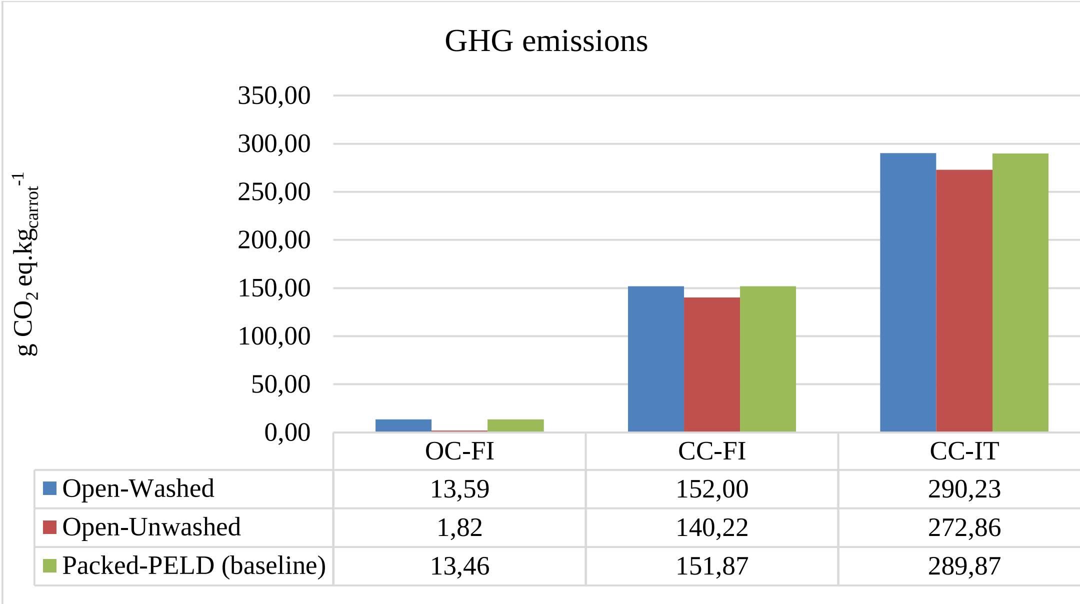
Alternative Packaging Solution

In Finnish supermarkets, carrots are available in different forms, such as loose bulk or packaged. The carrots available in bulk are often stored and displayed in corrugated boxes (cartons). Furthermore, the bulk carrots are also available either washed or unwashed. In this section, GHG emissions and energy demand from carrots available in cartons (washed and unwashed) are compared with carrots packed in PELD bags. However, washing at home by consumer in not taken into account as it is assumed to occur in the same manner independent of the form purchased.

In this study, it is assumed that a typical carton weighing 370 g can hold 10 kg of carrots and is filled with carrots by farmers and delivered to supermarkets. Once the boxes are emptied, they are used for energy recovery. That energy is used to replace traditionally produced natural gas based energy. In practice, bulk carrots available in cartons may not be equivalent to carrots packed in PELD bags because the latter ones are ready for customers to buy and take home while bulk carrots need an additional bag in order to be able to weigh and take them home.

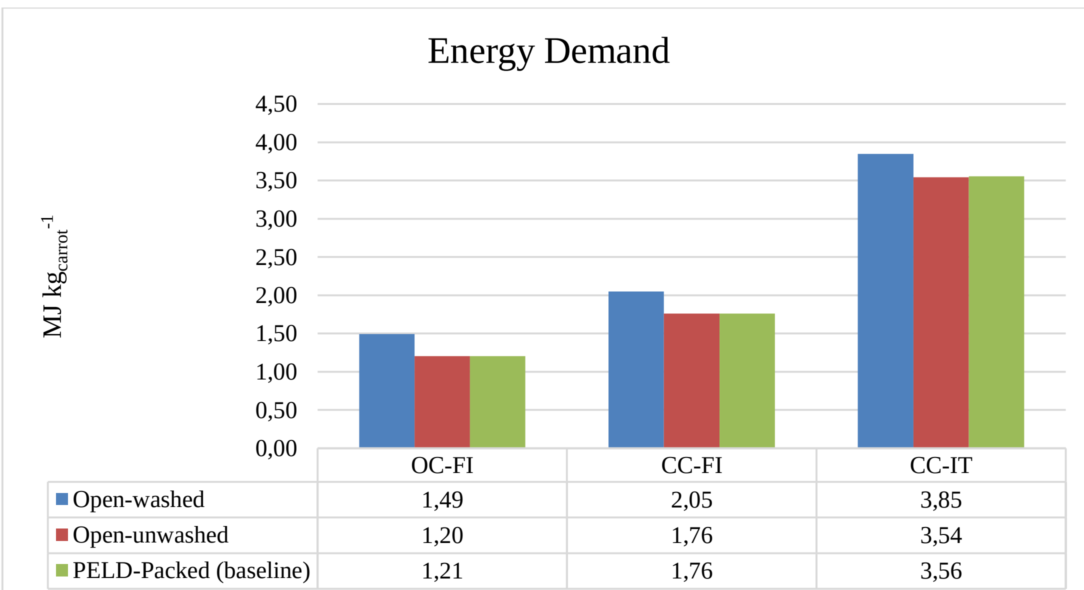
In Finnish supermarkets, high-density polyethylene (HDPE) bags, also known as ‘solmupussi’ (in Finnish), are typically used as a secondary packaging material. Thus, environmental loadings from HDPE bags are assessed as an equivalent to the baseline. It is assumed that a single HDPE bag weighs 2g and holds one kg of carrots (same as functional unit). However, weighing of carrots on a typical electric store scale is not taken into account as it is deemed a negligible activity in terms of GHG emissions and energy use.

The results in this section include environmental loadings from the production of packaging material, their incineration after use for energy recovery and avoided emissions. Similar to the previous section, transportation of packaging wastes is not taken into account. Further information regarding energy demand and GHG emissions for different packaging solutions is illustrated in Appendix 12 and 13, respectively.



	OC-FI	CC-FI	CC-IT
Open-Washed	13,59	152,00	290,23
Open-Unwashed	1,82	140,22	272,86
Packed-PELD (baseline)	13,46	151,87	289,87

Figure 12. Sensitivity analysis regarding GHG emissions from carrots available in different packages. (See Appendix 13 for further details)



	OC-FI	CC-FI	CC-IT
Open-washed	1,49	2,05	3,85
Open-unwashed	1,20	1,76	3,54
PELD-Packed (baseline)	1,21	1,76	3,56

Figure 13. Sensitivity analysis regarding energy demand of carrots available in different packages. (See Appendix 12 for further details)

Different packaging alternatives are compared in Figure 12 and 13. The organic carrots cultivated in the South-Savo region delivered in cartons without washing have the least GHG emissions of approximately 1,82g kg_{carrot}^{-1}, but once the carrots are washed the emissions increase by 11,77g. Interestingly, washed carrots available in open boxes have almost similar GHG emission to carrots sold in PELD bags. It should be noted that even though greater amounts of material are used in corrugated boxes, the GHG emissions are comparatively lower than PELD packaged carrots. The potential reason behind this is that cartons are composed of renewable material thus considered as a carbon sink (PE Americas *et al.* 2009). In contrast, washed carrots available in corrugated boxes have the highest energy demand whereas unwashed carrots available in corrugated boxes and carrots packed in PELD bags have approximately similar energy demand.

4.2.2 Comparison with Previous Studies

There are very few published reports regarding conventional carrots and a surprising lack of literature on organic carrots. In this section, results from studies on conventional carrots are compared with the results found in scientific literature.

In Sweden, Röös *et al*. (2013) conducted a comparative LCA on local and imported (from Italy and the Netherlands) conventional carrots. In that study, one of the main phases, such as packaging, is not included, but the production of capital goods, such as machinery, is included. The carbon footprints of locally produced and imported (Italy) carrots are 110 and 310 gCO_2 eq. kg_{carrot}^{-1}, respectively. The carbon footprint of Swedish carrots is considerably lower than Finnish carrots but Italian carrots consumed in Sweden have comparatively higher GHG emissions than Italian carrots imported to Finland.

Lagerberg *et al.* (2006) have reported LCAs on conventionally produced local (Sweden) and imported (from the Netherlands) carrots. The energy demands for a one kg package of carrots at a wholesaler for local and imported carrots are 2,38 MJ and 4 MJ, respectively. These results are slightly higher than this current study: 1,88 MJ kg_{carrot}^{-1} and 3,68 MJ kg_{carrot}^{-1} for their respective counterparts.

In contrast to energy demand, GHG emissions per kg carrots in that study are considerably lower than this study; 69g and 155g compared to 142g and 280g for local and imported carrots, respectively. However, the study by Lagerberg *et al*. (2006) does not have enough information in order to provide evidence of what caused the significant difference compared to this study.

In a Norwegian study, Svanes (2012) has reported a carbon footprint of carrots of 380g CO_2 eq. using a cradle-to-gate system boundary. However, the emissions increase to 550g when waste management after consumption is included. Additionally, the study by Svanes (2012) does not have enough information to claim what caused such significant difference to this study.

5 DISCUSSION

5.1 Implications

The main implication of this study is that Finnish organic carrots have a significantly lower carbon footprint than conventionally produced carrots. One of the main features of organic farming is that it sequesters carbon from the atmosphere thereby reducing overall emissions which eventually reduces the actual emissions. On the other hand, imported conventional carrots have two-fold emissions compared to their local counterparts thanks to a dominant contribution by long haul transportation. Similarly, local and imported conventional carrots consume about 0,55 MJ and 2,35 MJ more than organic carrots, respectively. Thus, local organic carrots are recommended in order to minimize the individual GHG emissions and energy consumption.

5.2 Role of N-fixing Ley Cultivation and its Explicitness

In this study, it is realized that ley cultivation and N incorporated into soil has an extremely important role to play in GHG emissions of individual cash crops cultivated in the same crop rotation period. The amount of N incorporated into the soil, which depends on the N content of the silage, is based on an expert's judgment (Leinonen 2014) . Thus, the generic data used in this study makes this study sensitive to replication. Appropriate caution should be exercised when interpreting results.

The use of grass silage as animal feed in the second year of crop rotation helps to avoid GHG emissions and energy consumption. However, one should note that the silage feed not only avoids traditional feed related emissions but also avoids soil emissions had the grass been incorporated into the soil. Thus, feed based on grass has multiple environmental benefits.

5.3 Importance of Allocation Method

The method used for the allocation of impacts caused by N-fixing leys plays an important role in calculating the carbon footprint of cash crops. In organic farming, N-fixing leys are significant as they are one of the major sources of N and thus help to avoid the use of synthetic fertilizers. In this study, such impacts are allocated based on the DM yield of respective cash crops. However, the N-uptake efficiency may vary from crop to crop. This means, regardless of their yield, carrot and rye may have utilized different amounts of N from the soil (Leinonen 2014). Thus, a harmonized allocation method is essential for food-based LCAs.

5.4 Role of Packaging

The environmental impacts of all three scenarios are significantly influenced by packaging material, a production mix of fossil-based PELD. The impacts regarding packaging material may have been different had recycled polythene been used instead of virgin PELD. However, the selection of packaging material may impact on the carbon footprints of individual scenario but does not affect a comparative study. This is due to the fact that all scenarios in this study use the same packaging material.

5.5 Role of Transportation

The results have shown that transportation has a major role to play in both GHG emissions and energy consumption. As a result, Italian carrots are carbon and energy intensive. Furthermore, impacts related to transportation are dominated by truck transportation (see Appendix 3). There is about 2784 km of total transportation by truck compared to 1132 km by ship. However, the emissions per km travelled by one kg carrots are significantly higher for truck transport than ship. Thus, it is shown that the location of the farm and mode of transportation play an important role in the carbon footprint of imported carrots. Moreover, further investigations are necessary in order to identify the effect of carrot origin on the environment.

5.6 Need for Further Research

Several issues raised in this study need further research in order to make results more representative. These issues are illustrated as follows:

- Standard allocation method

  The use of economic, mass and several other means of co-product allocation are already discussed in the study. However, it is realized that there is a need of a standard allocation method for allocating impacts from ley cultivation. This is due to the fact that the mass allocation method may not be representative, as N-uptake efficiency may vary from crop to crop.

- More realistic information on packaging material

  Due to a data gap, fossil-based PELD is used as a packaging material in this study instead of recycled material, which would have been more realistic. Thus, data on recycled plastic is necessary in order to make results more representative. However, in comparative LCAs, the nature of data may have the least impact on final results as long as it is consistent throughout the study.

- Soil carbon change

  Several studies that are reviewed in Section 2 have opted to exclude carbon sequestration, stating that it may be highly uncertain and invalid once a particular farming practice reaches its equilibrium (Tuomisto *et al*. 2012). However, it is deemed worthwhile to consider when comparing organic with conventional farming because soil carbon change is one of the major features of organic farming. Thus, inclusion of soil carbon change is a subject of consideration in further research.

REFERENCES

Aflatuni, A. and Luoma, S., 2001. Eri lannoitustyyppien vaikutus kolmeen mustaherukkalajikkeeseen pohjois-pohjanmalla. In: Aflatuni. A., Soile. P. and Sirkka. L. 2001. Mustaherukan lannoitus ja alasleikkaus. 99. Jokioinen. ISSN 1239-0844: MTT Publications.

Bastin, S. and Henken, K., Water Content of Fruits and Vegetables. Kentucky Cooperative Extension Service. Available: www2.ca.uky.edu/enri/pubs/enri129.pdf. [05/25/2014].

Carlsson, A. 1997. Greenhouse gas emissions in the life-cycle of carrots and tomatoes. *IMES/EESS Report*, vol. 24.

Cellura, M., Ardente, F. and Longo, S. 2012. From the LCA of food products to the environmental assessment of protected crops districts: A case-study in the south of Italy. *J.Environ.Manage.* vol.93, (1), pp. 194-208.

Cellura, M., Longo, S. and Mistretta, M. 2012. Life Cycle Assessment (LCA) of protected crops: an Italian case study. *J.Clean.Prod.* vol.28, pp. 56-62.

Charles, R., Jolliet, O., Gaillard, G. and Pellet, D. 2006. Environmental analysis of intensity level in wheat crop production using life cycle assessment. *Agric., Ecosyst.Environ.* vol.113, (1–4), pp. 216-225.

Cooper, J., Butler, G. and Leifert, C. 2011. Life cycle analysis of greenhouse gas emissions from organic and conventional food production systems, with and without bio-energy options. *NJAS-Wageningen Journal of Life Sciences,* vol. 58, (3), pp. 185-192.

Dalgaard, R., Schmidt, J., Halberg, N., Christensen, P., Thrane, M. and Pengue, W.A. 2008. LCA of soybean meal. *The International Journal of Life Cycle Assessment,* vol. 13, (3), pp. 240-254.

De Backer, E., Aertsens, J., Vergucht, S. and Steurbaut, W. 2009. Assessing the ecological soundness of organic and conventional agriculture by means of life cycle assessment (LCA): A case study of leek production. *Br.Food J.,* vol. 111, (10), pp. 1028-1061.

Eurostat.2014.Crop Products-Annual Data.Eurostat. Available: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=apro_cpp_crop&lang=en. [04/04/2014].

FAO. 2011. Organic Agriculture and Climate Change Mitigation: A Report of the Round Table on Organic Agriculture and Climate Change. Rome: Food and Agriculture Organization of the United Nations (FAO).

Fertilizerseurope. 2011. Energy efficiency and greenhouse gas emissions. In: European mineral fertilizer production and use. Belgium: FertilizersEurope. Available: http://goo.gl/jdwTZk. [05/23/2014].

Forsman, K., Väisänen, J., Kakriainen-Rouhiainen, S. and Lötjönen, T., 2004. Viherlannoituksen esikasviarvio viljoille-kirjallisuuskatsaus. In: Väisanen. J., Forsman. K., Kakriainen-Rouhiainen. S., Lötjönen. T. and Avikainen. H. Kaasuvoima luomuohralle. 52. Jokioinen: MTT.

Gabi Database. 2011. PE International AG*; LBP-GaBi.* 6 edn. Leinfelden-Echterdingen, Germany: University of Stuttgart: GaBi Software System.

Girgenti, V., Peano, C., Bounous, M. and Baudino, C. 2013. A life cycle assessment of non-renewable energy use and greenhouse gas emissions associated with blueberry and raspberry production in northern Italy. *Sci.Total Environ.,* vol.458–460, pp. 414-418.

Google Map. 2014. Map of Italy and Finland. Google. Available: www.google.com. [05/27/2014].

Gracia, A.and de Magistris, T. 2008. The demand for organic foods in the South of Italy: A discrete choice model. *Food Policy,* vol.33, (5), pp. 386-396.

Grönroos, J., Seppälä, J., Voutilainen, P., Seuri, P. and Koikkalainen, K. 2006. Energy use in conventional and organic milk and rye bread production in Finland. *Agric., Ecosyst.Environ.* vol.117, (2), pp. 109-118.

Halinen, A., Palojärvi, A., Karinen, P., Heinonen-Tanski, H. and Tontti, T., 2007. Jätekompostit lannoitteena peltoviljelyssä- biologiset ja kemialliset vaikutukset (edited version). 81. Jokioinen: Maa-ja elintarviketalous.

IFOAM. 2014. Definition of organic agriculture. Available: www.ifoam.org. [05/23/2014].

Iivonen, S. 2013. Personal Communication. Crop Rotation. Helsinki University. Ruralia-Institute.

IPCC. 1996. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Available: http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html. [06/05/2014].

IPCC. 2006. IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston *H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds).* 4. Japan: IGES.

ISO 14040, 2006. Environmental Management - Life Cycle Assessment - Principles and Framework. Geneva: International Organization for Standardization (ISO).

Jokinen, J. 2014. Rödingin Tila. Personal Communication.

Knudsen, M.T., Yu-Hui, Q., Yan, L. and Halberg, N. 2010. Environmental assessment of organic soybean (Glycine max.) imported from China to Denmark: a case study. *J.Clean.Prod.* vol.18, (14), pp. 1431-1439.

Kajalo, M. 2013. Varhaisporkkanan viljely harsokatteessa. MTT. Available: http://goo.gl/M2ZmX0. [05/05/2014].

Knudsen, M.T., Meyer-Aurich, A., Olesen, J.E., Chirinda, N. and Hermansen, J.E. 2013. Carbon footprints of crops from organic and conventional arable crop rotations – using a life cycle assessment approach. *J.Clean.Prod*, pp. 1-10.

KTBL. 2014. KTBL fuel consumption calculator.
Association for Technology and Structures in Agriculture (KTBL). Available: http://daten.ktbl.de/dieselconsumption/main.html. [02/27/2014].

Lagerberg, C. and Carlsson-Kanyama, A. 2006. Environmental assessment of foods– an LCA inspired approach. In: Fuentes, C. and Carlsson, A. 2006. Environmental information in the food supply system.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science*, vol. 304, (5677), pp. 1623-1627.

Leinonen, P. 2014. Crop Residues from N-fixing Grasses. Personal Communication. Elomestari Oy. Tornio. Tornio: Elomestari Oy.

Luostarinen, S., Logren, J., Grönroos, J., Lehtonen, H., Paavola, T., Rankinen, K., Rintala, J., Salo, T., Ylivainio, K. and Järvenpää, M., 2011. Lannan kestävä hyödyntäminen. 21. Jokioinen: MTT.

Luttikholt, L.W. 2007. Principles of organic agriculture as formulated by the International Federation of Organic Agriculture Movements. *NJAS-Wageningen Journal of Life Sciences*, vol. 54, (4), pp. 347-360.

Meisterling, K., Samaras, C. and Schweizer, V. 2009. Decisions to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. *J.Clean.Prod.* vol.17, (2), pp. 222-230.

MTT. 2014. Feed Table Calculator. Maa-ja elintarviketalouden tutkimuskeskus. Available: www.mtt.fi. [04/04/2014].

Nemecek, T., Dubois, D., Huguenin-Elie, O. and Gaillard, G. 2011. Life cycle assessment of Swiss farming systems: I. Integrated and organic farming. *Agricultural Systems,* vol. 104, (3), pp. 217-232.

Niggli, U., Schmid, H. and Fliessbach, A., 2008. Organic farming and climate change. MDS-08-152.E. Geneva: International Trade Centre (ITC).

NIR, 2013. Greenhouse gas emission in Finland 1990-2011. National Inventory Report under the UNFCCC and the Kyoto Protocol. Statistics Finland.

Nykänen, A., Granstedt, A. and Jauhiainen, L. 2008. Residual effect of clover-rich leys on soil nitrogen and successive grain crops. *Agricultural and food science,* vol.17, (1), pp. 73-87.

Palonen, J. and Oksanen, H.E., 1993. Labour, Machinery and Energy Databases in Plant Production. 330. Helsinki: Työtehoseura.

PE Americas and Five Winds International, 2009. Life Cycle Assessment of U.S. Industry-Average Corrugated Product. www.corrugated.org. [04/04/2014].

Pishgar-Komleh, S.H., Ghahderijani, M. and Sefeedpari, P. 2012. Energy consumption and CO_2 emissions analysis of potato production based on different farm size levels in Iran. *J.Clean.Prod.,* vol.33, pp. 183-191.

Rigby, D. and Cáceres, D. 2001. Organic farming and the sustainability of agricultural systems. *Agricultural systems,* vol.68, (1), pp. 21-40.

Röös, E. and Karlsson, H. 2013. Effect of eating seasonal on the carbon footprint of Swedish vegetable consumption. *J.Clean.Prod.* vol.59, pp. 63-72.

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N. and Shiina, T. 2009. A review of life cycle assessment (LCA) on some food products. *J.Food Eng.,* vol.90, (1), pp. 1-10.

Schau, E.M. and Fet, A.M. 2008. LCA studies of food products as background for environmental product declarations. *The International Journal of Life Cycle Assessment*, vol.13, (3), pp. 255-264.

Stranddorf, K.H., Hoffmann, L. and Schmidt, A., 2005. Impact categories, normalization and weighing in LCA. Update on selected EDIP97-data. 78. FORCE Technology.

Svanes, E., Comparison of current guidelines to calculate the carbon footprint of carrots. In: Corson, M.S., van der Werf, H.M.G. (Eds.), Proceedings of the 8th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2012), 1-4 October 2012, Saint Malo, France. INRA. Rennes, France. p. 920.

Tike. 1014. Cereals balance sheet 2012-2013.
[Maataloustilastot]. Available: www.maataloustilastot.fi. [05/25/2014].

Torrellas, M., Antón, A., López, J.C., Baeza, E.J., Parra, J.P., Muñoz, P. and Montero, J.I. 2012. LCA of a tomato crop in a multi-tunnel greenhouse in Almeria. *The International Journal of Life Cycle Assessment*, vol.17, (7), pp. 863-875.

Tuomisto, H., Hodge, I., Riordan, P. and Macdonald, D. 2012. Comparing global warming potential, energy use and land use of organic, conventional and integrated winter wheat production. *Ann.Appl.Biol.* vol.161, (2), pp. 116-126.

Ulloa, S.M., Datta, A., Bruening, C., Neilson, B., Miller, J., Gogos, G. and Knezevic, S.Z. 2011. Maize response to broadcast flaming at different growth stages: Effects on growth, yield and yield components. *Eur.J.Agron.* vol.34, (1), pp. 10-19.

Vidjeskog, C. 2014. Polyethylene Consumption for Baling. Personal Communication. Teerijärvi: www.raniplast.com.

Wagner, S. C. 2011. Biological Nitrogen Fixation. Nature Education Knowledge. Vol.3 (10):15. Available:
http://www.nature.com/scitable/knowledge/library/biological-nitrogen-fixation-23570419. [06/04/2014]

APPENDICES

APPENDIX 1**.** Lifecycle phases and activities regarding organic carrot produced in Finland. GHG emissions and energy demand are calculated based on (GaBi Database 2011) unless otherwise stated. The sources for fuel consumption are referred to in table footnotes.

Lifecycle phases	**Activities**	**GWP g CO_2 eq. kg_{carrot}^{-1}**	**Energy Demand MJ kg_{carrot}^{-1}**
Crop protection	Liquefied Petroleum Gas (LPG) (70% propane, 30% butane), production mix, at refinery [a]	1,24	0,01
	Flaming, hand held broadcast flaming	4,99	0,08
	Total	6,23	0,09
Farm activities	Harrowing, [c]	0,37	0,01
	Harvesting, by complete harvester, [d]	10,87	0,07
	Precision drill, Sowing [c]	0,40	0,00
	Solid manure loading and spreading, by hydraulic loader and spreader [d]	0,40	0,01
	Tillage, harrowing, by spring tine harrow, [c]	0,93	0,01
	EU-27: Diesel mix at refinery, 5,75% bio component [a]	1,23	0,03
	EU-27: Polypropylene fibers (pp), production mix, crude oil based, without additives, 17g/m^2 [e]	6,52	0,23
	Ridging [d]	0,78	0,01
	Universal Tractor (Gauze application) [a]	0,89	0,01
	Tillage, ploughing [c]	2,74	0,03
	Total	25,12	0,43
Packaging	EU-27: Diesel mix at refinery, 5,75% bio component [a]	0,02	0,00
	FI: Electricity grid mix, consumer mix [a]	11,78	0,29
	Truck, 3,3t payload, 0,85 utilization [a]	0,21	0,00
	RER: Polyethylene film (PE-LD) PlasticsEurope, production mix [a,]	14,69	0,51
	Total	26,70	0,81
Transportation	EU-27: Diesel mix at refinery, 5,75% bio component [a]	0,09	0,00
	GLO: Truck-trailer (Farm-market), 27t payload, 5,75% bio component [a]	0,85	0,01
	Total	0,93	0,01
Carrot field		35,41	0,00
Sum		**94,39**	**1,34**

[a] (GaBi Database 2011), [b](Ulloa *et al.* 2011), [c] (Palonen *et al*. 1993), [d] (KTBL 2014)

APPENDIX 2. Lifecycle phases and activities regarding conventional carrots produced in Finland. GHG emissions and energy demand are calculated using (GaBi Database 2011) unless otherwise stated. The sources for fuel consumption are referred in table footnotes.

Lifecycle phases	**Activity description**	**Quantity (gCO_2 eq. kg_{carrot}^{1})**	**Energy Demand (MJ kg_{carrot}^{-1})**
Field activities	Fertilizing, by broadcaster [a]	0,84	0,01
	Harrowing [b]	0,28	0,01
	Harvesting, by complete harvester [b]	8,15	0,05
	Precision drill, Sowing [b]	0,30	0,00
	Harrowing, by spring tine harrow [b]	0,35	0,01
	EU-27: Diesel mix at refinery PE, 5,75% bio components [a]	0,93	0,02
	EU-27: Polypropylene fibers (PP), crude oil based production mix at plant [a]	4,89	0,18
	Ridging [b]	0,58	0,01
	Universal Tractor for gauze application [a]	0,66	0,01
	Ploughing, 25,1 l/ha [b]	2,06	0,02
	Total	19,04	0,32
Fertilization	Lime, from carbonation, at regional storehouse [a]	0,58	0,01
	NPK 6-5-20 at regional storehouse	25,29	0,27
	EU-27: Diesel mix at refinery, 5,75% bio components [a]	0,08	0,00
	Calcium nitrate, as N, at regional storehouse [a]	25,94	0,40
	GLO: Truck, 188km, 17,3t payload, 0,85 utilization [a]	0,07	0,00
	GLO: Truck, 188km, 17,3t payload, 0,85 utilization [a]	0,49	0,01
	GLO: Truck, 188km, 17,3t payload, 0,85 utilization [a]	0,19	0,00
	Total	52,63	0,69
Crop protection [a]	Application of plant protection products, by field sprayer, 3 times	0,42	0,01
	EU-27: Diesel mix at refinery, 5,75% bio components	0,04	0,00
	FI: fenix, aclonifen, at regional storage,	0,62	0,01
	FI: Afalon, linuron, at regional storehouse	0,27	0,01
	RER: glyphosate, at regional storehouse	1,30	0,03
	Total	2,65	0,05
Packaging [a]	EU-27: Diesel mix at refinery, 5,75% bio components	0,02	0,00
	FI: Electricity grid mix, consumption mix	11,78	0,29
	GLO: Truck, 270km, 3,3t payload, 0,85 utilization	0,21	0,00
	RER: Polyethylene film (PELD) PlasticsEurope, production mix at plant	14,69	0,51
	Total	26,70	0,81
Transportation [a]	EU-27: Diesel mix at refinery, 5,75% bio components	0,09	0,00
	GLO: Truck-trailer (Farm-market), 20km, 27t payload, 0,85 utilization	0,85	0,01
	Total	0,93	0,01
Carrot field	Direct and indirect soil N_2O emissions and CO_2 emissions due to lime application	40,35	0,00
Total		142,30	1,88

[a] (GaBi Database 2011), [b] (Palonen *et al.* 1993), [c] (KTBL 2014)

APPENDIX 3. Lifecycle phases and activities regarding conventional carrot produced in Italy. GHG emissions and energy demand are calculated using (GaBi Database 2011) unless otherwise stated. The sources for fuel consumption are referred in table footnotes.

Lifecycle phases	**Activities**	**Quantity g CO_2 eq.kg_{carrot}^{-1}**	**Energy Demand MJ ha^{-1}**
Crop protection	Application of plant protection products, by field sprayer	0,38	0,01
	EU-27: Diesel mix at refinery, 5,75% bio component [a]	0,04	0,00
	FI: fenix, aclonifen, at regional storage [a]	0,56	0,01
	FI: Afalon, linuron, at regional storehouse [a]	0,24	0,00
	RER: glyphosate, at regional storehouse [a]	1,18	0,02
	Total	2,41	0,05
Field activities [d]	CH: fertilizing, by broadcaster [c]	0,76	0,01
	CH: Harrowing [c]	0,25	0,01
	CH: harvesting, by complete harvester [c]	7,41	0,05
	CH: Precision drill, Sowing [c]	0,27	0,00
	CH: tillage, harrowing, by spring tine harrow [c]	0,32	0,00
	EU-27: Diesel mix at refinery, 5,75% bio component [a]	0,84	0,02
	EU-27: Polypropylene fibers (PP)	4,45	0,16
	GLO: Ridging [c]	0,53	0,01
	GLO: Universal Tractor (Gauze application) [a]	0,60	0,01
	Natio: tillage, ploughing [c]	1,87	0,02
	Total	17,30	0,29
Fertilization	Lime, from carbonation, at regional storehouse [a]	0,53	0,01
	NPK 6-5-20 [b]	22,99	0,24
	EU-27: Diesel mix at refinery, 5,75% bio component [a]	0,07	0,00
	FI: calcium nitrate, as N, at regional storehouse [a]	23,58	0,37
	GLO: Truck, 17,3t payload, 0,85 utilization [a]	0,06	0,00
	GLO: Truck, 17,3t payload, 0,85 utilization [a]	0,44	0,01
	GLO: Truck,17,3t payload, 0,85 utilization [a]	0,18	0,00
	Total	47,85	0,63
Washing and Packaging [a]	EU-27: Diesel mix at refinery, 5,75% bio component	0,00	0,00
	GLO: Truck, 3,3t payload, 0,85 utilization	0,00	0,00
	IT: Electricity grid mix, consumer mix	17,38	0,31
	RER: Polyethylene film (PE-LD) PlasticsEurope, production mix	14,69	0,51
	Total	32,07	0,82
Transpor-tation [a]	DE: Heavy fuel oil at refinery (1.0 wt.% S)	0,45	0,00
	EU-27: Diesel mix at refinery, 5,75% bio component	11,77	0,28
	GLO: Bulk commodity carrier (Tra- Hel), 160000 DWT, 0,48 utilization	7,82	0,05
	GLO: Truck-trailer (Hel-Mkl),27t payload, 0,85 utilization	10,31	0,13
	GLO: Truck-trailer (Sicily-Tra), 27t payload, 0,85 utilization	113,40	1,44
	Total	143,75	1,89
Field	Soil N_2O emissions and CO_2 emissions due to lime application	36,92	0,00
Sum		280,30	3,68

[a] (GaBi Database 2011), [b] (FertilizersEurope 2011), [c] (Palonen *et al.* 1993), [d] diesel consumption rate assumed to be same as Finnish conventional carrots.

APPENDIX 4. Lifecycle phases and activities regarding non-cash crops applicable for allocation. GHG emissions and energy demand are calculated using (GaBi Database 2011) unless otherwise stated. The sources for fuel consumption are referred in table footnotes

Lifecycle phases	**Activities**	**Quantity g CO_2 eq.kg_{carrot}^{-1}**	**Energy Demand MJ kg_{carrot}^{-1}**
Year 1			
Field activities	EU-27: Diesel mix at refinery, 5,75% bio component [a]	0,27	0,006
	Mowing, by rotary mower [b]	0,45	0,015
	Sowing [b]	0,40	0,007
	Harrowing, by spring tine harrow [b]	0,47	0,015
Clover Field	Direct and indirect soil N_2O emission [c]	32,89	
Year 1 total		34,48	0,043
Year 2			
Field activities	Baling [a]	0,09	0,001
	Loading bales [a]	0,45	0,006
	Mowing, by rotary mower [a]	0,40	0,007
	Sowing, 5,6 l/ha [b]	0,47	0,007
	Tillage, harrowing, by spring tine harrow [b]	1,48	0,022
	Tillage, rotary cultivator [b]	0,41	0,010
	Diesel mix at refinery, 5,75% bio component [a]	0,02	0,000
	GLO: Truck [a]	1,04	0,036
	RER: Polyethylene film (PE-LD, baling) PlasticsEurope [a,] , 1,3 kg/bale [d]	44,36	0,000
Field emissions	Direct and indirect soil N_2O emission [c]	1330,87	
Total		49,49	0,100
Replacement Barley feed (Follow Appendix 7)		-47,40	-0,233
Year 2 total		2,10	-0,133
Year 4			
Field activities	Sowing [b]	0,40	0,007
	Sowing [b]	0,40	0,007
	Tillage, harrowing, by spring tine harrow [b]	0,47	0,007
	Tillage, rotary cultivator [b]	1,48	0,022
	Tillage, rotary cultivator [b]	1,48	0,022
	EU-27: Diesel mix at refinery, 5,75% bio component [a]	0,48	0,011
Field emissions	Direct and indirect soil N_2O emission [c]	43,98	
Year 4 Total		48,69	0,076
Grand total	**Year1 + Year 2 + Year 4**	**85,27**	**-0,015**

(GaBi Database 2011), [b] (Palonen *et al*. 1993), [c] (IPCC 2006), [d] (Vidjeskog 2014)

APPENDIX 5. Direct and indirect soil N_2O emissions from carrot ley field. Numbers may not add up to the sum due to the round up.

Year	**Biomass type**	**Applied Amount DM kg ha^{-1}**	**N fraction**	**N gkg$_{carrot}^{-1}$**	**Direct N_2O emissions g kg$_{carrot}^{-1}$**	**Indirect N_2O emissions by leaching and runoff g kg$_{carrot}^{-1}$**	**Indirect N_2O emission by atmospheric deposition g kg$_{carrot}^{-1}$**	**Total N_2O emissions g kg$_{carrot}^{-1}$**
Y1	Above ground	6000[b]	0,025 [b]	5,73	0,0901	0,02027		0,110
	Belowground	1000 [b]	0,022 [b]					
Y2	Above ground	4000 [b]	0,025 [b]	7,73	0,1215	0,027		0,149
	Belowground	6000 [b]	0,022 [b]					
Y4	Above ground	8000 [b]	0,025[b]	7,76	0,1205	0,027		0,147
	Belowground	1500 [b]	0,020[b]					
Total								0,406 [d]
Y5	Manure	30000	0,005[c]	5,38	0,0844	0,019	0,015	0,119
	Carrot residues	900[a]	0,015 [a]					
Carrot total (after allocation)								**0,392**

[a] Assumed to be same as conventional corresponding items, NIR (2013)

[b] Leinonen (2014)

[c] Aflatuni *et al*. (2001)

[d] 67% is allocated to carrot

APPENDIX 6. Carbon sequestered over the five-year organic crop rotation. Calculations are based on the estimation by Knudsen *et al.* (2013), which states 10% of the total carbon added to soil sequesters over the 100 years period of time. Note that total carbon sequestered during ley cultivation is allocated based on the DM yield of cash crops.

Year	**Grasses**	**Biomass Type**	**Amount kg DM/ha**	**N%**	**N (kg/ha)**	**Total N (kg/ha)**	**C:N**	**Total carbon added kg/ha**	**CO2 sequestered g CO_2 kg_{carrot}^{-1}**
Y1	Clover grass red clover (25%) +timothy (75%)	Above ground	6000	0,025	150	172	20[a]	3440	42
		Below ground	1000	0,022	22				
Y2	2nd year Clover grass	Above ground	4000	0,025	100	232	20[a]	4640	57
		Below ground	6000	0,022	132				
Y4	Catch crops Oat+pea+vetch	Above ground	8000	0,025	200	230	15[b]	3496	43
		Below ground	1500	0,020	30				
Sum								**11576**	**141**

Year	**Crop**	**Biomass type**	**Amount (kg DM/ha)**	**C content**	**Total kg CO2-C/ha**	**CO2 sequestered (g CO2 kgcarrot-1)**	**Allocation amount g CO2 kgcarrot-1**	**Allocation %**	**Total (after allocation) g CO_2 kg_{carrot}^{-1}**
Y5	Carrot	Compost	30000	14 % [c]	4308	53	141	67,33 %	147,93

a (Nykänen *et al*. 2008)
b (Forsman *et al*. 2004)
c (Halinen *et al*. 2007)

APPENDIX 7. Production of feed barley grain replaced grass silage (4t DM) and lifecycle phases and their environmental impacts. GHG emissions and energy demand are calculated using (GaBi Database 2011) unless otherwise stated. The sources for fuel consumption are referred in table footnotes.

Lifecycle phases	**Activities**	**Quantity g CO_2 eq. kg_{carrot}^{-1}**	**Energy Demand MJ kg_{carrot}^{-1}**
Field activities [a]	Combine harvesting	2,79	0,038
	Solid manure loading and spreading, by hydraulic loader and spreader	1,47	0,020
	Sowing	0,32	0,004
	Tillage, cultivating, chiseling	1,31	0,018
	Tillage, currying, by weeder	0,40	0,006
	Tillage, harrowing, by spring tine harrow	0,75	0,010
	Tillage, ploughing	2,20	0,030
	EU-27: Diesel mix at refinery, 5,75% bio component	0,95	0,022
	Field Total	10,21	0,149
Grain Drying [a]	FI: Electricity grid mix (production mix)	0,46	0,013
	FI: Thermal energy from light fuel oil (LFO)	5,09	0,072
	Drying Total	5,55	0,084
Barley Field [b]	Direct and indirect soil N_2O emissions	31,64	
Total	Avoided emissions and avoided energy consumption	47,40	0,23

Inventories regarding barley cultivation

Yield (kg DM/ha)	Diesel consumption (l/ha)	Manure nitrogen (kg/ha)	Residue to the soil (kg DM/ha)
3198 [a]	105 [a]	148 [c]	4,4 [d]

[a] (GaBi Database 2011)
[b] (IPCC 2006)
[c] Assumed to be 30 t DM/ha
[d] NIR (2013)

APPENDIX 8. Description of impact categories. (Stranddorf *et al*. 2005).

Impact categories	Symbol	Unit	Description
Global warming potential with 100 year time frame	GWP100	kg CO_2 eq	Global warming potential, also known as climate change is referred to a phenomenon where number of chemical compounds called GHGs help to absorb infrared radiation (IR) and trap in lower atmosphere resulting in increase in temperature of lower atmosphere. Following compounds are referred as GHGs: CO_2 CH_4, N_2O, CFCs, HCFCs, HFCs, halons, tetrachloromethane, 1,1,1-tetrachloromethane and carbon monoxide. However, kg CO_2 eq is standardized as a reference unit.
Ecotoxicity potential	EP (TETP and AEP)	m3 soil/g substance and m3 water/g substance	Terrestrial ecotoxity potential (TETP) and aquatic ecotoxicity potential (AEP) can be commonly defined ad Ecotoxicity porential (EP). Number of substances such as metals, persistent organic pollutants, pesticides and organotin compounds are responsible for EP.
Photochemical ozone creation potential	POPC	kg C2H4- eq	Ozone is a secondary pollutant and is formed in the troposphere when nitrogen oxide come in contact to sunlight. Tropospheric ozone is considered as one of the most dangerous environmental threats. High concentration of ozone is hazardous to human health. Nitrogen oxides (NOx), volatile organic compounds (VOCs) and carbon monoxide (CO) are responsible for forming ozone. However, ethene (C2H4) is used as a standard unit.
Eutrophication potential	EP	kg NO_3^{-1} eq.	The potential impact of nutrient such as nitrogen and phosphorous on large bodies is water severe which results in degrease in amount of dissolved oxygen. The increase in nutrient in water body is also known as nutrient enrichment. The standard reference unit is kg NO_3^{-1} eq.
Acidification potential	AP		The release of protons into the environment causes acidification. Acidification occurs only when the anions from the acidifying chemical release to the environmental. However, it does not apply to organic acids since they are mineralized and cannot be leached to the environment. The acidification is caused by number of substances notably sulfur dioxide and trioxide, nitrogen oxides, hydrogen chloride, nitric acid, hydrochloric acid, hydrogen fluoride, hydrogen sulfide and ammonia. kg SO2- eq. is standardized as a reference unit.

APPENDIX 8. Continued. Description of impact categories. (Stranddorf *et al*. 2005).

Human toxicity potential	HTP		In LCA context, human toxicity includes acute toxicity, irritation effects, allergenic effect, organ damages, carcinogenic effect, effect on reproductive systems and neurotoxicity. The exposure to contaminated air, water and soil may cause aforementioned effects. Following substances are categorized to cause HTP: VOCs, NOx, SO2, chlorinated organic compounds, persistent organic compounds and particulate matter (PM10). It is expressed in three different units depending type of exposure such as air, water or soil: m^3 air/g substance, m^3 water/g substance and m^3 soil/g substance.
Ozone depletion potential	ODP	kg CFC-11 eq.	The life-threatening ultraviolet radiation from sun are absorbed by the ozone molecules (O_3) present in stratosphere. However, the reactive nature of O_3 makes it vulnerable to number of chemical compounds such as methane, nitrous oxide and water vapor. The potential of depletion of stratospheric ozone is quantified for number of halogenated compounds such as chlorofluorocarbons (CFCs). However, CFC-11 is chosen as a reference point and used as a unit.

APPENDIX 9. Description of unit processes regarding incineration of packaging alternatives. (Gabi database 2011).

Packaging types	Phases	Description
Corrugated box	Production	In this study it is assumed that corrugated box is composed of 16,6% primary fiber whereas as rest being recycled fiber. The data represent average technology rather than any certain technology.
	Incineration	A waste-to- energy plant is assumed to be facilitated with dry flue gas treatment and does not include waste collection and pre-treatment. Net calorific value of plastic is 15 MJ/kg. The average efficiency of the steam production is assumed to be 82% whereas 38% as a net efficiency. Of the total energy output, thermal and electrical outputs are 72% and 28% respectively. Due to the unavailability of local information of waste -to-energy plants, data from Germany is taken.
HDPE	Production	The data regarding HDPE production are taken from the association of plastic manufacturer (Plastic Europe). All data used belong to European industry average data with 2005 as a reference year.
	Incineration	A waste-to- energy plant is assumed to be facilitated with dry flue gas treatment and does not include waste collection and pre-treatment. Net calorific value of plastic is assumed as 43,5 MJ/kg. The efficiency of the plant is assumed to be 82%. Due to the unavailability of local information on waste -to-energy plants, data from Germany is taken.

APPENDIX 10. Energy production from natural gas as a traditional source of energy. (Gabi database 2011)

Source	Type	Description
Energy from natural gas	Electricity	The electrical energy is generated in either specific plants or combined heat and power (CHP) plants. The internal consumption of energy is taken from statistics. National and regional technologies regarding efficiency, flue gas treatment, desulphurization, NOx removal and de-dusting are considered. The datasets includes all relevant processes and technologies along the supply chain. Finnish national carrier mix is taken for thermal energy production. All relevant transport phases are considered.
	Heat	The thermal energy is generated in certain heat plants. National and regional technologies regarding efficiency, flue gas treatment, desulphurization, NOx removal and de-dusting are considered. The datasets includes all relevant processes and technologies along the supply chain. Finnish national carrier mix is taken for thermal energy production. All relevant transport phases are considered.

APPENDIX 11. Impacts of PELD waste incineration on GHG emissions and energy demand.

Categories	Phases	OC-FI	CC-FI	CC-IT
GHG Emissions g CO_2 eq. kg_{carrot}^{-1}	Baseline [b]	4	142	280
	Incineration [a]	19	19	19
	Avoided emissions [a]	-10	-10	-10
	Cradle-to-grave (total)	14	152	290
	Difference	10	10	10
Energy Demand MJ kg_{carrot}^{-1}	Baseline [b]	1,33	1,88	3,68
	Energy production [a]	0,12	0,12	0,12
	Net energy demand	1,21	1,76	3,56
	Difference	-0,12	-0,12	-0,12

[a] Gabi Database (2011)
b Results from main study, Section 4

APPENDIX 12. Impact of waste incineration on overall of energy demand (MJ kg_{carrot}^{-1})

Packaging alternative	OC-FI			CC-FI			CC-IT		
	Initial demand	Energy production	Net energy demand	Initial demand	Energy production	Net energy demand	Initial demand	Energy production	Net energy demand
Open-washed	1,77 [b]	0,27 [a]	1,49	2,32 [b]	0,27 [a]	2,05	4,12 [b]	0,27 [a]	3,85
Open-unwashed	1,48 [c]	0,27 [a]	1,20	2,03 [c]	0,27 [a]	1,76	3,82 [c]	0,27 [a]	3,54
PELD-Packed (baseline)	1,33	0,12	1,21	1,88	0,12	1,76	3,68	0,12	3,56

[a] Gabi database (2011), includes incineration of both corrugated box and HDPE bags.
[b] includes production of corrugated box and HDPE bags
[c] includes production of corrugated box and HDPE bags but excludes washing of carrots

APPENDIX 13. Impact of waste incineration on overall GHG emissions (g CO_2 kg_{carrot}^{-1}).

Packaging alternatives	OC-FI			CC-FI			CC-IT		
	Initial Emission [b]	Avoided Emission [a]	Net emissions	Initial Emission [b]	Avoided emission [a]	Net emissions	Initial Emission [b]	Avoided Emission [a]	Net emissions
Open-washed	35,00	-21,41	13,59	173,41	-21,41	152,00	311,64	-21,41	290,23
Open-unwashed	23,22	-21,41	1,82	161,63	-21,41	140,22	294,26	-21,41	272,86
PELD-Packed (baseline)	23,01	-9,54	13,46	161,41	-9,54	151,87	299,41	-9,54	289,87

a Emissions from energy production from natural gas, Gabi Database (2011)
b Cradle-to-grave system boundary, meaning packaging waste incineration is included