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LIFE CYCLE ASSESSMENT OF BIODIVERSITY IMPACTS FROM FINNISH GREENHOUSE VEGETABLES AND BERRIES

Lappeenranta–Lahti University of Technology LUT
Master's Programme in Circular Economy
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ABSTRACT

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Life cycle assessment of biodiversity impacts from Finnish greenhouse vegetables and berries

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81 pages, 14 figures, 19 tables and 16 appendices
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Keywords: biodiversity, LCA, LC-IMPACT, tomato, cucumber, lettuce, strawberry, blackcurrant, lingonberry, bilberry, greenhouse vegetable, cultivated berry, wild berry, Finland

Biodiversity loss is a global environmental problem, and agriculture is recognized as a major contributor to it. Since the number of biodiversity impact assessments for Finnish plant products is limited, the objective of this master's thesis was to assess the biodiversity impacts of Finnish greenhouse vegetables (tomato, cucumber, lettuce) and berries (strawberry, blackcurrant, bilberry, and lingonberry) as global species loss. For comparison, European average strawberry was assessed. The assessment was done using the Life Cycle Assessment (LCA) methodology and the LC-IMPACT method. The investigated impact categories were climate change, land stress, freshwater eutrophication, marine eutrophication, and water stress. The study was conducted as part of the Luonnon monimuotoisuus lautasella -project.

For greenhouse vegetables, the greatest impacts resulted from the impact categories of climate change and water stress, while the cultivation phase was the major contributor to the results. For cultivated berries (strawberries and blackcurrant), the biggest impacts came from climate change and water stress, and the main contributing life cycle phases were cultivation and processing depending on the impact category. EU strawberry showed higher total impacts compared to Finnish cultivated berries. However, marine eutrophication impacts were notably higher for Finnish cultivated berries compared to EU strawberry, highlighting the sensitivity of Archipelago Sea. The biggest biodiversity impacts of wild berries (lingonberry and bilberry) were related to climate change and transportation. Wild berries showed the lowest total biodiversity impacts among the investigated products, even with the berry picker's transportation from Thailand. Including the transportation of berry pickers from Thailand to Finland increased the biodiversity impacts of wild berries two- to threefold, nearly reaching the impact level of Finnish strawberry production.

The study observed that it is difficult to rank products as more or less environmentally friendly from the biodiversity point of view, since they affect biodiversity through different pathways. The study also found out that Finnish electricity production contributes to biodiversity loss through multiple pathways beyond climate change, and therefore future research on the biodiversity impacts of Finnish energy system is suggested.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT
LUTin energiajärjestelmien tiedekunta
Ympäristötekniikka

Annika Sopo

Suomalaisten kasvihuonevihannesten ja marjojen biodiversiteettivaikutusten elinkaariarviointi

Ympäristötekniikan diplomityö
2025
81 sivua, 14 kuvaa, 19 taulukkoa ja 16 liitettä
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Luontokato on maailmanlaajuinen ympäristöongelma, ja maatalous on sen yksi merkittävä aiheuttaja. Suomalaisten kasvikunnan tuotteiden biodiversiteettivaikutuksia on arvioitu rajallisesti, jonka takia tämän diplomityön tavoitteena oli arvioida suomalaisten kasvihuonevihannesten (tomaatti, kurkku, salaatti) ja marjojen (mansikka, mustaherukka, puolukka ja metsämustikka) aiheuttamat biodiversiteettivaikutukset maailmanlaajuisena lajien häviönä. Vertailun vuoksi arvioitiin myös Euroopan keskimääräinen mansikka. Arviointi tehtiin käyttämällä elinkaariarviointia (LCA) ja LC-IMPACT-menetelmää. Tutkitut vaikutusluokat olivat ilmastonmuutos, maankäyttö, makean veden rehevöityminen, meriveden rehevöityminen ja vedenkäyttö. Tutkimus toteutettiin osana Luonnon monimuotoisuus lautasella -hanketta.

Kasvihuonevihannesten suurimmat vaikutukset aiheutuivat ilmastonmuutoksesta ja veden käytöstä, ja viljelyvaihe oli elinkaaren merkittävin tuloksiin vaikuttava tekijä. Puutarhamarjoilla (mansikat ja mustaherukka) suurimmat vaikutukset aiheutuivat ilmastonmuutoksesta ja vedenkäytöstä, ja tärkeimmät elinkaaren vaiheet olivat viljely ja prosessointi vaikutusluokasta riippuen. EU-mansikan kokonaisvaikutukset olivat suuremmat verrattuna suomalaisiin puutarhamarjoihin. Kuitenkin meriveden rehevöitymisvaikutukset olivat huomattavasti korkeammat suomalaisilla puutarhamarjoilla verrattuna EU-mansikkaan, mikä korostaa Saaristomeren herkkyyttä. Villimarjojen (puolukka ja metsämustikka) suurimmat biodiversiteettivaikutukset liittyivät ilmastonmuutokseen ja kuljetuksiin. Villimarjat osoittivat alhaisimmat kokonaisvaikutukset kaikista tutkituista tuotteista, myös silloin kun marjanpoimijoiden kuljetukset Thaimaasta huomioitiin osaksi niiden elinkaarta. Marjanpoimijoiden kuljetusten sisällyttäminen Thaimaasta Suomeen 2–3 kertaisti villimarjojen kokonaisvaikutukset, jolloin niiden vaikutukset olivat lähes suomalaisen mansikan vaikutusten tasolla.

Tutkimuksessa havaittiin, että tuotteita on vaikea asettaa järjestykseen ympäristöystävällisyydessä biodiversiteettivaikutusten näkökulmasta, koska ne vaikuttavat biodiversiteettiin eri vaikutusketjujen kautta. Lisäksi tutkimuksessa havaittiin Suomen sähköntuotannon merkittävä vaikutus biodiversiteettiin myös muissa vaikutusluokissa kuin ilmastonmuutoksessa. Siksi Suomen energiantuotannon biodiversiteettivaikutuksia olisi syytä tutkia jatkossa tarkemmin.

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Finally, I want to thank my friends and loved ones for your constant support and for bringing joy and balance to my everyday life.

Annika Sopo
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ABBREVIATIONS

AE	Aquatic Ecosystem
AoP	Areas of Protection
CF	Characterization factor
CHP	Combined Heat and Power
CO2	Carbon Dioxide
eq	Equivalent
EU	European Union
EU-FP7	European Union's Seventh Framework Programme
FAO	Food and Agriculture Organization of the United Nations
FIN	Finland
GHG	Greenhouse Gas
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
I/O	Input-Output model
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LDPE	Low-Density Polyethylene
LUKE	Natural Resources Institute Finland
LULUC	Land Use and Land Use Change
LUT	Lappeenranta–Lahti University of Technology LUT
ME	Marine Ecosystem
N	Nitrogen
NCA	Natural Capital Accounting
P	Phosphorus
PDF	Potentially Disappeared Fraction of Species
TE	Terrestrial Ecosystem
yr	Year

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DECLARATIONS

Turnitin

The originality of this thesis has been reviewed with the Turnitin similarity checking service.

AI usage

The author of the thesis, Annika Sopo, used the following AI-tools during the preparation of the thesis:

1. ScopusAI
    a. Purpose of use: To search for relevant scientific references and to create overview of research topics.
    b. Explanation of the use of the tool: Used primarily for finding scientific publications related to the research themes.
2. ChatGPT
    a. Purpose of use: For quick overview of the topics and support for language correction.
    b. Explanation of the use of the tool: Used to clarify basic concepts, support understanding of the topics, as well as used as a dictionary and language editor.
3. Google NotebookLM
    a. Purpose of use: To quickly analyse articles and reports in order to determine whether they contained the specific needed information.
    b. Explanation of the use of the tool: Used to identify whether the selected sources included the desired findings or specific detailed information.

Responsibility

The author, Annika Sopo, takes full responsibility for the content of this thesis and has reviewed and edited the content generated by the possible use of AI tools.

1 Introduction

Biodiversity loss is a prominent environmental issue that our society has become more aware of over the past few decades (WFF 2021, 6, 12). It is estimated that approximately one third of the global biodiversity has already been lost by human actions (Syke 2024) and the scenarios indicate increasing numbers of extinction in the future as well (Pereira et al. 2010, 1496). Besides, biodiversity is understood as an essential part of functional ecosystems, it also builds up base for vital goods and services human society consumes (Gamfeldt, Hillebrand & Jonsson 2008, 1223). Therefore, the growing concern for the condition of natural environments is not negligible and actions for effective biodiversity conservation are needed.

The main direct drivers for biodiversity loss have been identified as land use and land use change (LULUC), climate change, invasive species, overexploitation of natural resources and pollution (Souza, Teixeira and Ostermann 2015, 32), and agriculture as well as food systems have been identified as one of the most significant contributors for these. It is estimated that over one third of all terrestrial land surface and ¾ of the freshwater resources are devoted to agricultural production. (IPBES 2019a, XVI, 58–59.) Land use and conversion disrupt ecosystems, and intensification of land use decrease the quality of remaining habitats. Usage of agrochemicals, like fertilizers and pesticides, decrease the quality of water resources, causing harm to freshwater and marine ecosystems. (Frieri & Morone 2025, 3523–3524.) Moreover, agrifood systems covered nearly 30 % of the anthropogenic greenhouse gas (GHG) emissions in 2022, which makes food sector significant driver of climate change (FAO 2024, 3). All of this highlights the importance of effective actions towards more sustainable agricultural practices and food systems.

Biodiversity loss has been recognized as severe threat as climate change (Diaz & Bhardwaj 2019), yet climate actions have become much more common in companies (CDP 2025). According to Uusitalo (2022), the lack of effective actions for biodiversity can be explained by the lack of comprehensive calculation methods for a complex problem at hand. As the impacts on climate change can be measured and contributed relatively easily by controlling GHGs, biodiversity loss is a cause of several interconnected problems that cannot be affected without collaboration beyond borders (Uusitalo 2022.) Moreover, agricultural systems and their environmental impacts are rather complex to be analyzed, due to the factors such as multiple products allocation from single system, regional and crop specific management techniques, seasonal and annual variations, spatial variations with multilocated product life cycle phases, and the large quantity of nonpoint emissions sources (Caffrey et al. 2013, 1). Several methods have been developed to assess biodiversity impacts even though the standardization is still lacking (Bhattarai et al. 2024, 1). One of the most widely used tools for product-level environmental assessment is Life Cycle Assessment (LCA) framework (Caffrey et al. 2013, 1).

It has already been proven by several agricultural studies that animal-based products have higher biodiversity impacts than plant-based products (Crenna, Sinkko & Sala 2019, 383–388; Vartiainen et al. 2025, 17, 21). Earlier studies have also concluded that most of the biodiversity impacts from Finnish food consumption are related to the imported products (Sandström et al. 2017, 33). However, the number of biodiversity impact assessments for Finnish plant products is limited, which is why this master's thesis aims to provide information related to it.

The objective of this master's thesis is to assess biodiversity impacts of Finnish plant products as global species loss. The assessed Finnish products are tomato, cucumber, lettuce, strawberry, blackcurrant, bilberry and lingonberry. Also, European strawberry is assessed for comparison to Finnish one. The study is conducted as part of Luonnon monimuotoisuus lautasella -project, which aims to create food procurement criteria for decision making of food and tourism operators in Southwest Finland and Archipelago Sea region. In this study, the impacts are quantified by using LCA methodology and LC-IMPACT method. The investigated impact categories are climate change, land stress, freshwater eutrophication, marine eutrophication, and water stress.

The research aims to provide answers for the following questions:

-What are the quantified biodiversity impacts of defined Finnish plant products as global species loss?
-What are the most significant impact categories and contributing processes to biodiversity impacts in the production chains of defined Finnish plant products?

The second and third chapters of the thesis introduces the theory around the topic. Some general information about biodiversity, as well as environmental issues related to food production are presented. In fourth chapter, methodology of the study is explained, including LCA methodology, LC-IMPACT method, and chosen impact categories according to the method. Fifth chapter concentrates on the implementation of life cycle biodiversity assessment for eight plant products assessed in this study. Step-by-step analysis is provided from goal and scope definition and inventory analysis to impact assessment and interpretation of the results. In the final chapter, assessment is discussed in broader literature context, and the recommendations and conclusions are provided.

2 Biodiversity

This chapter introduces the concept of biodiversity. First, definitions and common ways to categorize biodiversity are explained, since defining biodiversity form basis to measure it (Magurran & MacGill 2011, 1). Next, quantification of biodiversity is described from the biological point of view. The biological quantification of biodiversity provides groundwork for understanding biodiversity assessment in the LCA context, which is further explained in chapter 4. Finally, the direct drivers of current biodiversity loss are explained.

2.1 Definitions

The term biodiversity is abbreviation of biological diversity (Dyke 2008, 84). A widely used definition is created by Convention on Biological Diversity (CBD). It determines that

> "'Biological diversity' means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic systems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems." (Convention on Biological Diversity 2008)

Generally biological diversity is separated into three different forms of diversity: genetic, species and ecosystem diversity. Genetic diversity describes the variation within species, and it provides resilience and capacity for species to adapt to environmental changes. (Hoban et al. 2021, 2; IPBES 2019a, XIV, 832.) Species diversity reflects variation between species and is the most used type of diversity in biodiversity metrics, also in LCA context (Curran et al. 2011; Dyke 2008, 89, 170). Ecosystem diversity describes the variation between ecosystems, which are systems consisting of interactions between living and non-living components of the environment (Otekenari & Felix 2020, 34).

Dyke (2008, 86) notes that biodiversity also includes both structural and functional variety in different levels of diversity. This definition highlights that the biological diversity is not just the collection of individual species or ecosystems, but also the functions and interactions between them. (Dyke 2008, 86.) However, Currant et al. (2011, 70) explaines that functional and structural attributes of biodiversity are largely neglected in LCA context.

2.2 Quantification

The complexity of biological diversity is difficult to quantify, and there is no single metric that perfectly describes it (Duelli & Obrist 2003, 87). Magurran & McGill (2011, 2, 4) emphasises that it must be specified which aspects of biodiversity is being measured and choose the metrics that are suitable for the purpose. There are increasing number of diversity measurements being developed. (Magurran & McGill 2011, 2, 4.)

Easiest way to measure biological diversity is to separate it into components, that can be measured. Typical components for measuring biological diversity are the number of different species (richness), number of individuals among one species (abundance) and the distribution of species' relative abundances (evenness). Species richness is the most used and generic determination for quantifying biological diversity and typically can be expected that diversity increases when species richness does. However, diversity is assumed to increase also when evenness increases. (Magurran 2005, 116–117; Magurran & McGill 2011, 2–3). Well known indexes for richness-evenness measures are Simpson's Index and Shannon-Weiner Index (Duelli & Obrist 2003, 90).

Magurran (2005, 117) explains that basic measures do not tell whether a community with a high species richness but dominated by only a few species is more or less valuable than a community with a lower number of species where individuals are distributed evenly. The valuing of different species can be based on, for example, phylogenetic attributes of species or functional diversity of community. Valuing of species can reveal for example, conservation interests and patterns of relations between different species. (Magurran 2005, 117.)

There are also other measures for assessing biodiversity, than species richness, abundance, and evenness. Magurran & McGill (2011, 2) states that evaluation of geographical occurrence of taxa, range sizes, and vulnerability of species as well as functional features and phylogenetic diversity are all investigated to better understand biodiversity.

Biological diversity has spatial and temporal dimensions, which means that it is linked to certain place and time. According to Andermann et al. (2022, 1–2), spatial dimension means that the species are distributed unevenly across space. For example, the diversity increases when moving from the poles towards the equator. This distribution is called latitudinal gradient. However, there are also spatial differentiation in regional scale, for example, between forested areas and an open grassland. (Andermann et al. 2022, 1–2.)

Spatial patterns in biodiversity are often described with concepts of alpha-, beta- and gamma diversity. Alpha diversity describes the local diversity within a functional community. Beta diversity, instead, occurs when moving from one place to another, in other words, between two alpha diversities. Gamma diversity is overall diversity, which covers the two previous. (Andermann et al. 2022, 1–2.)

Beta diversity provides first approximation of area diversity or regional diversity. Beta diversity can be considered important measure of the diversity when environmental gradients, such as moisture or soil pH, are changing. When the communities are measured along the gradient, it gives knowledge about the sensitivity of species towards environmental changes and whether the species are interdependent. (Dyke 2008, 91–92.)

Gamma diversity is the most used level of species diversity and is often described with biogeographic or political aspects, for example, ecoregions, countries, or biodiversity hotspots. It is notable that meanwhile alpha diversity can be relatively easily measured, measuring gamma diversity is much more difficult and requires huge effort. Therefore, some form of modelling and estimations are usually used to create diversity maps for larger areas. (Andermann et al. 2022, 1–2.)

Temporal dimension of biological diversity describes the changes in ecological communities over time. Communities are always facing temporal changes and assessing these temporal processes of biodiversity is important part for the quantification of diversity. There must always be a baseline for which to compare the current situation. (Magurran 2011, 85–86.)

2.3 Direct drivers of biodiversity loss

Anthropogenic activities, which means activities that are caused or influenced by humans, are the main reason for current biodiversity loss. Activities that directly affect biodiversity are LULUC, climate change, overexploitation, pollution, and invasive species. Direct drivers are driven by indirect ones, such as socio-economic and demographic trends, as well as societal factors. The first include, for example, consumption patterns and technological solutions that create the need of natural resource use. Societal drivers, like culture and governance, affect the values and decision making of human behaviour. (IPBES 2019a, 26, 54–61.) Figure 1 illustrates the direct and indirect drivers of the current biodiversity loss.

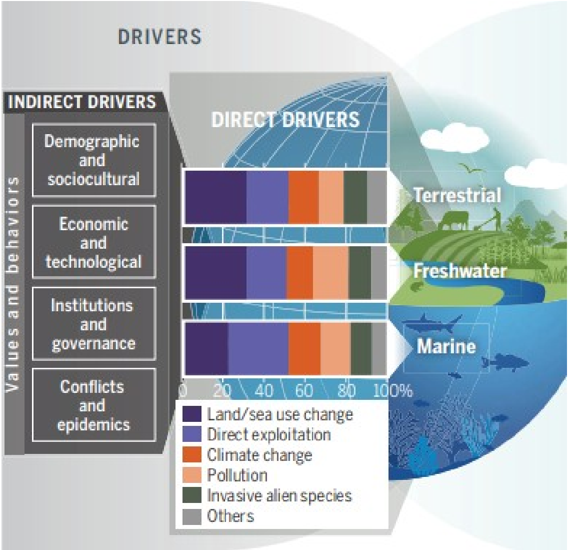

Figure 1: Direct and indirect drivers of the current biodiversity loss (IPBES 2019a, XXIX).

LULUC is currently the biggest driver of biodiversity loss (IPBES 2019b, 2). It causes not only habitat loss and fragmentation but also changes the landscape and the properties of soil and surface (Kollner et al. 2013, 1194). Despite most of LULUC happens in terrestrial systems and impacts on terrestrial biodiversity, also freshwater and marine environments are affected by it. Rivers are dammed for water, energy and transportation purposes, and wetlands are lost due to the drainage. Marine habitats are affected through fishing practices, coastal engineering, and aquaculture. (Pereira et al. 2012, 36–37.)

Biodiversity is expected to respond to changing climate by changing the ecosystem functioning as well as migration of species and entire ecosystems. Also, global temperature increase is expected to increase ocean temperatures and acidification, which will affect the marine ecosystems. (IPBES n.d.) Pereira et al. (2024, 5) suggests that climate change might become even more important driver of terrestrial biodiversity loss than land use change by 2050.

Pollution is a significant driver of biodiversity loss in all biomes, but especially in freshwater and marine environments. One remarkable source of pollution are nitrogen-phosphorous fertilizers that easily lead to eutrophication in freshwater and marine environments. In addition, atmospheric deposition of nitrogen has been recognized as an important disturbance to terrestrial biodiversity. (IPBES n.d.)

Overexploitation drives biodiversity loss by consuming natural resources faster than species and ecosystems can regenerate. It includes unsustainable fishing, hunting, logging, and harvesting for the pet and medicinal trade. This reduce population sizes and push many species towards extinction. Marine fish, invertebrates, trees, tropical vertebrates are among the most overexploited species. Invasive species, instead, threaten biodiversity by outcompeting native species for natural resources and therefore disrupting the ecological processes. (IPBES n.d.)

3 Food system and biodiversity

This chapter explains the multifaceted linkages between food system and biodiversity, where both have reciprocal impacts on each other. The chapter addresses how food supply chain affect on biodiversity, and highlights also the need for change in food production and consumption as a system. Reciprocally, the chapter addresses that food production is dependent on healthy and diverse ecosystems.

3.1 Linkages between food and biodiversity

Food system is a significant driver of LULUC and climate change, which are known to be among the major drivers of biodiversity loss (Boakes et al. 2024, 2). It is estimated that even 49 % of the Earth's habitable land is used for agricultural purposes (Benton et al. 2021, 8). At the same time, food production is dependent on biodiversity, because functional ecosystems provide valuable ecosystem services for agriculture, such as soil health, pollination, and natural pest control. (Kumar et al. 2024, 1). Figure 2 illustrates some of the factors and connections between food system and biodiversity loss.

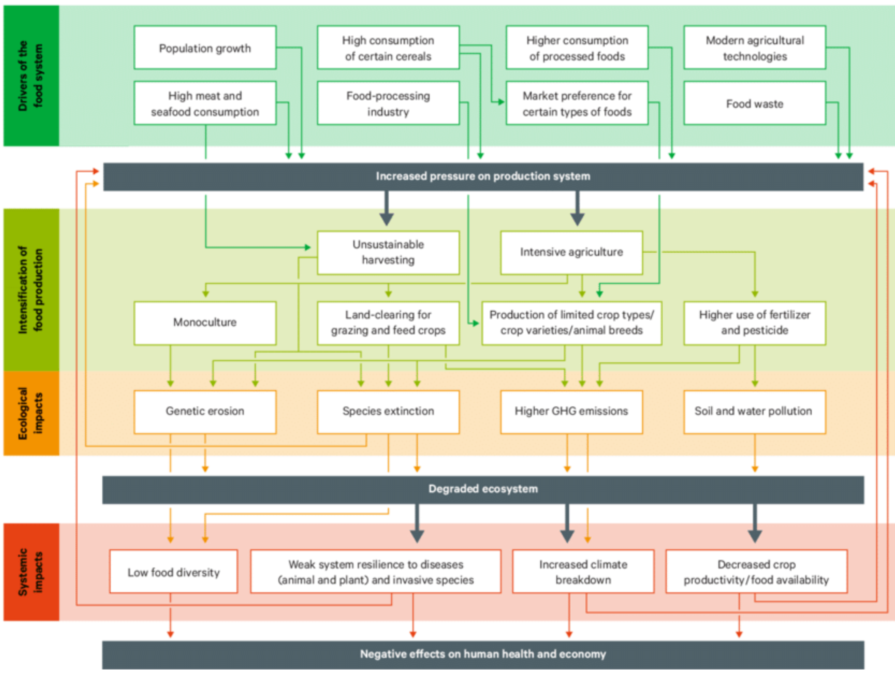

Figure 2: Multiple factors of food system, and their impacts on biodiversity (Benton et al. 2021, 16).

Agriculture impacts on biodiversity by converting natural habitats to managed systems, which disturbs the natural ecosystems that wildlife depends on (Frieri & Morone 2025, 1). Habitats are lost and fragmented, and landscapes as well as the properties of soil and surface are changed (Kollner et al. 2013, 1194). Pereira et al. (2012, 36) categorises terrestrial land use change dynamics into three categories: conversion of natural habitats to human-dominated habitats, intensification of land use in human dominated habitats, and recovery of natural vegetation and forest in areas that have been previously cleared by humans.

Most conversion of natural to human-dominated habitats happens in tropical forests (Pereira et al. 2012, 36). At the same time, tropical forests are known to include many biodiversity hotspots, which means that in the defined area, there are more than 1500 plant species as endemic and at least 70 % of the primary vegetation is lost (Myers et al. 2000, 854–855). Smallholder and industrial agriculture are one of the main reasons for tropical deforestation. However, there are also underlying causes like international trade and demand in commodities, as well as industrialized agriculture replacing more and more the small-scale agriculture due to the global market chains. (Bernhard et al. 2024, 2–6.)

In addition to spatial expansion of human-dominated habitats, the intensification of land already in use impacts on the environmental conditions. Pereira et al. (2012, 36) claims that agricultural areas are an example of a surrounding where intensification happens (Pereira et al. 2012, 36). Intensification in agriculture means using more inputs to increase the amount of outputs. This is usually done by increasing the amount of pesticides, herbicides, fertilizers, equipment and land used. (Benton et al. 2021, 7). Intensive farming practices have become more common because of the need to increase the food production due to the growing population and increasing food demand. Also, more sustainable agricultural practices, such as organic farming, are less productive with lower yields. (Frieri & Morone 2025, 9.)

GHG emissions from agrifood system were 16.2 billion tonnes of carbon dioxide equivalent (Gt CO_2eq) in 2022. This covers approximately 29.7 percent of all anthropogenic GHG emissions in that year, which makes food sector a significant driver of climate change. (FAO 2024, 3.) At the same time, agriculture as well as food security is under a severe threat when it comes to changing climate; flooding, storms and hurricanes, temperature changes, sea level rise and melting of ice (Benkeblia 2022, 1, 5).

Tubiello et al. (2022, 1795) explains that the GHG emissions in agrifood systems are generated mostly within farm gate (Tubiello et al. 2022, 1795). Agriculture, including crop and livestock production activities, covered 48 % of the global agrifood systems GHG emissions in 2022 (FAO 2024, 3). Other sources of GHGs in agrifood systems are emissions from soil due to the land use change as well as pre and post-production processes (Tubiello et al. 2022, 1796). Land use change include conversion of natural ecosystems to agricultural use by deforestation and peatland degradation, which releases the carbon stored in vegetation and soil (Adesiji et al. 2015, 228). Pre and post-production processes mean the processes along food supply chain, such as fertilizer manufacturing, energy use, food processing, transportation, retail, packaging, household consumption and food system waste disposal. (Tubiello et al. 2022, 1796.)

When comparing GHG emissions, pre and post-production processes emit the most carbon dioxide emissions, while farm gate activities are the major emitter of methane and nitrous oxide. (Tubiello et al. 2022, 1799.) The biggest cause for methane generation within farm gate is enteric fermentation of livestock, and for nitrous oxide, manure (FAO 2024, 4). However, it is notable that also pre and post-production processes release significant amounts of methane, mostly because of solid food waste in landfills and open dumps. Moreover, GHG emissions from pre and post-processing activities have increased significantly in recent decades due to increased utilization of processed food. (Tubiello et al. 2022, 1799.)

Purvis et al. (2019, 220) points out that biodiversity loss does not concern only wild ecosystems but also diversity of species that are used for food production. Agrodiversity covers the variety and variability of animals, plants and micro-organisms that are used directly or indirectly for food and agriculture. This includes crops, livestock and fisheries as well as species that support production, like soil micro-organisms, predators and pollinators. Agrodiversity can be considered as an essential part of global food security. (Purvis et al. 2019, 220.)

Agrodiversity, as biodiversity in general, can be separated into genetic, species and ecosystem diversity. Genetic diversity covers variabilities and breeds within species used in food, fodder, fiber, fuel and pharmaceutical production. Ecosystem diversity covers the differences in agro-ecosystems. (Purvis et al. 2019, 220.) Especially genetic agrodiversity has decreased, when global food supply chains rely on only small selection of food crops. Such trend decreases not only the state of biodiversity but also the resilience of food system towards changes in the environment. Therefore, loss in agrodiversity is a threat to global food security. (Frieri & Morone 2025, 1.)

After all, Frieri & Morone (2025, 9) states that it is important not to concentrate only on supply side of the food system but also the demand and consumption side (Frieri & Morone 2025, 9). Over the past decades, the food consumption patterns have changed towards energy-intensive and animal-based diets (Paris et al. 2022, 151437), even though meat and dairy products are proved to have high environmental impacts compared to plant-based options. Moreover, it is estimated that even one third of produced food for human consumption is wasted along the supply chain, which means that part of the environmental impacts is in vain. The influence of consumer behaviour is essential when it comes to environmental impact management. (Scherhaufer et al. 2018, 98–99.)

4 LCA methodology

There is no standardized method for assessing biodiversity impacts yet, however, increasing number of methods are being developed for this purpose. According to CircHive project (2022–2027) – an EU funded project aiming to promote the information, quantification and reporting about the value of nature – the three most used methodologies for biodiversity impact accounting are Life Cycle Assessment (LCA), Natural Capital Accounting (NCA) and Input-Output (I/O) models (Bhattarai et al. 2024, 1). In this study, LCA is used for assessing impacts on biodiversity, since it is the most suitable methodology for product specific calculations. NCA is more suitable for a performance assessment in a geographical area, such as country, region or production site. I/O models are used mostly for risk assessment based on supply chain, sector, industry, region or country. (Bhattarai et al. 2024, 21–25.)

This chapter presents the methodology of the study. The chapter presents the standardized principles of LCA as a tool, as well as LCA as a method for assessing impacts on biodiversity. Also, LC-IMPACT method and impact categories of land stress, climate change, eutrophication and water stress according to the method, are explained.

4.1 Life Cycle Assessment (LCA)

LCA is a tool to assess the environmental aspects and potential environmental impacts of a product's life cycle (SFS-EN ISO 14040:2006, v). It aims to provide a systematic overview and perspective to avoid shifting the environmental burdens from one life cycle stage to another. LCAs can be used for many applications and there are detailed approaches for assessing, for example, carbon and water footprints. The scientific community broadly agrees that LCAs are among the most effective methods for evaluating the environmental impact of products and services. (Soukka et al. 2023, 2219, 2221.)

The general principles of LCA study are set in standards 14040 and 14044 by International Organization for Standardization (ISO). The standards read out that LCA study should consists of four phases: the goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation (SFS-EN ISO 14040:2006, v).

Goal and scope definition defines the purpose and the nature of the study as well as the target group of the outputs (Soukka et al. 2023, 2221). The goal should define reasons for carrying out the study, intended applications and audience. The scope should include the functions of the product system, functional unit and system boundaries, allocation procedures, selected impact categories and methodology of impact assessment. Also, data requirements, assumptions and limitations are important to be defined for ensuring the good outcome of the study. (SFS-EN ISO 14040:2006, 11.) The system boundaries are usually illustrated by using a flow diagram (SFS-EN ISO 14044:2006, 8).

The LCI phase includes data collection for input and output flows of the system. The extend of collected data should be aligned with the intended goal and scope, since the collected data will have an impact to the results of the following stage of impact assessment. (SFS-EN ISO 14040, 2006, 13.) Moreover, aligning with the determined goal and scope will help the study to stay focused on the relevant information and the unnecessary data collection can be avoided (Soukka et al. 2023, 2223). Due to the iterative nature of LCI, new data requirements and limitations have to be added as the study progresses and more is learned about the system. Sometimes, even the goal and scope must be refined during the later steps of the study. (SFS-EN ISO 14040:2006, 13.)

The aim of LCIA is to evaluate the significance of potential environmental impacts. LCIA has three mandatory elements and four optional. Mandatory elements consist of choosing the impact categories, category indicators and characterization models, then connecting input and output flows to relevant impact categories (classification) and finally calculating the category indicator results (characterization). Non-mandatory elements are normalization, grouping, weighting and data quality analysis. The aim of non-mandatory phases is to further facilitate the interpretation of the findings. (SFS-EN ISO 14040:2006, 14–15; Soukka et al. 2023, 2223–2224.)

It is important to note that the methods for quantifying the biodiversity impacts in LCIA are not complete yet. According to Verones et al. (2020a, 1202), there are several methods for implementing the phase of LCIA, but none of them is yet truly complete. Most of the methods still need to broaden the potential impacts they consider, for example, by developing missing impact categories, such as salinization, plastic pollution and invasive species. Examples of LCIA methods used to quatify biodiversity impacts are ReCiPe2016, LC-IMPACT and IMPACTWorld+. (Verones et al. 2020a, 1202.)

The final step of assessment process is interpretation, where the findings of the study are presented understandably and consistently. Interpretation combines the results from inventory analysis and impact assessment. Interpretation should reflect the fact that the LCIA results are relative expressions of the potential environmental effects. (SFS-EN ISO 14040:2006, 16, 30.)

4.2 LCA as a method for assessing biodiversity impacts

In the context of biodiversity, LCA aims to understand and quantify the impacts of human activities on natural environment. Several models and methods have been developed to assess biodiversity loss in the field of LCA but capturing the complexity of biodiversity in assessment metrics is still challenging. (Damiani et al. 2023, 1–2.) According to UNEP/SETAC Life Cycle Initiative (2017, 127), the ideal biodiversity indicator should not only describe the complexity of biodiversity but also reflect its spatial and temporal dimensions. At the same time, the indicator should be easy to measure and communicate, as well as support decision making especially when comparing systems. (UNEP/SETAC Life Cycle Initiative 2017, 127.) Currently operational methods quantify mostly species diversity, even though there are methods being under developments for all levels of diversity: genetic, species and ecosystem diversity (Winter et al. 2017, 96).

Midpoint and endpoint methods in LCIA indicate different stages in the process of assessing environmental impacts. Midpoint models look at the environmental consequences earlier in the process, usually by connecting inventory flows to impacts on the environment. Endpoint models, instead, focus on the final effects, linking those environmental impacts to damage in areas of protection (AoPs). Typically, AoPs are human health, ecosystem quality and natural resources. Biodiversity loss is used as a metric to assess damages to ecosystem quality. (Crenna et al. 2020, 9716–9717.) In other words, midpoint categories can be defined as problem-oriented, for example global warming potential, and endpoint categories as damage-oriented, for example human health or ecosystem quality (Winter et al. 2017, 89).

Examples of currently operational endpoint methods for biodiversity assessments are ReCiPe2016, LC-IMPACT, Impact world+ and GLAM. (Crenna et al. 2020, 9716–9717, 9723; Scherer et al. 2023, 19612.) All of the methods have advantages and disadvantages. As GLAM is a project implemented by United Nation Environment Programme’s Life Cycle

Initiative, aiming to consolidate and update recommendations for choosing impact indicators and assessing multiple impact categories (Scherer et al. 2023, 19612), it can be considered as one of the most up-to-date LCIA methods for biodiversity impact assessments. However, LC-IMPACT was used in this study to make the results comparable and consistent with other food related assessments conducted in LUT University and to enable their use in future research.

ReCiPe2016, LC-IMPACT, Impact world+ are all methods that performed well in the comparative study of 23 LCIA methods conducted by Damiani et al. (2023, 1, 8), however, GLAM was not included in the study. The study evaluated how well different methods cover the pressures of biodiversity loss, different ecosystems and taxonomic groups, essential biodiversity variable classes and fundamental biodiversity aspects (Damiani et al. 2023, 8).

4.3 LC-IMPACT

LC-IMPACT is developed under the European Union's Seventh Framework Programme (EU-FP7) as part of the project "Development and application of environmental Life Cycle Impact assessment Methods for Improved Sustainability Characterisation of Technologies". The AoPs in LC-IMPACT method are human health, ecosystem quality and natural resources. Ecosystem quality is further divided into terrestrial, freshwater and marine ecosystem quality. There are 11 impact categories and seven of them are related to ecosystem quality. Each impact category is connected to one or two AoPs. (Verones et al. 2020a, 1202–1203). The impact categories and their linkages to different areas of protection are illustrated in Figure 3. Since biodiversity loss is related to ecosystem quality, only the calculation procedures of that are presented here.

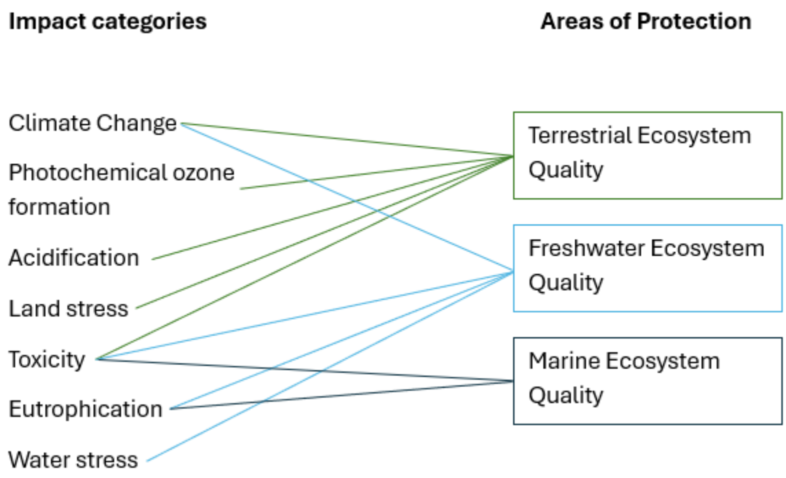

Figure 3: Impact categories and AoPs related to ecosystem quality in LC-IMPACT method. Adapted from (Verones et al. 2020a, 1203).

LC-IMPACT provides characterization factors (CFs) for marginal approach and average/linear approach. A marginal approach measures the additional impact compared to the current state. Marginal approach is usually chosen when the increase in pressure is small. Instead, average approach uses the distance between the current state and either the state of zero impact, preferred state, or realistically accessible state. If the information of background level is lacking, which is usually the case with average approach, a linear approach can be used instead. Average/linear approach is usually chosen if the changes in pressure are larger. (Verones et al. 2020a, 1203–1204; Verones et al. 2020b, 10–11.)

For spatial levels, CFs are provided for global and regional data. Regional CFs are further divided into native spatial levels: country average, continental average and global average. It depends on the impact category, which CFs are provided. The global CFs are meant for those impact categories, which impacts are distributed across the world, despite of the place of emission or extraction. The regional CFs, instead, are meant for impacts that are limited to regional or local scale, and which impacts significance varies a lot depending on the place of action. In the case of ecosystem quality, only climate change is presenting global impacts. The rest reflects regional impacts. (Verones et al. 2020a, 1203.)

CFs can be chosen for time horizon and the level of evidence of impacts. Time horizons are determined as 100 years of impacts or longer-term impacts. The level of evidence is determined as “high degree of scientific confidence only” or “all impacts included”. These aspects result in four different combinations of CFs. (Verones et al. 2020a, 1207.)

Some CFs consider only part of the taxonomic groups, and some takes into account all taxonomic groups provided in the method. Taxonomic groups in LC-IMPACT are mammals, birds, reptiles, amphibians and vascular plants. If all taxonomic groups are considered, the weighted average is used with 50 % share for both plants and animals. The vulnerability of species towards environmental pressures is included whenever possible. (Verones et al. 2020a, 1206; Verones et al. 2020b, 8.)

The unit for ecosystem quality is "potentially disappeared fraction of species over time" (PDF•yr). Some of the CFs contain time dimension and some do not, but the final impact scores are always the same, PDF•yr. The endpoint of LC-IMPACT aims to quantify global PDF whenever possible because it reflects the irreversible extinction of species on a global level and is therefore better indicator for the risk of extinction than regional PDF. This is because if a species is extinct in a certain region, it is not automatically extinct on a global level and therefore not irreversible. (Verones et al. 2020a, 1206.)

The PDF must be considered as a relative number, which refers to the fraction of species that is committed to become globally extinct. For example, PDF of 0.01 means that 1 % of all global species is committed to go extinct if the pressure continues to happen. It is also notable that the change in biodiversity does not happen immediately when the pressure occurs, but gradually over time. Therefore, impact scores should be interpreted as an increase in global extinction risk over a certain exposure period of time, not so much as an instantaneous global species loss. (Verones et al. 2020a, 1206.)

4.3.1 Land stress

In LC-IMPACT, land use is divided into land occupation and land transformation. Land occupation means that the land is used in its intended purpose, such as agriculture. It keeps the ecosystems at different position compared to its natural state and therefore impacts on local biodiversity. Land transformation, instead, means that the land is modified to make it useful for intended purpose. For example, deforestation for the purpose of agriculture is considered as land transformation. In this form of land use, the biodiversity is affected by changing the characteristics of ecosystem. In different parts of the world, biodiversity responds in a different ways to land use. This is why the impact category of land stress requires regionalized approaches for assessing biodiversity impacts. (Verones et al. 2020b, 135.)

LC-IMPACT provides both marginal and average CFs for six different land use types, which are annual crops, permanent crops, pastures, urban, extensive forestry and intensive forestry. CFs are provided for 804 ecoregions as well as for 245 countries and different continents. Country and continental averages are calculated based on the share of different ecoregions within them. If the geographical location of land use is unknown, also world average CFs can be used for different land use types. Each given CF is aggregation of impacts of five taxa; mammals, birds, reptiles, amphibians and vascular plants. (Verones et al. 2020b, 141.)

The information for land transformation is provided for time horizon of 100 years and for time horizon of infinite (after 100 years). The further away in time the impact is, the higher is uncertainty of the results. However, the method claims that the level of robustness for the whole characterization model is high. This is due to the rely on global datasets and statistical analysis, as well as ecological models. (Verones et al. 2020b, 142.)

4.3.2 Climate change

The method separates climate change impacts to terrestrial (TE) and aquatic (AE) ecosystems. Climate change affects to TE by shifting their distribution, while some species are not able to migrate nor adapt to the changes in vegetation. For AE, the climate change affect by decreasing the discharge in rivers, which might lead to changes in biodiversity. (Verones et al. 2020b, 22.)

For climate change impacts, the method provides global CFs for four types of sets: 100 years or 1000 years, and certain effects vs all effects. CFs are illustrated as mix of marginal and average approaches. For TE, all species are included for all sets. For AE, only fish represents the whole freshwater ecosystem in all sets. However, the method stresses out that the level of robustness for aquatic ecosystems is low. The reason for this is the fact that it is not likely that fish species are representative of the total freshwater ecosystem. (Verones et al. 2020b, 25–26. 31.)

4.3.3 Eutrophication

Eutrophication impacts are primarily driven by the discharge of nutrients like nitrogen and phosphorus into soil or freshwater bodies, leading to increased nutrient levels. The rise in nutrient concentrations increases the productivity of organisms like cyanobacteria and algae, which further leads to increased water turbidity and temperature, odor, organic matter decomposition, depletion of dissolved oxygen and finally changes in biodiversity of aquatic ecosystems. (Verones et al. 2020b, 83–84.)

For freshwater eutrophication impacts, LC-IMPACT considers only phosphorus (P) emissions to water bodies and soil. The CFs are provided for P released to freshwater, P released to soil and P emissions from soil erosion, based on resolution of 0.5° x 0.5°. CFs are for different countries and continents, and the taxonomic coverage is fish species richness. Time horizon for the impact category is considered irrelevant, since the impacts are assumed to happen at the moment the nutrients are released to the water bodies. Level of robustness for freshwater eutrophication impacts is considered high, since the effects of nutrient increase have been verified in several different ways. (Verones et al. 2020b, 84, 88–89, 92–94.)

For marine eutrophication impacts, only nitrogen (N) emissions are considered. The method provides country specific CFs for N emissions soil, N emissions to freshwater environments and, for countries that are in the coastal site, release of N straight to the coastal marine system. Also, CFs for different continents are provided. CFs are based on 66 different marine ecosystems. Time horizon is determined as infinite, and the taxonomic coverage is limited to four marine species: cartilaginous fish, bony fish, lobsters and sea cucumbers. The overall level of robustness for this category is considered from moderate to high, even though there are uncertanties related to some features in the model. (Verones et al. 2020b, 103, 106– 112.)

4.3.4 Water stress

Water can be seen as one of the most important resources for humans and ecosystems. From all water use, approximately 70 % is used for agriculture as irrigation water. It is also expected, that water consumption will increase in many parts of the world due to the climate change, population growth and increasing food demand. The anthropogenic water consumption impacts on ecosystems since they have to compete for the same resource. (Verones et al. 2020b, 160.)

LC-IMPACT quantifies the water stress as water consumption. The impacts are modelled for wetlands and terrestrial systems. Wetlands represents the estimation of impacts for aquatic and riparian habitat, and covers the taxonomic groups of birds, mammals, amphibians and reptiles. Vascular plants are used to estimate the impacts to terrestrial ecosystems. CFs are provided for different countries and continents, with infinite time horizon. Moreover, CFs are provided for all impacts and certain impacts. All impacts include both, surface water and groundwater consumption. CFs for certain impacts include only impacts of surface water consumption. The method points out that the level of robustness for groundwater is low and, therefore, CFs for all impacts should be used only if comprehensive impact assessment is applied. (Verones et al. 2020b, 160. 168.)

5 Biodiversity impact assessment of Finnish plant products

In this chapter, the biodiversity impacts as global species loss of eight different plant products are calculated based on the LCA methodology. In the first chapter, the goal and scope of the assessment are explained, following the description of life cycle inventory anaysis procedures in the second chapter. In third chapter, life cycle impact assessment is done with LC-IMPACT and the results are presented in the form of table. The fourth chapter interpretates the results with figures and graphs, and sensitivity analysis is conducted for two assumptions of the study. Limitations and uncertainties of the study are collected into the final chapter of the LCA. Normalization or weighting are not included in the study.

5.1 Goal and scope of the study

The primary goal of this LCA was to assess the biodiversity impacts as global species loss for seven different Finnish plant products, and for comparison, one EU average plant product delivered to Finland. The assessed Finnish products were tomato, cucumber, lettuce (in pot), strawberry, blackcurrant, bilberry and lingonberry. The comparative product was strawberry delivered from central Europe to Finland. The impacts were calculated for 1 kg of each product, which is the functional unit of the study.

The study was conducted as a part of Luonnon monimuotoisuus lautasella -project, which aims to create food procurement criteria for food and tourism operators in Southwest Finland and Archipelago Sea region. Project is implemented by University of Turku, while LUT University is responsible for the calculation of biodiveristy impacts. (Maaseutuverkosto 2025.) The assessed products were chosen since the project had a need to identify the Finnish specific biodiversity impacts of such plant products. The intended audience for the study are the project contributors, but the results will be published also in repository of LUT University as a public document.

5.1.1 System boundary

According to Päivittäistavarakauppa ry (2020), most of the ingredients that hotels, restaurants and catering sector uses, comes from foodservice wholesalers (PTY 2020). Therefore, the system boundary of this LCA covers the products life cycle from cradle to wholesale. Wholesale is located in Turku since the project is located in Southwest Finland and Archipelago Sea region.

Unit processes included in the study are cultivation, processing, packaging and transportation. Cultivation phase includes on-farm activities, such as machinery for field operations, infrastructure, fertilizers and pesticides, irrigation water, as well as energy and fuel inputs. Also, the upstream production of the inputs are included in cultivation phase, meaning for instance fertilizer or pesticide manufacturing or production of irrigation equipments. Required resources for cultivation and their magnitudes vary between different crops and cultivation methods. For bilberry and lingonberry, cultivation phase was deemed unnecessary since they occur naturally in boreal forests without human intervention.

After harvesting, products are processed into products that are delivered to food service sector. Required inputs in processing phase are for example, energy, water and machinery. Processing was not included for tomato, cucumber and lettuce, as they were assumed to be delivered as fresh and raw. Berries processing consists of freezing and cleaning of the berries (Polarica 2024).

Packaging phase includes the energy consumption related to packaging, production of packaging material, as well as other upstream processes related to it. Transportation phases between life cycle stages is accounted for using road and marine transportation, and it includes fuel consumption as well as construction of vehicles and road network.

Cultivation, processing and packaging phases generate wastes. Waste streams generated throughout production are, for example, biowaste, recyclables, and residual waste. The generated wastes are managed in different ways, such as through composting, recycling, landfilling, and wastewater treatment. Waste management operations are included in each unit process.

Food loss during the life cycles was excluded from the study due to the limited amount of time to collect the data related to it. The system boundary of this study is presented in Figure4.

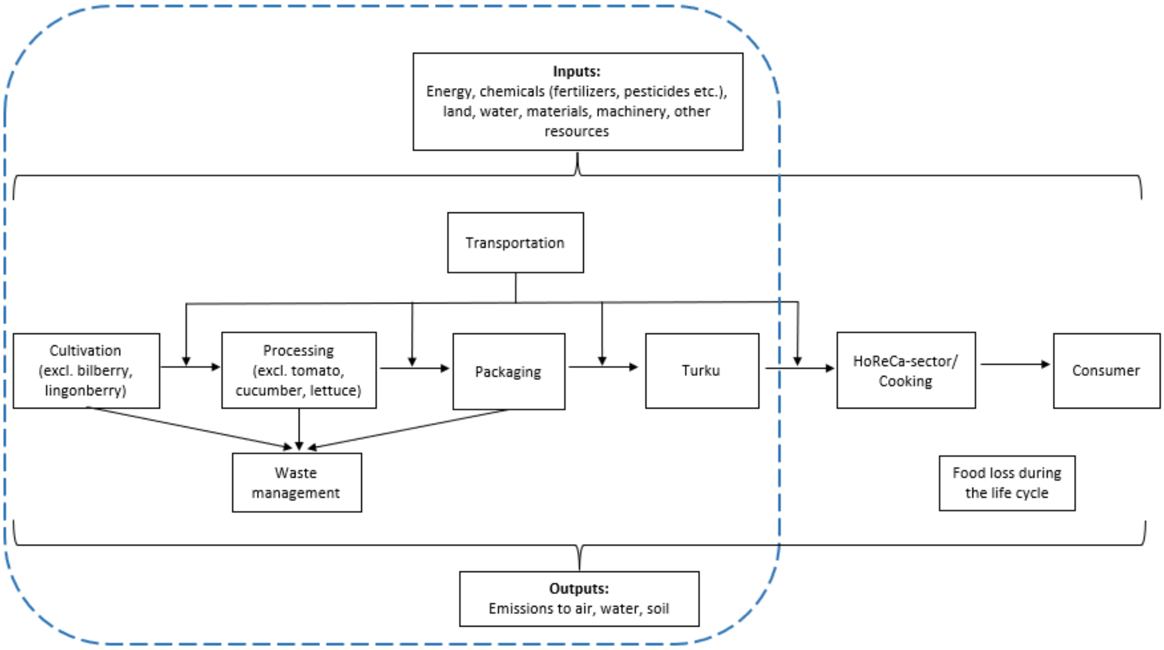

Figure 4: System boundary of the conducted LCA.

5.1.1 Assumptions of the products life cycle

Tomato, cucumber and lettuce were assumed to be cultivated in greenhouses, with facilities for year-round cultivation. Strawberries and blackcurrant were assumed to be cultivated in open fields. Bilberry and lingonberry were considered as wild berries, with no need for separate cultivation procedures. Cultivation was considered as conventional for all of the products.

Only primary packaging of the products was deemed necessary for the study to keep the product life cycles as comparative as possible. Assumed cultivation methods, primary packaging materials and the type of final delivered products are listed in table 1.

Table 1: List of assessed plant products, their cultivation methods, packaging materials and type of final delivered output. LDPE is abbreviation of low-density polyethylene.

Product	Type of cultivation	Packaging	Type of final product
Tomato	Heated greenhouse	Corrugated box	Fresh, raw
Cucumber	Heated greenhouse	LDPE	Fresh, raw
Lettuce	Heated greenhouse	LDPE	Fresh, raw
Strawberry (FIN)	Open field	LDPE	Frozen
Strawberry (EU)	Open field	LDPE	Frozen
Blackcurrant	Open field	LDPE	Frozen
Bilberry	Wild	LDPE	Frozen
Lingonberry	Wild	LDPE	Frozen

Location for cultivation, or habitat in case of wild berries, was defined by identifying the region where the crop is grown most in Finland, and then defining the locations of large producers inside Finland. European strawberry was assumed to be transported from the central Europe to Finland. The cultivation locations or the growing habitat for each product, as well as the location of processing and packaging are presented in table 2. Most of the transportations were considered as refrigerated in order to keep the products cool or frozen. Detailed transportation distances as well as the need for refrigenerated transport for each product individually are listed in inventory tables in appendices.

Table 2: Locations of cultivation and processing/packaging.

Product	Location of cultivation/ habitat of the product	Location of processing and/or packaging	References
Tomato	Närpiö	Närpiö	Luke 2024a
Cucumber	Närpiö	Närpiö	Luke 2024a
Lettuce	Oripää	Oripää	Luke 2024a
Strawberry (FIN)	Suonenjoki	Suonenjoki	Luke 2024b
Strawberry (EU)	central Europe	central Europe	Lindfors et al. 2024
Blackcurrant	Suonenjoki	Suonenjoki	Luke 2024b
Bilberry	Lapland	Suomussalmi	Marsi 2024, Kiantama Oy representative 2025a
Lingonberry	Western Finland	Mustasaari	Marsi 2024, Marja Bothnia Berries Oy Ltd representative 2025

For clarity of the report, products are mostly discussed by cultivation method, such as greenhouse vegetables, cultivated berries and wild berries. The products with similar cultivation practices have rather similar input requirements, which makes them comparable to each other. Products with different cultivation method have differences in their life cycles and system boundaries. Therefore, only products with similar cultivation type, system boundary and final delivered output can be considered as fully comparative to each other.

5.2 Inventory analysis (LCI)

In the inventory analysis, all necessary data for the modelling was collected and/or calculated. The data sources and collection procedures are described in the first section, followed by an overview of the most relevant aspects of data collection. Detailed inventory tables and calculation procedures for each product are presented separately in the appendices.

5.2.1 Data sources and collection

As the modelling of product life cycles was conducted in SimaPro version 10.2.0.1 with the Professional database version 87.3, a lot of the data for the models was obtained from the software databases. The included databases from Professional database were Ecoinvent 3.11 and Agri-footprint 6.3. Moreover, Agribalyse 3.1.1. database was used. The latter two databases contain information about agricultural products, their cultivation processes as well as pre- and post-production processes. However, Agribalyse represents the French food markets (Agribalyse 2024) and Agri-footprint contains Finnish specific data mainly for arable crops, like cereals and potatoes. Therefore, an additional inventory of Finnish specific data for the products assessed in this study was necessary.

The Finnish specific inventory data was mainly gathered from the statistics and publications provided by Luke. Data was also sourced from scientific literature and other institutes, such as Food and Agriculture Organization of the United Nations (FAO) and Finnish Food Authority. Some details were also collected from the Finnish producers of each product via email. Only the most essential data sources and calculations are explained in this report since the detailed inventory analysis tables for each product are presented in appendices. These tables gather all data sources as well as calculations made to obtain the Finnish specific input values for the models. Since a lot of life cycle data was used directly from the databases, the specific database processes used in the modelling are also listed in the appendices for each product individually.

Cultivation phase typically covers majority of the total life cycle impacts of food products, even if especially GHG emissions might be generated in several life cycle stages (Jennings et al. 2023). Therefore, the data collection of this study was mainly focusing on cultivation phase. The inventoried data included information on land use, fertilizer and pesticide application, irrigation water consumption and nutrient runoff. Moreover, electricity and heat demand in greenhouse production were also inventoried. Pre and post-production processes were modelled according to the used databases, assuming them to be rather similar to other European countries. As an exception, the processing phase for berries was modelled in this study and can be found from the appendices 15 and 16.

The allocation and cut-off principles follow the default settings of the used databases. When allocation was necessary for inventory analysis, mass based allocation was applied. For example, the land area of the processing plant for cultivated berries was allocated by production quantities (see appendices 8, 10 and 12).

5.2.2 Climate change data

The climate impacts were not directly modelled in this study, but assessed based on climate impact dataset provided by National Resource Institute Finland (Luke). The dataset was considered sufficient to represent most of the climate impacts needed in this study. The dataset includes carbon footprints for 1233 food products typically consumed in Finnish food services (Lindfors et al. 2024). Carbon footprints were further converted to the units of global species loss by using the CFs of LC-IMPACT method for TE and AE. For climate impacts to TE, the CF used was 1.76E-15 PDF•year/kgCO2eq, and for climate impacts to AE 5.47E-16 PDF•year/kgCO2eq.

For wild berries, the climate impacts were assessed separately, as Luke’s dataset does not include product specific carbon footprints for them but only a category average value for cultivated berries. To reach more accurate estimation of climate impacts for bilberry and lingonberry, the impacts were assessed based on life cycle models and inventory tables presented in appendices 13 and 14.

Luke’s climate impact values are calculated as weighted averages between domestic and imported products based on national consumption shares (Lindfors et al. 2024). Therefore, the domestic carbon footprint values were obtained from the dataset’s author via email. The Finnish carbon footprints provided by the author for the products assessed in this study are listed in table 3.

Table 3: Domestic carbon footprints (Lindfors 2025).

Product	**Carbon footprint [kgCO2eq/kg product]**
Tomato	3.05
Cucumber	2.05
Iceberg lettuce	2.75
Strawberry (FIN)	2.09
Strawberry (EU)	2.19
Blackcurrant	1.19

Luke’s database is compatible with Finnish Food Composition Database Fineli. Each product has an indentity number which can be connected to similar product in Fineli. (Lindfors et al. 2024). According to Fineli, strawberries and blackcurrants assessed in Luke’s dataset are delivered to the food service as fresh and raw products (Fineli 2025). In this study, the final product output for berries is frozen, which was the reason for adding the processing phase impacts for all cultivated berries.

5.2.3 Land use

Finnish specific land occupation values of cultivation phase were considered as the most relevant factors to be inventoried for land stress impacs of the products life cycles. For greenhouse vegetables and Finnish garden berries, land occupation values were inventoried based on Luke’s Horticultural Statistics 2024, which provides information about production volumes, harvest areas and yields. For EU strawberry, FAO statistics were used. The data for EU strawberry is for year 2023 since it was the latest information available. The yields for cultivated products are presented in table 4.

Table 4: Yields for the assessed products.

Product	Yield [kg/ha]	Source
Tomato	478306	Luke 2024a
Cucumber	1133966	Luke 2024a
Lettuce	476747	Luke 2024a
Strawberry (FIN)	3292	Luke 2024b
Strawberry (EU)	11773	FAO 2025
Blackcurrant	910	Luke 2024b

LC-IMPACT categorizes also types of land use. Most of the products were considered as annual crops. Only blackcurrant was considered as permanent crop, since the plant can bear berries even 10–15 years (HML 2020).

5.2.1 Fertilizers and nutrient runoff

In the LC-IMPACT method, eutrophication impacts on freshwater environments are assessed based on phosphorus runoff, and on marine environments based on nitrogen runoff (Verones et al. 2020b, 83, 97). Therefore, the modelling of eutrophication impacts in this study focused on fertilizer inputs as well as nutrient outputs to water and soil during the cultivation phase.

Obtaining specific data on fertilizer inputs and nutrient outputs for different crops cultivated in Finland was challenging due to the wide range of factors influencing fertilization requirements, such as crop type and local soil properties (Yara 2025). Therefore, for cultivated berries, fertilizer inputs and nutrient outputs were adopted from the French strawberry cultivation data available in the databases used in this study. However, CFs for domestic products were changed to Finnish specific, which was then expected to illustrate the impacts in different regions.

For greenhouse vegetables, fertilizer input was inventoried based on Luke’s climate and water footprint calculation (Silvenius et al. 2019). The nutrient output for greenhouse vegetables was defined according to ELY Center report about greenhouse drain waters (Salo 2023, 9).

5.2.2 Irrigation

The inventory of water stress impacts was limited to irrigation water. LUOKO ry notes that in Finland the irrigation is applied mainly to high yield special crops, even though the need for irrigation might be increasing in the future due to the changing climate conditons. Instead, the soil drainage has been the most important action for the soil water economy, because it is common that there is more rain than evaporation from the ground. (LUOKO ry 2023, 5, 7–8). Moreover, Luke states that in 2023 only 2.2 % of the agricultural and garden land in Finland had infrastructure for irrigation (Luke 2025a). ProAgria argues that for blackcurrants the irrigation is usually not profitable, however, for strawberry the irrigation is considered important, because lack in water could limit the yield. The most recommended method for strawberry irrigation is drip irrigation. (ProAgria 2019, 31.) As a result, irrigation was considered essential only for greenhouse vegetables and strawberries. The amounts of inventoried irrigation requirements are presented in table 5.

Table 5: The use of irrigation water for the products that irrigation was considered relevant.

Product	Irrigation water use [m3/kg product]	Source
Tomato	0.020	Silvenius et al. 2019
Cucumber	0.011	Silvenius et al. 2019
Lettuce	0.019	Silvenius et al. 2019
Strawberry (FIN)	0.051	Tahvonen et al. 2001
Strawberry (EU)	0.133	Agribalyse v.3.1.1.

For greenhouse vegetables, the irrigation was calculated based on Luke's climate and water footprint assessment. The report offers water footprints for tomato, cucumber and lettuce in a pot, calculated based on AWARE method (Silvenius et al. 2019). In AWARE, the amount of water consumed to produce the functional unit, is multiplied by CF, as can be seen from the equation 1 (Boulay et al. 2018, 373–374). Luke provides the CFs used for Finnish agricultural products (Silvenius et al. 2019, 9). By dividing the water footprint of the product with the factor, the total amount of water used during the products life cycles is gotten. According to Luke, most of the water use comes from the irrigation (Silvenius et al. 2019, 20), so assumption was made that all the consumed water was for irrigation. However, for lettuce 8 % of the water consumption was due to the plastic packaging, which was considered in the calculations (Silvenius et al. 2019, 20.)

$$\text{Water Scarcity Footprint} = \text{Water consumption inventory} * CF_{AWARE} \quad (1)$$

According to Tahvonen et al. (2001, 7, 9), the irrigation water need for Finnish strawberry during growing season is approxiamtely three litres per week. With this amount of drip irrigation, the plant produces 900 grams of strawberries. The irrigation is needed until the end of harvest season, and later in August and September one liter per plant per week is applied if there is no sufficient rainfall. (Tahvonen et al. 2001, 7, 9.) In this study, the assumption was made that the need for irrigation was three litres/plant/week from the beginning of May to the end of August, which makes the irrigation need totally for 17 weeks. For European strawberry, the amount of irrigation water was the one provided in Agribalyse database. The process used for European average strawberry model can be found from the appendix 9.

5.2.3 Electricity

In the used databases, Finnish electricity mix represented the year 2021. This process was considered outdated since Finland's electricity production has changed towards low-emission sources in recent years. Imported fuels from Russia has decreased since 2021, which has reduced the consumption of natural gas, oil and coal (Statistics Finland 2024). At the same time, the share of renewable electricity production has increased, and by 2024 even 95 % of electricity generated in Finland was fossil free (Statistics Finland 2025). Therefore, the Finnish electricity mix was updated with the data from Statistics Finland's electricity production and supplies in 2024 (Statistics Finland 2025). The distribution of electricity production and supply in the updated model is presented in table 6.

Table 6: Distribution of Finnish electricity production and supply in 2024 (Statistics Finland 2025).

Source of electricity	**Share from the total electricity consumption [%]**
Nuclear	37.6
Hydro	17.1
Wind	24.0
Solar	1.4
Combined heat and power (CHP)	14.3
Conventional condensing power	1.7
Net import Norway	0.3
Net import Sweden	8.0
Net import Russia	0.0
Net import Estonia	-4.4

The fuels used for combined heat and power (CHP) as well as for conventional condensing power generation were modelled based on statistics provided by Finnish Energy (2023). The fuel shares from 2023 were adjusted to reflect the relative proportions of CHP and conventional condensing power in 2024. The adjusted fuel shares used in the modelling are presented in table 7.

Table 7: Distribution of fuels used to produce CHP and conventional condensing power generation in 2024. Fuel shares modified from Finnish Energy (2023).

Source of electricity	**Share from the total electricity consumption [%]**
Biomass	10.9
Peat	1.4
Waste fuel	0.7
Oil	0.2
Coal	2.1
Natural gas	0.7

5.2.4 Heat for greenhouses

The fuels used for heating in Finnish greenhouses were inventoried based on Luke's Horticultural Statistics 2024. According to Luke, the most common fuel for greenhouse heating in 2024 was wood chips. Together with field biomass and imported renewable fuels, renewable fuels accounted for total of 45 % of heat consumption. The second most used fuel was peat, which covered about 30 % of the total heat consumption in greenhouses. The share of other non-renewable fuels was 25 %. (Luke 2025b.) In this study, wood chips were used as an estimate for all renewable fuels. For non-renewable fuels other than peat, consumption was divided between natural gas and oil. Distribution of fuels used for heating are listed in table 8.

Table 8: Distribution of fuels used for heating in Finnish greenhouses. Shares modified from Luke (2025b).

Source of heat	**Share from the total heat consumption [%]**
Wood chips	45
Peat	30
Natural gas	12.5
Oil	12.5

5.3 Impact assessment (LCIA)

In life cycle impact assessment, the methodological choices for the modelling phase are explained. After that, the results of the study are presented.

5.3.1 Methodological choices

To reach a feasible extent for the study, assessment was limited only to impact categories of land stress, climate change, eutrophication to freshwater and marine environments, and water stress. Impact categories of climate change and land stress were chosen since they are known to be among the top contributors to biodiversity loss (IPBES 2019b). Since the goal of the project is to protect Arcipelago Sea from the environmental pressures caused by tourism (Maaseutuverkosto 2025), impact categories of eutrophication and water stress were also included for the assessment.

To ensure comparability of the results to the other similar food related biodiveristy assessments conducted in LUT University, LC-IMPACT version 1.3 was used as a method for LCIA. As a characterization model, marginal approach with 100 years time horizon and all impacts included, was preferred in the study. However, not all assessed impact categories had an option to use the preferred characterization model. For instance, Verones et al. (2020a, 1205) provides only mix of marginal and average approach for the impact category of climate change, as for both freshwater and marine eutrophication impacts, the only approach that method provides is linear. (Verones et al. 2020a, 1205.) Table 9 summarises the used characterization models, when ever the preferred model was not available.

Table 9: Characterization models used in this study for each impact category. Modified from (Verones et al. 2020a, 1205).

Impact category	**Modelling approach**	**Time horizon**	**Taxonomic coverage**	**Native spatial scale**
Climate change (terrestrial ecosystems)	Mix marginal/average	100 years	Mammals, birds, reptiles, amphibians and vascular plants	Global
Climate change (freshwater ecosystems)	Mix marginal/average	100 years	Fish	Global
Land stress	Marginal	100 years	Mammals, birds, reptiles, amphibians and vascular plants	804 terrestrial ecoregions
Freshwater eutrophication	Linear	Irrelevant	Fish	449 freshwater ecoregions of the world
Marine eutrophication	Linear	Irrelevant	Bony fish, cartilaginous fish, crustaceans, mol-luscs, echinoderms, annelids and cnidarians	River basins to large marine ecosystems (5,772 pairs)
Water stress	Marginal	Infinite	Mammals, birds, reptiles, amphibians and vascular plants	0.05^{o} x 0.05^{o}

As the modelling was done in SimaPro software with LC-IMPACT integrated, the software conducted the classification and characterization automatically based on chosen characterization model. Therefore, classification and characterization are not explained in details in this report.

5.3.2 Results

The results were gathered by each impact category separately. Table 10 presents the biodiversity impacts as global species loss for all plant products assessed in this study. Further interpretation of the results is done in chapter 5.4.

Table 10: The biodiversity impacts as global species loss [PDF•yr] for the plant products assessed in this study.

Product	Climate change TE	Climate change AE	Land stress TE	Freshwater eutrophication AE	Marine eutrophication ME	Water stress AE
Tomato	5.37E-15	1.67E-15	1.08E-15	7.26E-16	2.00E-18	1.31E-15
Cucumber	3.61E-15	1.12E-15	6.65E-16	7.15E-16	1.51E-18	1.62E-15
Lettuce	4.84E-15	1.50E-15	1.89E-15	1.51E-15	7.10E-18	3.90E-15
Strawberry (FIN)	4.03E-15	1.25E-15	8.45E-16	2.16E-16	2.69E-16	4.45E-16
Strawberry (EU)	4.66E-15	1.45E-15	2.33E-15	8.19E-16	1.48E-17	1.82E-15
Blackcurrant	2.44E-15	7.59E-16	5.25E-15	2.07E-16	2.69E-16	3.65E-16
Bilberry	1.08E-15	3.35E-16	1.74E-16	1.71E-16	4.57E-20	3.32E-16
Lingonberry	8.66E-16	2.69E-16	1.37E-16	1.45E-16	4.12E-20	3.09E-16

The total impacts to TE, AE and marine ecosystems (ME) for each product are presented in table 11. Total impacts to TE is a sum of climate impacts to TE and land stress. Total impacts to AE is a sum of climate impacts to AE, freshwater eutrophication and water stress. Marine eutrophication represents the total impacts to marine ecosystems. (Verones et al. 2020a, 1206.)

Table 11: Total impacts to terrestrial, aquatic and marine ecosystems for each product. The unit is PDF•yr.

Product	Total impacts to TE	Total impacts to AE	Total impact to ME
Tomato	6.45E-15	3.70E-15	2.0E-18
Cucumber	4.27E-15	3.46E-15	1.51E-18
Lettuce	6.73E-15	6.91E-15	7.10E-18
Strawberry (FIN)	4.87E-15	1.91E-15	2.69E-16
Strawberry (EU)	6.99E-15	4.09E-15	1.48E-17
Blackcurrant	7.69E-15	1.33E-15	2.69E-16
Bilberry	1.25E-15	8.38E-16	4.57E-20
Lingonberry	1.00E-15	7.23E-16	4.12E-20

5.4 Interpretation

The total biodiversity impacts for 1 kg of each product are presented in figure 5. The total result is a sum of impacts to TE, AE and ME. Verones et al. (2020a, 1206) highlights that the results to terrestrial, aquatic and marine ecosystems should be reported separately, since there is not yet generally agreed opinion on how to value the importance of different ecosystem types (Verones 2020a, 1206.) However, figure 4 enables the comparison of the total impacts to biodiversity from the life cycle of different cultivation methods.

The graph shows that the highest impacts to biodiversity are caused by the production of greenhouse vegetables and cultivated berries. The lowest impacts are caused by wild berries. All Finnish berries show lower biodiversity impacts than EU strawberry. Impacts to marine ecosystems is highlighted in Finnish products that are cultivated in open field.

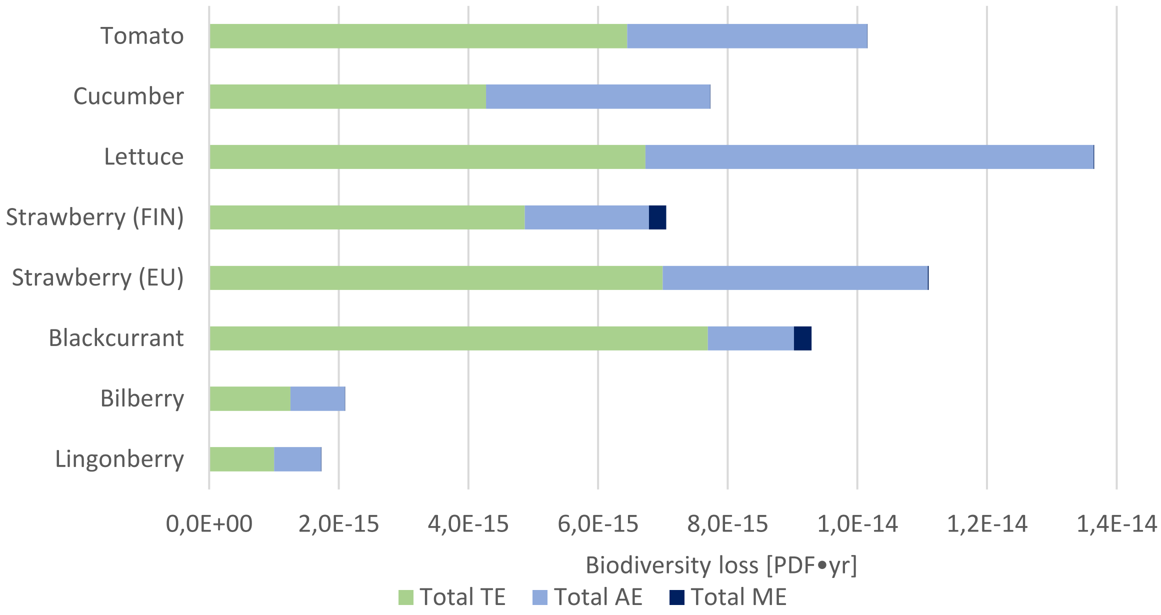

Figure 5: Total biodiversity impacts of each product to terrestrial, aquatic and marine ecosystems.

The assessed products are grouped to make the analysis of the results clear. The biodiversity impacts of greenhouse vegetables are analyzed separately from berries. For climate change impacts, the analysis and illustration about the biggest contributing factors is not done, since climate impacts were not modelled in this study for most of the products.

5.4.1 Greenhouse vegetables

The biodiversity impacts for 1kg of each greenhouse vegetable are presented in tables 12, 13 and 14 by impact categories. Table 12 presents the impacts to TE, table 13 to AE and table 14 to ME. The highest impact category contributing to total impacts for each ecosystem type is highlighted by red.

Table 13 presents the biodiversity impacts to TE for all greenhouse products in two different impact categories. The highest total impacts among greenhouse vegetables comes from lettuce production, as the lowest impacts are caused by cucumber production. Most of the biodiversity impacts to TE are caused by impact category of climate change and minor impacts are caused by land stress.

Table 12: Results of greenhouse vegetables production for terrestrial ecosystems.

	Tomato [PDF•yr]	Share from total TE [%]	Cucumber [PDF•yr]	Share from total TE [%]	Lettuce [PDF•yr]	Share from total TE [%]
Climate change TE	5.37E-15	84.26	3.61E-15	84.35	4.84E-15	71.92
Land stress	1.08E-15	16.74	6.65E-16	15.55	1.89E-15	28.08
Total TE	**6.45E-15**		**4.28E-15**		**6.73E-15**	

Figure 6 illustrates the results to TE from land stress impact category by life cycle phases for all greenhouse vegetables. As can be seen from the figure, cultivation phase has the biggest contribution to land stress impacts for all vegetables. Lettuce production show the highest biodiversity impacts during cultivation phase, and cucumber shows the lowest. For tomato production, cultivation phase covers 73 % of the total land stress impacts, and the same number for cucumber is 92 % and for lettuce 97 %. For tomato, packaging phase covers 23 % of the land stress results.

The biggest contributing factor for land stress impact category for all products was wood chips used for electricity production and heating of greenhouses. Wood chips covered 48–54 % of the land stress impacts of cultivation phase. Moreover, peat moss used as a growing media for cultivation covered 16–28 % of the impacts of cultivation phase of greenhouse vegetables. As the electricity, heat and peat moss consumption for lettuce production are higher compared to tomato and cucumber production (see inventory tables in appendices), also the land stress impacts for lettuce are higher. Similarly, cucumber with lowest peat moss and heat consumption represents the lowest land stress impacts. Land use required for cultivation covered only 1–7 % of the land stress impacts of cultivation phase. The low land requirement for cultivation correlates with the high yields of greenhouse vegetable cultivation. The higher the yield, the less land is required to cultivate the same amount of crop (Balmford et al. 2018).

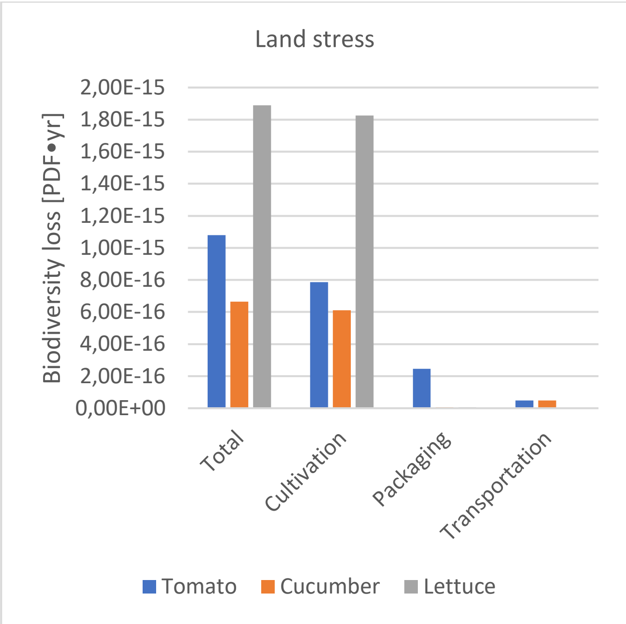

Figure 6: Land stress impacts on terrestrial ecosystems in each life cycle phase of greenhouse vegetable production.

Table 13 presents the biodiversity impacts to AE for all greenhouse products in three different impact categories. The highest total impacts among greenhouse vegetables comes from lettuce production, and lowest are caused by cucumber production. For lettuce and cucumber production, the highest impacts come from water stress impact category, as for tomato production, climate change causes the highest impacts.

Table 13: Results of greenhouse vegetables production for aquatic ecosystems.

	Tomato [PDF•yr]	Share from total AE [%]	Cucumber [PDF•yr]	Share from total AE [%]	Lettuce [PDF•yr]	Share from total AE [%]
Climate change AE	1.67E-15	45.01	1.12E-15	32.41	1.50E-15	21.71
Freshwater eutrophication	7.26E-16	19.57	7.15E-16	20.70	1.51E-15	21.85
Water stress	1.31E-15	35.31	1.62E-15	46.88	3.90E-15	56.44
Total	**3.71E-15**		**3.46E-15**		**6.91E-15**	

Figure 7 illustrates the biodiversity impacts to aquatic ecosystems from water stress and freshwater eutrophication impact categories by life cycle phases for all greenhouse vegetables. It can be seen that most of the impacts in both impact categories come from the cultivation phase. For tomato, cultivation phase covers 87 % of the water stress impacts and

76 % of the freshwater eutrophication impacts. For cucumber, cultivation phase covers 96 % of the water stress impacts and 91 % of the freshwater eutrophication impacts. For lettuce, cultivation phase covers 95 % of the water stress impacts and 89 % of the freshwater eutrophication impacts. Lettuce cultivation show the highest biodiversity impacts in both impact categories, as tomato shows the lowest impacts in both.

The biggest contributing factor for water stress results for all vegetables was decarbonized water consumption, with 63–77 % share of the biodiversity impacts in cultivation phase. Decarbonized water was used in nuclear power plants and thermal energy power plants for heat and power co-generation. Larin (2015, 154) explains that decarbonized water is the water used in boilers systems to generate steam, and highlights that the boiler water must be very high purity to prevent corrosion within the boiler (Larin 2015, 154). The share of irrigation from water stress results was minor for all vegetables. For freshwater eutrophication, the biggest contributing factor was spoil from hard coal and lignite mining (39–43 % of the cultivation) as well as sulfidic tailings from copper mine operations (29–43 % of the cultivation). The share of phosphorous discharge from freshwater eutrophication results was minor. All three highest contributing factors were mainly related to Finnish electricity production.

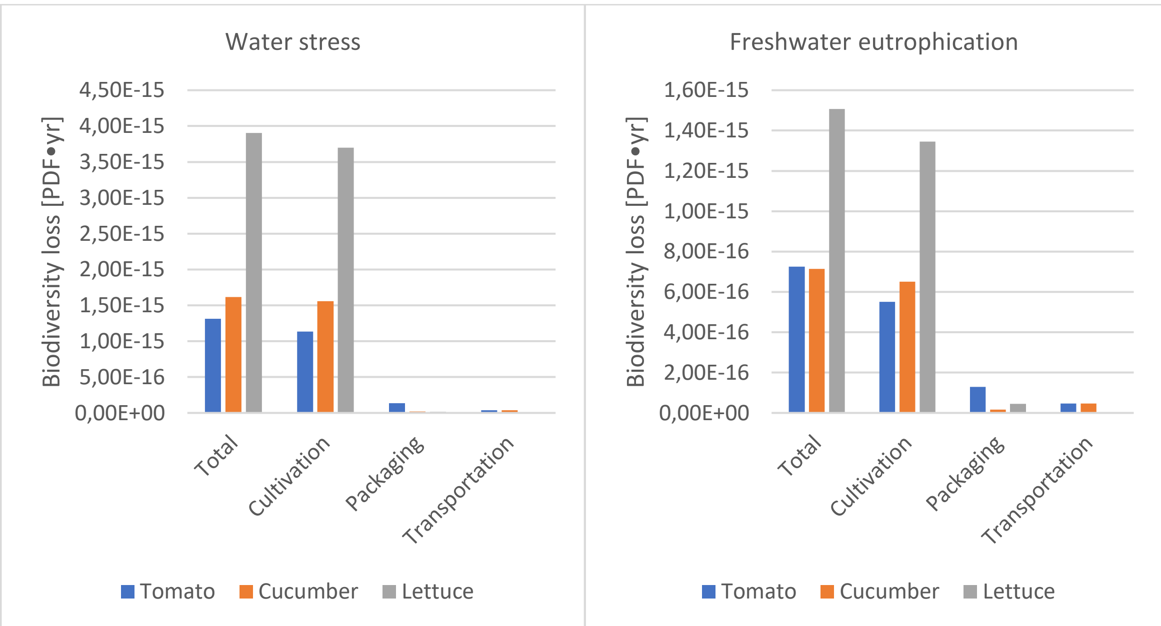

Figure 7: Water stress and freshwater eutrophication impacts on aquatic ecosystems in each life cycle phase of greenhouse vegetables production.

Table 14 presents the biodiversity impacts to marine ecosystems for all greenhouse vegetables. As the marine eutrophication was the only impact category affecting marine ecosystems, the results are presented only to that impact category. Lettuce production shows the highest impacts, while cucumber shows the lowest impacts to marine environments.

Table 14: Results of greenhouse vegetables production for marine ecosystems.

	Tomato [PDF•yr]	Cucumber [PDF•yr]	Lettuce [PDF•yr]
Marine eutrophication	2.00E-18	1.51E-18	7.10E-18

Figure 8 illustrates the biodiversity impacts to marine ecosystems from marine eutrophication impact category by life cycle phases for all greenhouse vegetables. It can be seen that the highest impacts to marine environments are caused during the cultivation phase. Lettuce cultivation have the highest impacts, and cucumber cultivation the lowest. The biggest contributing factor for marine eutrophication during the cultivation phase of all greenhouse products was nitrogen discharge in greenhouse drain waters.

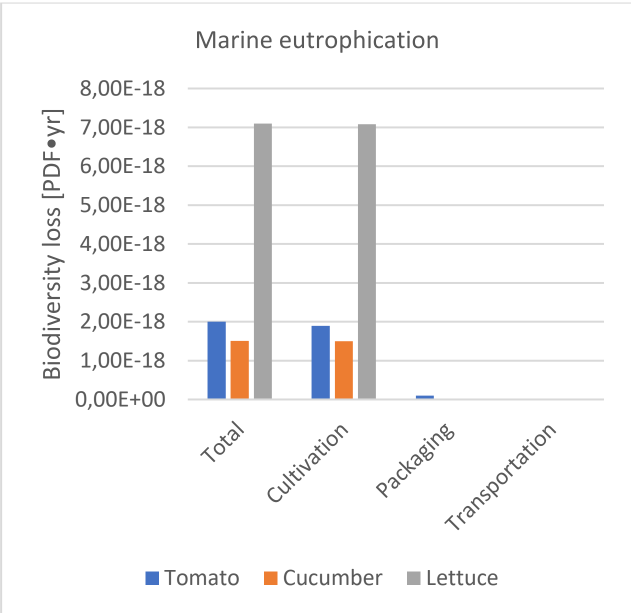

Figure 8: Marine eutrophication impacts from greenhouse vegetable production representing the impacts on marine ecosystems.

5.4.2 Berries

The biodiversity impacts for 1kg of each berry are presented in tables 15, 16 and 17 by impact categories. Table 15 presents the impacts to TE, table 16 to AE and table 17 to ME. The highest impact category contributing to total impacts for each ecosystem type is highlighted by red.

Table 15 presents the biodiversity impacts to terrestrial ecosystems for all berries in two different impact categories. The highest total impacts among cultivated berries comes from EU strawberry, as the lowest impacts are caused by Finnish strawberry. Wild berries show lower total impacts than cultivated berries. Most of the biodiversity impacts to TE are caused by impact category of climate change, except for blackcurrant which shows higher impacts in impact category of land stress.

Table 15: Results of berries production for terrestrial ecosystems.

	Climate change TE	Land stress	**Total TE**
Strawberry FIN [PDF•yr]	4.03E-15	8.45E-16	**4.87E-15**
Share from total TE [%]	82.65	17.35	
Strawberry EU [PDF•yr]	4.66E-15	2.33E-15	**6.99E-15**
Share from total TE [%]	66.69	33.31	
Blackcurrant [PDF•yr]	2.44E-15	5.25E-15	**7.69E-15**
Share from total TE [%]	31.74	68.26	
Bilberry [PDF•yr]	1.08E-15	1.74E-16	**1.25E-15**
Share from total TE [%]	86.12	13.88	
Lingonberry [PDF•yr]	8.66E-16	1.37E-16	**1.00E-15**
Share from total TE [%]	86.34	13.66	

Figure 9 illustrates the results to TE from land stress impact category by life cycle phases for all berries. As can be seen from the figure, cultivation phase has the biggest contribution to land stress biodiversity impacts for the cultivated berries. For blackcurrant, cultivation phase covers 99 % of the total land stress impacts, and the same number for Finnish strawberry is 91 % and for EU strawberry 95 %. Most of the impacts during cultivation phase are generated by the land area required for cultivation itself. Blackcurrant production shows the highest biodiversity impacts from land stress, and Finnish strawberry shows the lowest.

Wild berries production do not include cultivation, which is why the biggest land stress impacts come from processing phase and transportation. For bilberry production, transportation covers 58 % of the land stress impacts and processing 36 %. For lingonberry, transportation covers 49 % of the land stress impacts and processing phase 43 %. The biggest contributing factors for the impacts are road construction for transportation and wood chips used for electricity production.

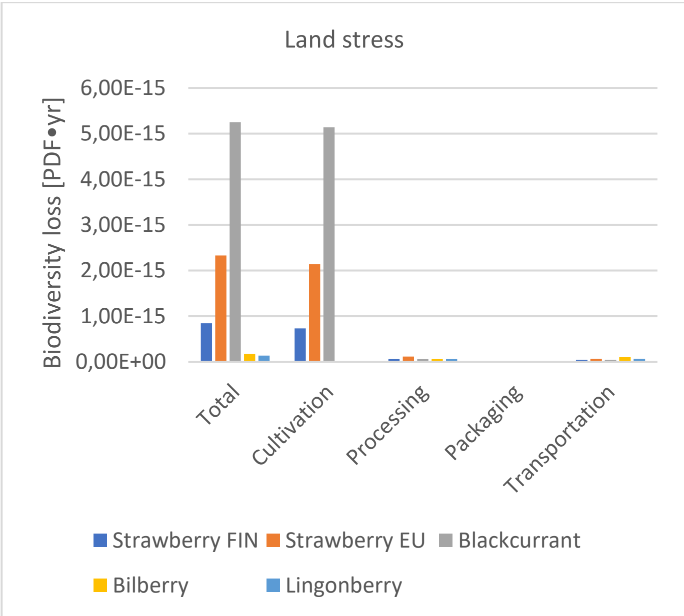

Figure 9: Land stress impacts on terrestrial ecosystems by each life cycle phase of berries production.

Table 16 presents the biodiversity impacts to AE for all berries in three different impact categories. The highest total impact among cultivated berries come from EU strawberry production, and lowest are caused by blackcurrant production. Wild berries show lower total impacts than cultivated berries. For EU strawberry and lingonberry, the biggest impact category is water stress, as for other berries climate change causes the highest impacts.

Table 16: Results of berries production for aquatic ecosystems.

	Climate change AE	Freshwater eutrophication	Water stress	**Total AE**
Strawberry FIN [PDF•yr]	1.25E-15	2.16E-16	4.45E-16	**1.91E-15**
Share from total AE [%]	65.43	11.30	23.27	
Strawberry EU [PDF•yr]	1.45E-15	8.19E-16	1.82E-15	**4.09E-15**
Share from total AE [%]	35.46	20.03	44.51	
Blackcurrant [PDF•yr]	7.59E-16	2.07E-16	3.65E-16	**1.33E-15**
Share from total AE [%]	57.02	15.55	27.43	
Bilberry [PDF•yr]	3.35E-16	1.71E-16	3.32E-16	**1.25E-15**
Share from total AE [%]	39.97	20.41	39.62	
Lingonberry [PDF•yr]	2.69E-16	1.45E-16	3.09E-16	**1.00E-15**
Share from total AE [%]	37.21	20.05	42.74	

Figure 10 illustrates the biodiversity impacts to aquatic ecosystems from water stress and freshwater eutrophication impact categories by life cycle phases for all berries. It can be seen that EU strawberry shows highest total impacts in both impact categories, and wild berries shows the lowest.

Analyzing water stress impact category, processing phase shows the highest contribution to all Finnish berries (49–71 % of the total impacts), and is mainly related to electricity consumption. For EU strawberry, the highest contribution to water stress impacts comes from cultivation phase (85 % of the total impacts), and is mainly related to irrigation water. The biggest contributing factor for water stress results for both strawberries was irrigation water, which covered 31 % of the total Finnish strawberry total water stress impact and 81 % of the EU strawberry total water stress impacts. Decarbonized water consumption was significant factor related to Finnish berries water stress impacts. It covered 20 % of the Finnish strawberry water stress impacts, 11 % of blackcurrant impacts, 57 % of bilberry impacts and 59 % of lingonberry impacts. For wild berries, packaging covered 13–14 % of the water stress impacts.

In freshwater eutrophication impact category, the highest impacts for Finnish strawberry and blackcurrant comes from cultivation phase (40–43 % of the total impacts), for EU strawberry from processing phase (72 % of the total impacts) and for wild berries from transportation (43–52 % of the total impacts). The biggest contributing factors for all cultivated berries were phosphorous runoff from fields and spoil from hard coal and lignite mining. For wild berries, the most significant factor was spoil from hard coal and lignite mining. The latter relates to coal usage in electricity production. The share of coal from Finnish electricity mix was 2 % and from EU electricity mix 11 %.

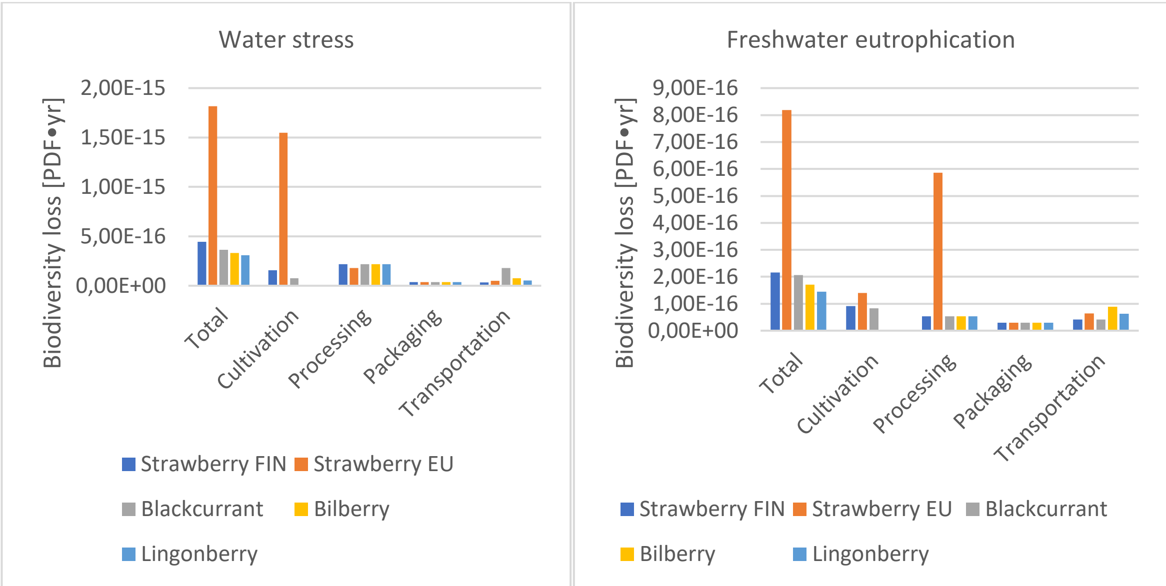

Figure 10: Water stress and freshwater eutrophication impacts on aquatic ecosystems in each life cycle phase of greenhouse vegetables production.

Table 17 presents the biodiversity impacts to marine ecosystems for all berries. As the marine eutrophication was the only impact category affecting marine ecosystems, the results are presented only to that impact category. Finnish cultivated berries production show the highest impacts, while wild berries show the lowest impacts to marine environments.

Table 17: Results of berries production for marine ecosystems.

	Strawberry FIN [PDF•yr]	Strawberry EU [PDF•yr]	Blackcurrant [PDF•yr]	Bilberry [PDF•yr]	Lingonberry [PDF•yr]
Marine eutrophication [PDF•yr]	2.69E-16	1.48E-17	2.69E-16	4.57E-20	4.12E-20

Figure 11 illustrates the biodiversity impacts to marine ecosystems from marine eutrophication impact category by life cycle phases for all berries. It can be seen that the highest impacts to marine environments are caused during the cultivation phase, and the impacts from other life cycle phases are minor. Finnish cultivated berries show the highest impacts, and wild berries the lowest. The biggest contributing factor for marine eutrophication during the cultivation phase was nitrogen discharge from the fields. As the nutritent discharge levels for all cultivated berries was same, the results illustrate the impacts in different locations. Impacts of Finnish cultivated berries are directed to Archipelago Sea, which shows high sensitivity towards eutrophication in the results.

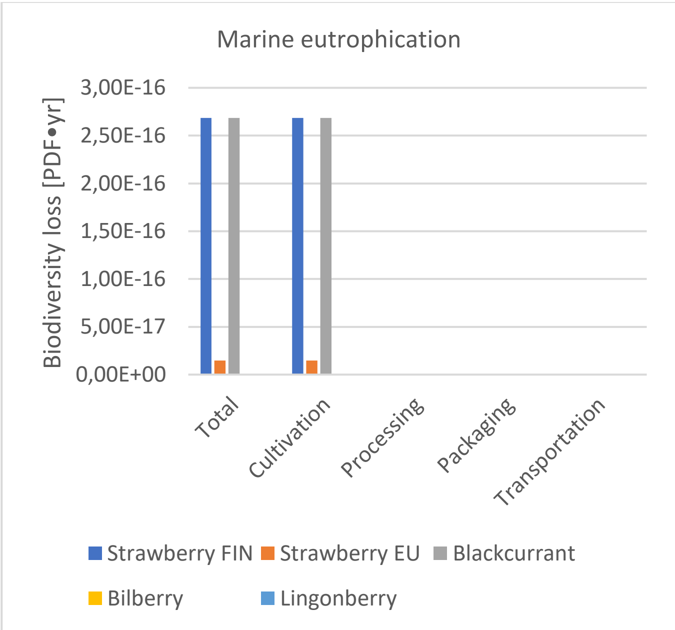

Figure 11: Marine eutrophication impacts from greenhouse vegetable production representing the impacts on marine ecosystems.

5.5 Sensitivity analysis

Sensitivity analysis was conducted for two assumptions of the study and the results are presented in table 18. The first assumption concentrated on nutrient release from greenhouse to the environment. In this study, the drain water was assumed to be released into the water bodies without any treatment. However, Finnish Glasshouse Growers' Association notes that only half of the greenhouse companies did not collect or treat the generated drain water in any way (Finnish Glasshouse Growers' Association 2021, 8). Some companies recycle the drain water and use it again for irrigation, as some companies direct the waters to the municipal wastewater treatment plants (Salo 2023, 9). The companies that did not yet recycle or treat drain water, but considered a recycling system feasible for their greenhouse, planned to invest in such system within the next five years (Finnish Glasshouse Growers' Association 2021, 8). In the sensitivity analysis, closed recycling system for drain waters without any leacing to the environment was assumed for the greenhouse products. In practice, nitrogen and phosphorous emissions from greenhouse cultivation were assumed as zero.

The second sensitivity analysis was conducted for the assumption that the transportation of berry pickers to collection sites should be included as part of the life cycle of wild berries. It is common for Finnish berry companies to hire pickers from abroad, especially from Thailand (Marsi 2024). The contribution of berry pickers' transportation to the overall biodiversity impacts of wild berries was considered relevant, as the natural habitats of the berries are often located far from settlements and may require remarkable travel distances.

The data related to berry pickers picking efficiency, length of the picking season and average travelling distances were obtained anonymously from the relevant authority. Transportation distances for berry pickers where estimated by Google Maps. Flight was added between Bangkok-Helsinki-Bangkok with the total travelling distance of 20 000 km. Transportation inside Finland was modelled for large size passenger car. For lingonberry, the transportation was assumed for Helsinki-Kokkola-Helsinki (1000 km), and for bilberry, Helsinki-Rovaniemi-Helsinki (1640 km), and the travelling distance was allocated for 5 berry pickers in a car. The distance between forest and reception was to be 80 km for both berries, and it was travelled every day during the picking season. Picking season for lingonberry was 45 days, and for bilberry 30 days. Picking efficiencies for the Thai berry pickers were average of 1350 kg/person/season and for lingonberry 2475 kg/person/season. All of the input values were allocated for 1 kg of berries picked.

Table 18: The results for greenhouse vegetables and wild berries after sensitivity analysis. The unit is PDF•yr.

	Climate change TE	Climate change AE	Land stress TE	Freshwater eutrophication AE	Marine eutrophication ME	Water stress AE
Tomato	5.37E-15	1.67E-15	1.08E-15	7.24E-16	2.35E-19	1.31E-15
Cucumber	3.61E-15	1.12E-15	6.65E-16	7.14E-16	1.66E-19	1.62E-15
Lettuce	4.84E-15	1.50E-15	1.89E-15	1.50E-15	3.61E-19	3.90E-15
Bilberry with picker from Thailand	4.34E-15	1.35E-15	3.15E-16	3.37E-16	7.61E-20	5.50E-16
Lingonberry with picker from Thailand	2.68E-15	8.32E-16	2.18E-16	2.43E-16	5.88E-20	4.34E-16

For greenhouse vegetables, sensitivity analysis shows no difference in other impact categories but freshwater and marine eutrophication. For wild berries, adding the berry picker transportation from Thailand to Finnish forests increase the impacts in all categories. Further interpretation of the results can be found in the following chapters.

5.5.1 Greenhouse drain waters

The results from sensitivity analysis of using recycling system for drain water in greenhouses is illustrated in figure 12. It can be seen that the usage of recycling system does not significantly reduce the freshwater eutrophication impacts from greenhouses. Instead, marine eutrophication impacts decrease remarkably due to the reduce in nitrogen discharge.

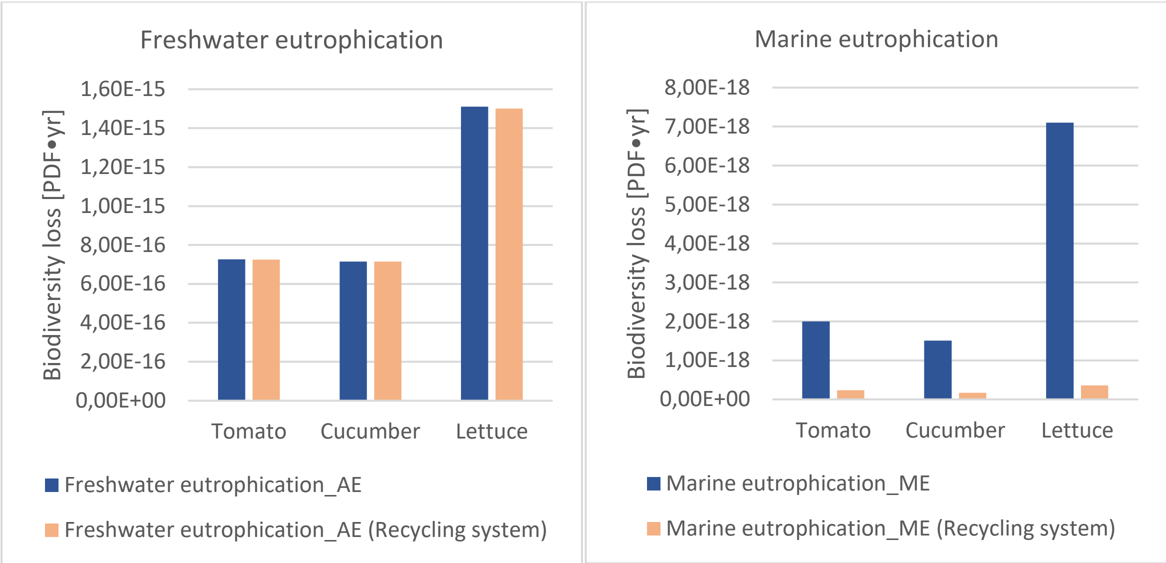

Figure 12: The comparative results for impacts from greenhouse vegetable production for freshwater and marine eutrophication with and without recycling system for drain water.

Finnish electricity production is the most impactful factor for freshwater eutrophication for greenhouse vegetables. Phosphorous discharge during cultivation represents only 0.1–0.2 % of the freshwater eutrophication impacts. Therefore, the reduction in phosphorous discharge does not significantly affect to the result. Instead, nitrogen discharge from greenhouses is the major contributor to marine eutrophication impacts, which explains the significant reduction in the results.

5.5.2 Wild berry pickers

The total biodiversity impacts for berries after sensitivity analysis is illustrated in figure 13. It can be seen that adding the berry picker transportation from Thailand to the picking site increases the impacts of wild berries increases the biodiversity impacts of wild berries two- to threefold. After sensitivity analysis, impacts of bilberry production reaches the level of Finnish strawberry production.

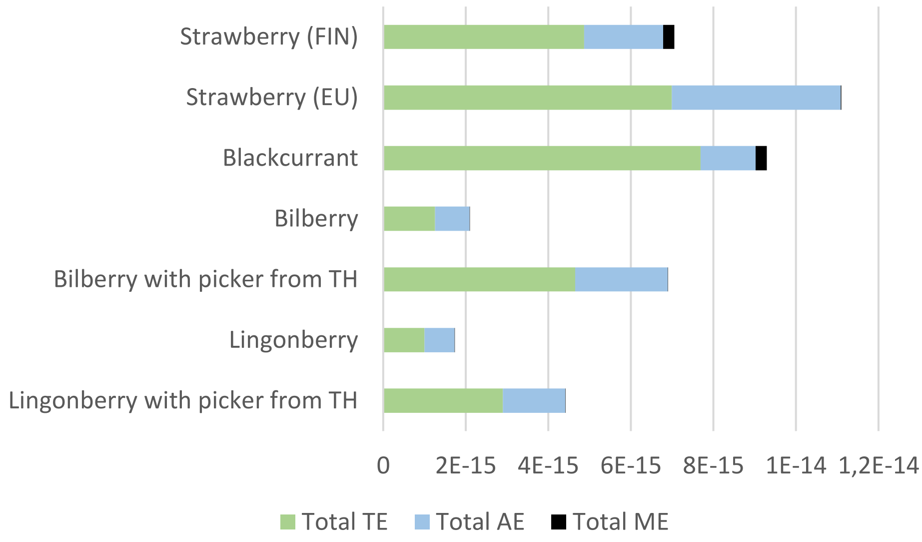

Figure 13: Total impacts on biodiversity for berries after sensitivity analysis about berry pickers contribution on wild berries production.

5.6 Limitations and uncertainties of the study

The calculations and models include uncertainties that might affect to the final results of the study. First, the used data sources have always influence to the outcome of the study. The assumptions related to products life cycles and data might differ in different assessments and databases, which might lead to variation in magnitudes of the results. In this study the climate impacts of wild berries are modelled, but for other products the biodiversity impacts were assessed based on carbon footprint dataset provided by Luke. Figure 14 illustrates the possible differences between different data sources. The comparison in the figure was done for a product which was not assessed in this study, but for which the impacts were available in both Agribalyse/Agri–footprint databases and Luke dataset. The difference in the results is remarkable.

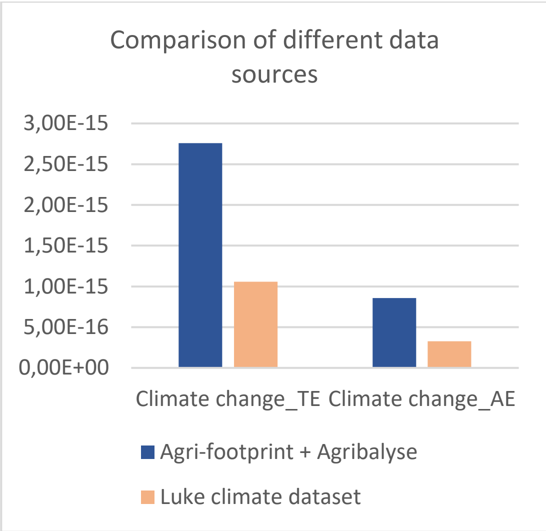

Figure 14: Comparison of climate change impacts from two different data sources. Unit is PDF•yr.

Second uncertainty of the study is related to the initial data. The initial data used in this study was limited to one year. However, it is recommended to use multiple year averages as initial data for agricultural LCAs, since seasonal variations and weather may cause remarkable changes of agricultural practices between different years (Caffrey et al. 2013, 4–5). For instance, yield levels and production quantities for the Finnish products are modelled according to year 2024, and for EU strawberry 2023. However, for wild berries the year 2024 has been historically very low production year, due to the lack of berry pickers from Thailand (Marsi 2024). Despite of the limitation, the biodiversity impacts from wild berry production are not expected to change significantly due to the uncertainty, since the annual production quantity of 2024 is only used to allocate the processing plant area for 1 kg of berries. Therefore, the uncertainty is expected to affect only to land use impacts of wild berries.

The used LCIA methods have usually uncertainties related to the provided CFs. In LC-IMPACT, the exact mechanisms through which environmental pressures cause changes, such as how climate change affects species richness or river discharge, are not fully understood. Moreover, the fate modelling often relies on simplified environmental compartments which limits accuracy in categories. (Verones et al. 2020a, 1215.)

The impact pathways are also modelled for all or certain taxonomic groups. For instance, fish is the only species representing the biodiversity impacts of freshwater eutrophication and climate change to AE, whereas the mammals, birds, reptiles, amphibians and vascular plants represent the impacts to climate change to TE and land stress. It is not likely that fish species represent the total freshwater ecosystem, which brings uncertainty to the results of those impact categories. (Verones et al. 2020a, 1205, Verones et al. 2020b, 26.)

Moreover, uncertainty is related to the value choices while using the method. The method provides time horizons of 100 years and infinite (Verones et al. 2020a, 1207). This study preferred time horizon of 100 years, but as all impact categories did not have the option for it, some categories used the CFs of infinite creating inconsistency between impact categories.

The GLAM method represents a more recent approach for assessing land stress impacts compared to LC-IMPACT. While LC-IMPACT provides CFs only for six different land use types, GLAM includes also land-use intensities. (Scherer et al. 2023, 19612; Verones et al. 2020b, 141.) By using GLAM, the accuracy of the biodiversity impacts assessed in this study could be improved.

6 Discussion

There are only a limited number of biodiversity impact assessments available for Finnish food products in the literature, even though calculation methods for biodiversity assessments have developed remarkably. Therefore, comparing the results of this study with other assessments of Finnish food items is challenging. Some examples exist, but the used methods vary, meaning that results are not necessarily directly comparable. In addition, the assessed impact categories often differ, which affect to the final results.

Savallampi, Järviö and Uusitalo (2025, 1) assessed the biodiversity impacts of conventionally and agroforestry-cultivated coffee in Colombia using GLAM and LC-IMPACT. The impact categories included land stress, climate change, freshwater and marine eutrophication, acidification, and water stress. The biodiversity impact of conventionally cultivated coffee was reported as 1.15E-12 PDF·yr/kg for TE, 2.18E-14 PDF·yr/kg for AE, and 4.85E-17 PDF·yr/kg for ME (Savallampi, Järviö & Uusitalo 2025, 1). These results are higher than for the products assessed in this study. As coffee is usually cultivated in areas with high biodiversity (Savallampi, Järviö & Uusitalo 2025, 2), the difference reflects the latitudinal gradient with more diversity closer to the equator. Moreover, the impacts from acidification increase the result from coffee production to TE, whereas acidification was not assessed in this study.

Vartiainen et al. (2025, 17) assessed the biodiversity impacts of certain food categories as part of the biodiversity impact assessment for City of Lahti. The used method in their assessment was GLAM for land stress impacts and LC-IMPACT for climate change impacts. Their total results by land occupation and climate change for food category of fruits, berries and nuts was 1.4 nPDF (PDF*10^9) and for vegetables 1.2 nPDF. (Vartiainen et al. 2025, 17.) Also these results show higher impacts compared to this assessment.

It should be noted that generally plant products have showed lower overall biodiversity impacts than animal-based products. This correlation is proved by many LCA studies for agricultural products. For example, Crenna, Sinkko & Sala (2019, 383–388) assessed the biodiversity impacts of typical food products consumed by EU-28 citizen, using ReCiPe2008 and 2016 methods. Their results showed that tomato biodiversity impacts can be even 148 times lower than the impacts from beef meat, and impacts for coffee 12 times lower than for beef meat (regarding the annual consumption). The high impacts of meat and other animal based products seemed to be because of animal feed production. (Crenna et al 2019, 383–388). Vartiainen et al. (2025, 17, 21) recognised the same while assessing biodiversity impacts of City of Lahti: red meat and milk based products showed higher biodiversity impacts than plant products, even though the higher impacts were partly related to the high consumption volumes of these products (Vartiainen et al. 2025, 17, 21). Therefore, the relative magnitude of the biodiversity impact from plants products assessed in this study should be noted.

The results in this study highlight electricity consumption as one of the key driver of biodiversity impacts for Finnish agricultural products. Several earlier studies have identified electricity and heat as the main contributors to the climate change impacts of greenhouse vegetables in Finland (Silvenius et al. 2019; Yrjänäinen et al. 2013). The energy transition from non-renewable energy, such as peat and oil, to renewables have been one of the key actions to reduce the climate impacts from greenhouse production already in recent decades (Silvenius & Katajajuuri 2021, 142–143). Even though 95 % of Finnish electricity production is already fossil free (Statistics Finland 2025), peat and other non-renewable sources still account for about 65 % of the heat consumption in Finnish greenhouses (Luke 2025b).

In addition to the climate change effects, the biodiversity impacts related to Finnish energy production should be investigated more. This study observed several biodiversity impact pathways linked to Finnish electricity production, including wood chip consumption for bioenergy, decarbonized water used in nuclear and thermal energy power plants, spoil from coal and lignite mining, and sulfidic tailings from copper mining. These findings are listed in table 19.

Table 19: Interesting biodiversity hotspots recognised in this study.

Hotspot	**Related process**	**The most affected impact category by the action**
Decarbonized water	Electricity production, nuclear and thermal energy power plants	Water stress
Spoil from coal and lignite mining	Electricity production, coal usage	Freshwater eutrophicaton
Sulfidic tailings from copper mining operations	Electricity production	Freshwater eutrophication
Wood chips	Electricity and heat production	Land stress
Peat	Heat consumption in greenhouses, growing media	Land stress, climate change
Hard coal ash	Electricity production, coal usage	Freshwater eutrophication

The water stress biodiversity impacts were dominated by decarbonized water consumption in nuclear power plants and boilers of thermal energy power plants. Pfiser et al. (2015, 1356) agrees that turbined water is the most important water flow for power production. However, the flow should be balanced with release of the water back to the river leading to relatively small consumptive use. (Pfiser et al. 2015, 1356). In this study, he processes from the Ecoinvent database showed very low release of water back to the water bodies.

This study observed also that despite of coal covering only 2 % of the Finnish electricity production, the phosphorous discharge and therefore freshwater eutrophication impacts from coal mining have remarkable biodiversity impacts. UNECE (2021, 7) agrees that freshwater eutrophication impacts are often influenced by hard coal mining processes. Hard coal mining generates tailings that leach phosphate to rivers and groundwater. (UNECE 2021, 7.) The large contribution of coal usage to freshwater eutrophication impacts was also observed in sensitivity analysis, where implementing a drain water recycling system in greenhouses (assuming zero phosphorous and nitrogen discharge) did not reduce the freshwater eutrophication impacts notably. However, marine impacts reduced remarkably. It is notable that during spring 2025, the use of coal was stopped in Finland completely (Finnish Government 2025), which means that the impacts from coal mining are not anymore relevant to Finland.

Yrjänäinen et al. (2013) observed that the lowest climate impacts for greenhouse heating were generated by using wood chips. However, in this study, wood chips consumption were observed to generated biodiversity loss through land use. This finding is in line with the observation that Finland’s forest use for energy and timber production contributes to biodiversity loss (IPBES 2019a, 59; Peura et al. 2022, 9–10).

It should be emphasized that biodiversity impact scores do not directly indicate the geographical location of the damage. As the inventory phase of this study was focused on land use during cultivation, nutrient runoff from the fields and irrigation water consumption, these factors are located in Finland. However, many of the key contributing processes are located in different parts of the world. For instance, coal has been typically imported to Finland from Russia, Australia and other countries (Finnish Coal Info 2025), which means that the eutrophication from coal mining does not straight affect to Finnish water bodies nor Archipelago Sea.

6.1 Recommendations

When comparing the biodiversity impacts of cultivated berries from different origins, Finnish berries showed lower overall biodiversity impacts to EU strawberry. However, the marine eutrophication category showed clearly higher results for Finnish strawberry and blackcurrant. The weighting of impact categories and ecosystems depend on the decision-making context, since there is not yet generally accepted opinion on how to value them (Verones et al. 2020a, 1206). For example, if the protection of the Archipelago Sea is prioritised, marine eutrophication impacts become more important. On the other hand, climate change and land-use related impacts are recognised as the most significant drivers of biodiversity loss, which gives more weight to those categories and suggests that cultivating strawberries in Finland could be environmentally preferable. Finnish blackcurrant, however, showed higher land stress than both Finnish and EU strawberry.

As a lot of the biodiversity impacts seemed to be generated during cultivation phase, wild berries low biodiversity impacts highlighted in the comparion. Wild berries grow naturally in forests without agricultural inputs, which significantly reduces their biodiversity impacts compared to other products. The main environmental hotspot related to wild berry production seemed to be transportation, as growing habitats are often located far from populated regions. A significant share of the impacts arose from the berry pickers travelling from Thailand to Finland. A comparison with berries picked by Finnish residents could provide useful insights into the most environmentally efficient way to harvest wild berries.

It is estimated that only 3–10 % of the bilberry and lingonberry crops are collected annually (Ruokatieto 2025), meaning that majority remains in the forest. This indicates a potential for consuming more wild berries instead of cultivated ones.

This study also found out the contribution of Finnish electricity production to biodiversity loss. More research on the biodiversity impacts of Finnish energy production is therefore suggested. While the climate impacts of the energy sector have been widely studied, effects on ecosystems and biodiversity have received less attention. Water stress, eutrophication and land stress impacts were all influenced by electricity generation through different pathways. For instance, water stress impacts were influenced by the consumption of decarbonised water in power plants, but the actual relevance of this impact pathway requires more detailed investigation. As biodiversity loss results from multiple interacting environmental pressures across several impact categories, and not only from GHG, future assessments should focus more on biodiversity impacts.

7 Conclusions

The objective of this master's thesis was to assess the biodiversity impacts of seven Finnish plant products and one EU average product as global species loss. Moreover, the study aimed to observe the highest impact categories and contributing factors to the impacts from life cycle of each product. LC-IMPACT was used as a method for all of the impact categories investigated in this study: climate change, land stress, freshwater and marine eutrophication and water stress. The assessed products were grouped and reported as greenhouse vegetables, cultivated berries and wild berries.

For greenhouse vegetable production, the most significant biodiversity impacts were caused by impact categories of climate change and water stress. Climate change showed particularly high impacts on TE, while water stress had more contribution on AE. Marine eutrophication was the only impact category affecting the impacts to ME. The cultivation phase caused the highest impacts on biodiversity in all investigated impact categories. Among the assessed greenhouse vegetables, lettuce production showed the highest overall impacts.

The main contributing factors from greenhouse vegetable production to TE were electricity and heat (wood chips) as well as growing media (peat). For AE, the largest contributors were electricity-related processes, including decarbonized water used in power plants, spoil from hard coal and lignite mining, and sulfidic tailings from copper mining. For ME, nitrogen discharge during the cultivation phase was identified as the most influential factor. It must be noted that the main contributing factors of climate change impacts to TE and AE were not analyzed in this study, and therefore the main contributors are related to other impact categories.

For cultivated berries, the largest biodiversity impacts were caused by impact categories of climate change and water stress. The climate impacts were highlighted in both TE and AE results. The biggest contributing life cycle phases were cultivation and processing, depending on the impact category. The impacts were related to land use during cultivation, electricity consumption during processing, irrigation needs as well as nitrogen discharge from the fields. Among the assessed berries, EU strawberry showed the highest total impacts as well as the highest impacts from most of the impact categories. Only land stress impacts were higher for Finnish blackcurrant, and impacts from marine eutrophication for Finnish cultivated berries.

Wild berries showed the lowest total biodiversity impacts among the assessed products. The most significant hotspots for wild berries were climate change impacts. However, as climate change impacts were not analyzed in this study, the biggest contributors to the results are related to other impact categories. The biggest impacts were caused by life cycle phases of transportation and processing. The biggest contributors were identified as road network construction (land stress), wood chips for electricity (land stress), decarbonized water for electricity (water stress), spoil from hard coal mining (freshwater eutrophication) and packaging (water stress). Sensitivity analysis demonstrated that including the berry pickers transportation from Thailand to Finnish forests increased the biodiversity impacts of wild berries two- to threefold, reaching nearly the level of impacts caused by Finnish strawberry production. However, the total biodiversity impacts from wild berries were lowest despite of the berry picker contribution.

Overall, this study observed the difficulty of characterizing products as more or less environmentally friendly, as they affect biodiversity through different impact pathways. The relative importance of climate change, land stress, eutrophication and water stress varies across products and contexts, making decision-making highly case-specific. In addition, the results underline that Finnish electricity production contributes to biodiversity loss through several pathways beyond climate change. Therefore, the environmental impacts of Finland’s energy system should be evaluated more broadly.

Measuring biodiversity proved to be a complex task, however, it is possible. There are already multiple methods that quantify biological diversity, as well as the losses in diversity due to the human actions. Most of the methods quantify species diversity, even if biodiversity also covers other levels, like genetic, ecosystem, structural and functional diversity. Despite of the limitations that current methods face, they help to make changes towards reduced biodiversity impacts.

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Appendix 1. Tomato life cycle model. Processes used in Simapro.

Original process	Database	Parameters changed to Finnish specific
Tomato, fresh grade {NL}| tomato production, fresh grade, in heated greenhouse | Cut-off, U	Ecoinvent	**Values changed:** LULUC, consumption of growing medias and irrigation water, pesticide use, fertilizer use, electricity and heat consumption, nutrient outputs **Characterization model changed:** LULUC of cultivation and seedling production, peat production, nutrient flows, water sources and waste glass **Processes modelled:** Finnish electricity modelled for 2024. Sources of heat used in Finnish greenhouses modelled for 2024.
Corrugated board box {RER}| market for corrugated board box | Cut-off, U	Ecoinvent	**Characterization model changed:** LULUC related to wood production **Processes modelled:** Finnish electricity modelled for 2024
Waste paperboard {FI}| market for waste paperboard | Cut-off, U	Ecoinvent	
Transport, freight, lorry with refrigeration machine, 7.5-16 ton, diesel, EURO 5, R134a refrigerant, cooling {GLO}| transport, freight, lorry with refrigeration machine, 7.5-16 ton, diesel, EURO 5, R134a refrigerant, cooling | Cut-off, U	Ecoinvent	

Appendix 2. Life cycle inventory for Finnish tomato produced in heated greenhouse (data collected from sources other than SimaPro).

FU=1kg tomatoes.

Unit process	Flows		Additional information	Unit	Amount	Source
Cultivation in heated greenhouse	**Inputs**	Production		kg/a	40 943 000	Luke 2024a
		Cultivation area		m2/a	856 000	Luke 2024a
		Land occupation (FU)	Cultivation area divided by production	m2/FU	0.02090712	Own calculation
		Land transformation to (FU)		m2/FU	0	Järviö et al. (Under revision)
		Land transformation from (FU)		m2/FU	0	Järviö et al. (Under revision)
		Pesticide use	Average use in Finland. Amount of active substance	kg/ha	0.6	Luke 2018
		Pesticide use (FU)	Pesticide use mulptilied by land occupation	kg/FU	1.2544269E-06	Own calculation
		Total use of N		kg/a	320 000	Silvenius et al. 2019
		Total use of N (FU)	N divided by production	kg/FU	7.8157438E-03	Own calculation
		Total use of P		kg/a	64 000	Silvenius et al. 2019
		Total use of P (FU)	P divided by production	kg/FU	1.5631488E-03	Own calculation
		Molecular mass of P		g/mol	30.974	NIH 2025
		Molecular mass of P2O5		g/mol	141,943	NIH 2025
		Total use of P2O5 (FU)	Total use of P scaled up by relation of molecular masses	kg/FU	7.1633637E-03	Own calculation
		Total use of K		kg/a	481 000	Silvenius et al. 2019
		Total use of K (FU)	K divided by production	kg/FU	11.748031E-03	Own calculation
		Molecular mass of K		g/mol	39.098	NIH 2025
		Molecular mass of K2O		g/mol	94.195	NIH 2025
		Total use of K2O (FU)	Total use of K scaled up by relation of molecular masses	kg/FU	28.3034074E-03	Own calculation
		Water footprint	Water footprint of tomato cultivation in heated greenhouse calculated by AWARE method	l/kg	34.7	Silvenius et al. 2019
		AWARE factor	Factor for Finnish agriculture	1,72		Silvenius et al. 2019
		Irrigation water (FU)	Tomato water footprint divided by AWARE factor	m3/FU	20.1744186E-03	Own calculation

		Use of stone wool	70% of the growing media used in Finnish tomato cultivation	m3/a	28 000	Silvenius et al. 2019
		Density of stone wool	Average	kg/m3	65	Bougoul et al. 2005
		Use of stone wool (FU)	Stone wool multiplied by density of stone wool, then divided by production	kg/FU	44.4520431E-03	Own calculation
		Use of peat moss	30% of the growing media used in Finnish tomato cultivation	m3/a	12 000	Silvenius et al. 2019
		Use of peat moss (FU)	Peat moss divided by production	m3/FU	0.2930903E-03	Own calculation
		Heat total		GWh/a	384	Silvenius et al. 2019
		Heat total (FU)	Heat total multiplied by total production	kWh/FU	9.3788926	Own calculation
		Electricity		GWh/a	129	Silvenius et al. 2019
		Electricity (FU)	Electricity multiplied by total production	kWh/FU	3.1507217	Own calculation
	Outputs	Drain water	Average drain water generated in Finnish greenhouses	m3/a	4750	Salo 2023
		Total N in drain water	Average in Finnish greenhouses	mg/l	400	Salo 2023
		Share of NO3- and NO2-		%	94	Salo 2023
		Molecular mass of N		g/mol	14.007	NIH 2025
		Molecular mass of NO3-		g/mol	62.007	NIH 2025
		Molecular mass of NO2-		g/mol	46.007	NIH 2025
		N released in drain water (FU)	6 % of the total N in drain water divided by production	kg/FU	2.7843587E-06	Own calculation
		NO3- released in drain water (FU)	94 % of the total N in drain water divided for NO3- and NO2-, then scaled up by relation of molecular masses	kg/FU	9.6553349E-05	Own calculation
		NO2- released in drain water (FU)	94 % of the total N in drain water divided for NO3- and NO2-, then scaled up by relation of molecular masses	kg/FU	7.1639176E-05	Own calculation
		Total P in drain water	Average in Finnish greenhouses	mg/l	41.6	Salo 2023
		Total P in drain water (FU)	Total P in drain water multiplied by drain water, then divided by production	kg/FU	4.8262218E-06	Own calculation
Packaging	**Inputs**	Corrugated board box (FU)		kg/FU	0.1	Own estimation
	Outputs	Waste paperboard (FU)	Based on input box	kg/FU	0.1	Own estimation
Transport	**Inputs**	Truck with refrigeration, cooling	Närpiö-Turku	kgkm	580	Google Maps

Appendix 3. Cucumber life cycle model. Processes used in Simapro.

Original process	Database	Parameters changed to Finnish specific
Tomato, fresh grade {NL}| tomato production, fresh grade, in heated greenhouse | Cut-off, U	Ecoinvent	**Values changed:** LULUC, consumption of growing medias and irrigation water, pesticide use, fertilizer use, electricity and heat consumption **Characterization model changed:** LULUC of cultivation and seedling production, peat production, nutrient flows, water sources and waste glass **Processes modelled:** Finnish electricity modelled for 2024. Sources of heat used in Finnish greenhouses modelled for 2024.
Packaging film, low density polyethylene {RER}| packaging film production, low density polyethylene | Cut-off, U	Ecoinvent	
Waste polyethylene {FI}| market for waste polyethylene | Cut-off, U	Ecoinvent	
Transport, freight, lorry with refrigeration machine, 7.5-16 ton, diesel, EURO 5, R134a refrigerant, cooling {GLO}| transport, freight, lorry with refrigeration machine, 7.5-16 ton, diesel, EURO 5, R134a refrigerant, cooling | Cut-off, U	Ecoinvent	

Appendix 4. Life cycle inventory for Finnish cucumber produced in heated greenhouse (data collected from sources other than SimaPro).

FU=1kg cucumber.

Unit process	Flows		Additional information	Unit	Amount	Source
Cultivation in heated greenhouse	**Inputs**	Production		kg/a	53 750 000	Luke 2024a
		Cultivation area		m2/a	474 000	Luke 2024a
		Land occupation (FU)	Cultivation area divided by production	m2/FU	8.8186047E-03	Own calculation
		Land transformation to (FU)		m2/FU	2.39935E-03	Järviö et al. (Under revision)
		Land transformation from (FU)		m2/FU	0	Järviö et al. (Under revision)
		Pesticide use	Average use in Finland. Amount of active substance	kg/ha	0.6	Luke 2018
		Pesticide use (FU)	Pesticide use mulptilied by land occupation	kg/FU	5.2911628E-07	Own calculation
		Total use of N		kg/a	200 000	Silvenius et al. 2019
		Total use of N (FU)	N divided by production	kg/FU	3.7209302E-03	Own calculation
		Total use of P		kg/a	35 000	Silvenius et al. 2019
		Total use of P (FU)	P divided by production	kg/FU	6.5116279E-04	Own calculation
		Molecular mass of P		g/mol	30.974	NIH 2025
		Molecular mass of P2O5		g/mol	141.943	NIH 2025
		Total use of P2O5 (FU)	Total use of P scaled up by relation of molecular masses	kg/FU	2.9841563E-03	Own calculation
		Total use of K		kg/a	260 000	Silvenius et al. 2019
		Total use of K (FU)	K divided by production	kg/FU	4.8372093E-03	Own calculation
		Molecular mass of K		g/mol	39.098	NIH 2025
		Molecular mass of K2O		g/mol	94.195	NIH 2025
		Total use of K2O (FU)	Total use of K scaled up by relation of molecular masses	kg/FU	11.6539405E-03	Own calculation
		Water footprint	Water footprint of cucumber cultivation in heated greenhouse calculated by AWARE method	l/kg	19.4	Silvenius et al. 2019
		AWARE factor	Factor for Finnish agriculture		1.72	Silvenius et al. 2019
		Irrigation water (FU)	Cucumber water footprint divided by AWARE factor	m3/FU	11.2790697E-03	Own calculation

		Use of stone wool	70% of the growing media used in Finnish cucumber cultivation	m3/a	28 000	Silvenius et al. 2019
		Density of stone wool	Average	kg/m3	65	Bougoul et al. 2005
		Use of stone wool (FU)	Stone wool multiplied by density of stone wool, then divided by production	kg/FU	33.860465E-03	Own calculation
		Use of peat moss	30% of the growing media used in Finnish cucumber cultivation	m3/a	12 000	Silvenius et al. 2019
		Use of peat moss (FU)	Peat moss divided by production	m3/FU	0.223256E-03	Own calculation
		Heat total		GWh/a	114	Silvenius et al. 2019
		Heat total (FU)	Heat total multiplied by land occupation	kWh/FU	2.1209302	Own calculation
		Electricity		GWh/a	298	Silvenius et al. 2019
		Electricity (FU)	Electricity multiplied by land occupation	kWh/FU	5.5441860	Own calculation
	Outputs	Drain water	Average drain water generated in Finnish greenhouses	m3/a	4750	Salo 2023
		Total N in drain water	Average in Finnish greenhouses	mg/l	400	Salo 2023
		Share of NO3- and NO2-		%	94	Salo 2023
		Molecular mass of N		g/mol	14.007	NIH 2025
		Molecular mass of NO3-		g/mol	62.007	NIH 2025
		Molecular mass of NO2-		g/mol	46.007	NIH 2025
		N released in drain water (FU)	6 % of the total N in drain water divided by production	kg/FU	2.1209302E-06	Own calculation
		NO3- released in drain water (FU)	94 % of the total N in drain water divided for NO3- and NO2-, then scaled up by relation of molecular masses	kg/FU	7.3547613E-05	Own calculation
		NO2- released in drain water (FU)	94 % of the total N in drain water divided for NO3- and NO2-, then scaled up by relation of molecular masses	kg/FU	5.4569726E-05	Own calculation
		Total P in drain water	Average in Finnish greenhouses	mg/l	41.6	Salo 2023
		Total P in drain water (FU)	Total P in drain water multiplied by drain water, then divided by production	kg/FU	3.6762791E-06	Own calculation
Packaging	**Inputs**	LDPE	One cucumber weight 350g	g/unit	2	K-ryhmä 2021
		LDPE (FU)	1kg/0,35kg * 2	g/FU	5.7143	Own calculation
	Outputs	Waste LDPE (FU)	Based on PE input	g/FU	5.7143	Own calculation
Transport	**Inputs**	Truck with refrigeration, cooling	Närpiö-Turku	kgkm	580	Google Maps

Appendix 5. Lettuce in pot life cycle model. Processes used in Simapro.

Original process	**Database**	**Parameters changed to Finnish specific**
Tomato, fresh grade {NL}| tomato production, fresh grade, in heated greenhouse | Cut-off, U	Ecoinvent	**Values changed:** LULUC, consumption of growing media and irrigation water, pesticide use, fertilizer use, electricity and heat consumption. Seedling production, stone wool and waste glass removed. **Characterization model changed:** LULUC of cultivation, peat production, nutrient flows, water sources **Processes modelled:** Finnish electricity modelled for 2024. Sources of heat used in Finnish greenhouses modelled for 2024.
Packaging film, low density polyethylene {RER}| packaging film production, low density polyethylene | Cut-off, U	Ecoinvent	
Waste polyethylene {FI}| market for waste polyethylene | Cut-off, U	Ecoinvent	
Transport, freight, lorry with refrigeration machine, 7.5-16 ton, diesel, EURO 5, R134a refrigerant, cooling {GLO}| transport, freight, lorry with refrigeration machine, 7.5-16 ton, diesel, EURO 5, R134a refrigerant, cooling | Cut-off, U	Ecoinvent	

Appendix 6. Life cycle inventory for Finnish lettuce in pot produced in heated greenhouse (data collected from sources other than SimaPro). FU=1kg lettuce.

Unit process	Flows		Additional information	Unit	Amount	Source
Cultivation in heated greenhouse	**Inputs**	Production		kpl/a	71 512 000	Luke 2024a
		Production by weight	Weight of one lettuce assumed 150g	kg/a	10 726 800	Own calculation
		Cultivation area		m2/a	225 000	Luke 2024a
		Land occupation (FU)	Cultivation area divided by production by weight	m2/FU	0.0209755	Own calculation
		Land transformation to (FU)		m2/FU	2.39935E-03	Järviö et al. (Under revision)
		Land transformation from (FU)		m2/FU	0	Järviö et al. (Under revision)
		Pesticide use	Average use in Finland. Amount of active substance	kg/ha	0.6	Luke 2018
		Pesticide use (FU)	Pesticide use mulptilied by land occupation	kg/FU	1.2585301E-06	Own calculation
		Total use of N		kg/a	20 000	Silvenius et al. 2019
		Total use of N (FU)	N divided by production by weight	kg/FU	1.8644889E-03	Own calculation
		Total use of P		kg/a	7 000	Silvenius et al. 2019
		Total use of P (FU)	P divided by production by weight	kg/FU	0.6525711E-03	Own calculation
		Molecular mass of P		g/mol	30.974	NIH 2025
		Molecular mass of P2O5		g/mol	141.943	NIH 2025
		Total use of P2O5 (FU)	Total use of P scaled up by relation of molecular masses	kg/FU	2.9906104E-03	Own calculation
		Total use of K		kg/a	45 000	Silvenius et al. 2019
		Total use of K (FU)	K divided by production by weight	kg/FU	4.1951001E-03	Own calculation
		Molecular mass of K		g/mol	39.098	NIH 2025
		Molecular mass of K2O		g/mol	94.195	NIH 2025
		Total use of K2O (FU)	Total use of K scaled up by relation of molecular masses	kg/FU	10.1069531E-03	Own calculation
		Water footprint	Water footprint of lettuce cultivation in heated greenhouse calculated by AWARE method	l/kg	36	Silvenius et al. 2019
		AWARE factors	Factor for Finnish agriculture		1.72	Silvenius et al. 2019

		Water use	Water footprint divided by AWARE factor	l/kg	20.9302326	Own calculation
		Irrigation water (FU)	Plastic packaging covers 8 % of the water use, rest is irrigation water	m3/FU	19.2558140E-03	Own calculation
		Weight of a growing pot	One pot includes peat moss and paper coverage	g/pot	40	Oksasen Puutarha Oy representative 2025
		Use of peat moss	Assumption that peat moss is 30g, paper coverage 10g	g/pot	30	Own calculation
		Density of peat moss		kg/m3	157	Vaughn et al. 2013
		Use of peat moss (FU)	Use of peat moss divided by weight of one salad, then divided by density of peat moss	m3/FU	1.2738853E-03	Own calculation
		Heat total		GWh/a	139	Silvenius et al. 2019
		Heat total (FU)	Heat total multiplied by land occupation	kWh/FU	12.9581982	Own calculation
		Electricity		GWh/a	149	Silvenius et al. 2019
		Electricity (FU)	Electricity multiplied by land occupation	kWh/FU	13.8904426	Own calculation
	Outputs	Drain water	Average drain water generated in Finnish greenhouses	m3/a	4750	Salo 2023
		Total N in drain water	Average in Finnish greenhouses	mg/l	400	Salo 2023
		Share of NO3- and NO2-		%	94	Salo 2023
		Molecular mass of N		g/mol	14.007	NIH 2025
		Molecular mass of NO3-		g/mol	62.007	NIH 2025
		Molecular mass of NO2-		g/mol	46.007	NIH 2025
		N released in drain water (FU)	6 % of the total N in drain water divided by production	kg/FU	1.0627587E-05	Own calculation
		NO3- released in drain water (FU)	94 % of the total N in drain water divided for NO3- and NO2-, then scaled up by relation of molecular masses	kg/FU	3.6853341E-04	Own calculation
		NO2- released in drain water (FU)	94 % of the total N in drain water divided for NO3- and NO2-, then scaled up by relation of molecular masses	kg/FU	2.7343875E-04	Own calculation
		Total P in drain water	Average in Finnish greenhouses	mg/l	41.6	Salo 2023
		Total P in drain water (FU)	Total P in drain water multiplied by drain water, then divided by production	kg/FU	1.8421151E-05	Own calculation
Packaging	**Inputs**	LDPE		g/pot	8	Own estimation
		LDPE (FU)	1kg/weight of one lettuce * 8g	g/FU	53.333	Own calculation
	Outputs	Waste LDPE (FU)	Based on input PE	g/FU	53.333	Own calculation
Transport	**Inputs**	Truck with refrigeration, cooling	Oripää-Turku	kgkm	60	Google Maps

Appendix 7. Finnish strawberry life cycle model. Processes used in Simapro.

Original process	Database	Parameters changed to Finnish specific
Strawberry, open field, conventional, at farm gate {FR} U	Agribalyse	**Values changed:** LULUC, consumption of irrigation water **Characterization model changed:** LULUC of cultivation, nutrient flows, water source **Processes modelled:** Finnish electricity modelled for 2024. Strawberry misted tips process changed to FI by characterizing irrigation water, land use related to peat production and electricity. Strawberry runners land use and irrigaton water characterized to FI.
Freezing_process_strawberry {FI}	Own model	See appendix 15: Processing/freezing of Finnish berries
Packaging film, low density polyethylene {RER}| packaging film production, low density polyethylene | Cut-off, U	Ecoinvent	
Waste polyethylene {FI}| market for waste polyethylene | Cut-off, U	Ecoinvent	
Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 {RER}| transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 | Cut-off, U	Ecoinvent	
Transport, freight, lorry with refrigeration machine, 7.5-16 ton, diesel, EURO 5, R134a refrigerant, freezing {GLO}| market for transport, freight, lorry with refrigeration machine, 7.5-16 ton, diesel, EURO 5, R134a refrigerant, freezing | Cut-off, U	Ecoinvent	

Appendix 8. Life cycle inventory for Finnish strawberry (data collected from sources other than SimaPro). FU=1kg berries

Unit process	Flows		Additional information	Unit	Amount	Source
Cultivation in open field	**Inputs**	Production		kg/a	11 503 000	Luke 2024b
		Cultivation area		m2/a	3494	Luke 2024b
		Land occupation (FU)	Cultivation area divided by production	m2/FU	3.0374684	Own calculation
		Land transformation to (FU)		m2/FU	0	Järviö et al. (Under revision)
		Land transformation from (FU)		m2/FU	0	Järviö et al. (Under revision)
		Irrigation need		l/plant/ week	3	Tahvonen et al. 2001
		Growing season	May-August	weeks	17	Own assumption
		Production of one plant	Production with drip irrigation	kg/plant	0.9	Tahvonen et al. 2001
		Irrigation need (FU)		m3/FU	56.6666667E-03	Own calculation
Processing/ freezing	**Inputs**	Plant area	Email information	m2	8000	Kiantama Oy representative 2025a
		Total production in the plant	Sum of strawberry and blackcurrant production	kg/a	13 231 000	Own calculation
		Plant area allocated for strawberries (FU)	Allocation by production quantities	m2/FU	5.2567312E-04	Own calculation
		Electricity (FU)	Email information	kWh/FU	1	Kiantama Oy representative 2025a
		Light fuel oil (FU)	Email information	l/FU	0.04	Kiantama Oy representative 2025a
		Water (FU)	Email information	l/FU	0.005	Kiantama Oy representative 2025a
	Outputs	Wastewater (FU)	Email information	l/FU	0.005	Kiantama Oy representative 2025a
		Biowaste (FU)	Email information	kg/FU	0.06	Kiantama Oy representative 2025a
Packaging	**Inputs**	LDPE (FU)		g/FU	10	Own estimation
	Outputs	Waste LDPE (FU)	Based on input LDPE	g/FU	10	Own estimation
Transport	**Inputs**	Truck	Cultivation-processing plant (Suonenjoki)	km	30	Pakkasmarja Oy representative 2025
		Truck (FU)	Travel distance for 1,06kg of berries	kgkm	31.8	Own calculation
		Truck with refrigeration, freezing	Suonenjoki-Helsinki-Turku	kgkm	500	Pakkasmarja Oy representative 2025

Appendix 9. EU average strawberry life cycle model. Processes used in Simapro.

Original process	**Database**	**Parameters changed to Finnish specific**
Strawberry, open field, conventional, at farm gate {FR} U	Agribalyse	**Values changed:** LULUC **Characterization model changed:** LULUC of cultivation, nutrient flows, water source **Processes:** Electricity changed to European average
Freezing_process_strawberry {RER}	Own model	See appendix 16: Processing/freezing of EU berries
Packaging film, low density polyethylene {RER}| packaging film production, low density polyethylene | Cut-off, U	Ecoinvent	
Waste polyethylene {FI}| market for waste polyethylene | Cut-off, U	Ecoinvent	
Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 {RER}| transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 | Cut-off, U	Ecoinvent	
Transport, freight, lorry with refrigeration machine, 7.5-16 ton, diesel, EURO 5, R134a refrigerant, freezing {GLO}| market for transport, freight, lorry with refrigeration machine, 7.5-16 ton, diesel, EURO 5, R134a refrigerant, freezing | Cut-off, U	Ecoinvent	
Transport, freight, sea, container ship with reefer, freezing {GLO}| market for transport, freight, sea, container ship with reefer, freezing | Cut-off, S - Copied from Ecoinvent U	Agribalyse	

Appendix 10. Life cycle inventory for EU average strawberry (data collected from sources other than SimaPro). FU=1kg berries

Unit process	Flows		Additional information	Unit	Amount	Source
Cultivation in open field	**Inputs**	Production		kg/a	1 778 614	FAO 2025
		Cultivation area		ha/a	151 082	FAO 2025
		Land occupation (FU)	Cultivation area divided by production	m2/FU	8.4943665E-05	Own calculation
		Land transformation to (FU)		m2/FU	0	Järviö et al. (Under revision)
		Land transformation from (FU)		m2/FU	0	Järviö et al. (Under revision)
Processing/ freezing	**Inputs**	Plant area	Email information	m2	8000	Kiantama Oy representative 2025a
		Total production in the plant	Sum of strawberry FIN and blackcurrant production	kg/a	13 231 000	Own calculation
		Plant area allocated for strawberries (FU)	Allocation by production quantities	m2/FU	5.2567312E-04	Own calculation
		Electricity (FU)	Email information	kWh/FU	1	Kiantama Oy representative 2025a
		Light fuel oil (FU)	Email information	l/FU	0.04	Kiantama Oy representative 2025a
		Water (FU)	Email information	l/FU	0.005	Kiantama Oy representative 2025a
	Outputs	Wastewater (FU)	Email information	l/FU	0.005	Kiantama Oy representative 2025a
		Biowaste (FU)	Email information	kg/FU	0.06	Kiantama Oy representative 2025a
Packaging	**Inputs**	LDPE (FU)		g/FU	10	Own estimation
	Outputs	Waste LDPE (FU)	Based on input LDPE	g/FU	10	Own estimation
Transport	**Inputs**	Truck	Cultivation-processing plant, kept as same for strawberry FIN in order to align the results	km	30	Pakkasmarja Oy representative 2025
		Truck (FU)	Travel distance for 1,06kg of berries	kgkm	31.8	Own calculation
		Truck with refrigeration, freezing	Central Europe-Coastal site	kgkm	700	Google Maps
		Sea, freight	To Turku	kgkm	2400	Google Maps

Appendix 11. Finnish blackcurrant life cycle model. Processes used in Simapro.

Original process	**Database**	**Parameters changed to Finnish specific**
Strawberry, open field, conventional, at farm gate {FR} U	Agribalyse	**Values changed:** LULUC, irrigation water and the electricity consumption related to it removed. **Characterization model changed:** LULUC of cultivation, nutrient flows **Processes modelled:** Finnish electricity modelled for 2024. Strawberry misted tips process changed to FI by characterizing irrigation water, land use related to peat production and electricity. Strawberry runners land use and irrigaton water characterized to FI.
Freezing_process_blackcurrant {FI}	Own model	See appendix 15: Processing/freezing of Finnish berries
Packaging film, low density polyethylene {RER}| packaging film production, low density polyethylene | Cut-off, U	Ecoinvent	
Waste polyethylene {FI}| market for waste polyethylene | Cut-off, U	Ecoinvent	
Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 {RER}| transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 | Cut-off, U	Ecoinvent	
Transport, freight, lorry with refrigeration machine, 7.5-16 ton, diesel, EURO 5, R134a refrigerant, freezing {GLO}| market for transport, freight, lorry with refrigeration machine, 7.5-16 ton, diesel, EURO 5, R134a refrigerant, freezing | Cut-off, U	Ecoinvent	

Appendix 12. Life cycle inventory for Finnish blackcurrant (data collected from sources other than SimaPro). FU=1kg berries

Unit process	Flows		Additional information	Unit	Amount	Source
Cultivation in open field	**Inputs**	Production		kg/a	1 728 000	Luke 2024b
		Cultivation area		m2/a	1898	Luke 2024b
		Land occupation (FU)	Cultivation area divided by production	m2/FU	10.9837963	Own calculation
		Land transformation to (FU)		m2/FU	0	Järviö et al. (Under revision)
		Land transformation from (FU)		m2/FU	0	Järviö et al. (Under revision)
Processing/ freezing	**Inputs**	Plant area	Email information	m2	8000	Kiantama Oy representative 2025a
		Total production in the plant	Sum of strawberry and blackcurrant production	kg/a	13 231 000	Own calculation
		Plant area allocated for blackcurrants (FU)	Allocation by production quantities	m2/FU	6.8654157E-05	Own calculation
		Electricity (FU)	Email information	kWh/FU	1	Kiantama Oy representative 2025a
		Light fuel oil (FU)	Email information	l/FU	0.04	Kiantama Oy representative 2025a
		Water (FU)	Email information	l/FU	0.005	Kiantama Oy representative 2025a
	Outputs	Wastewater (FU)	Email information	l/FU	0.005	Kiantama Oy representative 2025a
		Biowaste (FU)	Email information	kg/FU	0.06	Kiantama Oy representative 2025a
Packaging	**Inputs**	LDPE (FU)		g/FU	10	Own estimation
	Outputs	Waste LDPE (FU)	Based on input LDPE	g/FU	10	Own estimation
Transport	**Inputs**	Truck	Cultivation-processing plant (Suonenjoki)	km	30	Pakkasmarja Oy representative 2025
		Truck (FU)	Travel distance for 1,06kg of berries	kgkm	31.8	Own calculation
		Truck with refrigeration, freezing	Suonenjoki-Helsinki-Turku	kgkm	500	Pakkasmarja Oy representative 2025

Appendix 13. Wild berries life cycle model. Processes used in Simapro.

Original process	Database	Parameters changed to Finnish specific
Freezing_process_bilberry {FI}	Own model	See appendix 15: Processing/freezing of Finnish berries
Freezing_process_lingonberry {FI}	Own model	See appendix 15: Processing/freezing of Finnish berries
Packaging film, low density polyethylene {RER}| packaging film production, low density polyethylene | Cut-off, U	Ecoinvent	
Waste polyethylene {FI}| market for waste polyethylene | Cut-off, U	Ecoinvent	
Transport, passenger, car, diesel, large size, EURO 5 {RER}| transport, passenger, car, diesel, large size, EURO 5 | Cut-off, U	Ecoinvent	
Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 {RER}| transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 | Cut-off, U	Ecoinvent	
Transport, freight, lorry with refrigeration machine, 7.5-16 ton, diesel, EURO 5, R134a refrigerant, freezing {GLO}| market for transport, freight, lorry with refrigeration machine, 7.5-16 ton, diesel, EURO 5, R134a refrigerant, freezing | Cut-off, U	Ecoinvent	

Appendix 14. Life cycle inventory for Finnish wild berries (data collected from sources other than SimaPro). FU=1kg berries.

Unit process	Flows		Additional information	Unit	Amount	Source
Processing/ freezing	**Inputs**	Bilberry production		kg/a	1 160 700	Marsi 2024
		Lingonberry production		kg/a	3 957 400	Marsi 2024
		Plant area	Email information	m2	8000	Kiantama Oy representative 2025a
		Plant area for bilberries (FU)	Plant area divided by bilberry production	m2/FU	6.8923925E-03	Own calculation
		Plant area for lingonberries (FU)	Plant area divided by lingonberry production	m2/FU	2.0215293E-03	Own calculation
		Electricity (FU)	Email information	kWh/FU	1	Kiantama Oy representative 2025a
		Light fuel oil (FU)	Email information	l/FU	0.04	Kiantama Oy representative 2025a
		Water (FU)	Email information	l/FU	0.005	Kiantama Oy representative 2025a
	Outputs	Wastewater (FU)	Email information	l/FU	0.005	Kiantama Oy representative 2025a
		Biowaste (FU)	Email information	kg/FU	0.06	Kiantama Oy representative 2025a
Packaging	**Inputs**	LDPE (FU)		g/FU	10	Own estimation
	Outputs	Waste LDPE (FU)	Based on input LDPE	g/FU	10	Own estimation
Transport bilberry	**Inputs**	Van, 500kg	Forest-Rovaniemi	km	30	Kiantama Oy representative 2025b
		Van, 500kg (FU)	Transport allocated for 1,06kg of berries	km/FU	0.0636	Own calculation
		Truck, 15t	Rovaniemi-Suomussalmi	km	280	Kiantama Oy representative 2025b
		Truck, 15t (FU)	Transport for 1,06kg of berries	kgkm	296.8	Own calculation
		Truck with refrigeration, freezing	Suomussalmi-Helsinki-Turku	kgkm	850	Kiantama Oy representative 2025b
Transport lingonberry	**Inputs**	Van, 500kg	Forest-Kokkola	km	30	Marja Bothnia Berries Oy Ltd representative 2025
		Van, 500kg (FU)	Transport allocated for 1,06kg of berries	km/FU	0.0636	Own calculation
		Truck, 15t	Rovaniemi-Suomussalmi	km	120	Marja Bothnia Berries Oy Ltd representative 2025
		Truck, 15t (FU)	Transport for 1,06kg of berries	kgkm	127.2	Own calculation
		Truck with refrigeration, freezing	Suomussalmi-Helsinki-Turku	kgkm	600	Marja Bothnia Berries Oy Ltd representative 2025

Appendix 15. Finnish berries processing/freezing model. Processes used in Simapro.

Original process	Database	Parameters changed to Finnish specific
Water, unspecified natural origin, FI		
Occupation, urban, FI		
Electricity, medium voltage {FI}| market for electricity, medium voltage | Cut-off, U	Ecoinvent	Finnish electricity modelled for 2024.
Light fuel oil, burned in furnace 1MW of greenhouse {RER} U	Agribalyse	**Characterization model changed:** Emissions to air (ammonia, nitrogen oxides, sulfur dioxide)
Wastewater, average {Europe without Switzerland}| treatment of wastewater, average, wastewater treatment | Cut-off, U	Ecoinvent	**Characterization model changed:** Emissions to air (nitrogen oxides, sulfur dioxide, water), emissions to water (phosphate, nitrate, water). **Processes changed:** Finnish electricity modelled for 2024
Biowaste {RoW}| treatment of biowaste, industrial composting | Cut-off, U	Ecoinvent	**Characterization model changed:** Emissions to air (ammonia, nitrogen oxides, sulfur dioxide) **Processes changed:** Finnish electricity modelled for 2024

Appendix 16. EU berries processing/freezing model. Processes used in Simapro.

Original process	Database	Parameters changed to Finnish specific
Water, unspecified natural origin, RER		
Occupation, urban, RER		
Electricity, medium voltage {Europe without Switzerland}| market group for electricity, medium voltage | Cut-off, U	Ecoinvent	
Light fuel oil, burned in furnace 1MW of greenhouse {RER} U	Agribalyse	**Characterization model changed:** Emissions to air (ammonia, nitrogen oxides, sulfur dioxide)
Wastewater, average {Europe without Switzerland}| treatment of wastewater, average, wastewater treatment | Cut-off, U	Ecoinvent	**Characterization model changed:** Emissions to air (ammonia, nitrogen oxides, sulfur dioxide)
Biowaste {RoW}| treatment of biowaste, industrial composting | Cut-off, U	Ecoinvent	**Characterization model changed:** Emissions to air (ammonia, nitrogen oxides, sulfur dioxide) **Processes changed:** Electricity changed to European mix.