Degree Project in Sustainable Urban Planning and Design

Second Cycle, 30 credits

Modelling Resilience with LCA

A Case for Expanding Urban Agriculture in Nordic Cities for a more Robust and Sustainable Food System

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I Abstract

Food systems in the Nordics face critical challenges in resilience as they are largely dependent on food imports from areas such as Southern Europe. However, countries like Spain are facing increasing climate related impacts and have recently seen reduced agricultural production. This implies that reduced production or crop failures will become more common as climate change impacts become exacerbated. This study explores how resilience can be integrated into environmental decision-making using Life Cycle Assessment (LCA) methodology which usually prioritises efficiency and sustainability over resilience. Using Stockholm's lettuce supply system as a case study, resilience is measured by modelling different disturbance scenarios and comparing these environmental impacts to an alternative proposed resilient system to see at what point it is more environmentally sound to invest in resilience. The conventional system is lettuce sourced from Spain, as they are Sweden's largest importer of lettuce, and the Netherlands and the USA are modelled as alternative sources under disturbance. The resilient system proposed is when 50% of lettuce is sourced from Spain and the other 50% is grown in vertical farms in Stockholm. Results show that while the resilient system performs worse in water use due to the energy mix, it performs consistently better in global warming potential and acidification, as well as offering supply security. In general, increasing levels of disturbance are shown to make the resilient system an increasingly preferable option, depending on the source country. Current methodology was deemed insufficient for assessing the environmental impacts under scenarios of full crop failure and new equations were proposed to account for this. These results provide an improved framework for accounting for resilience in an LCA which can inform strategic planning and decision-making.

Keywords
Life Cycle Assessment, Resilience, Disturbance, Urban Agriculture, Sustainability, Preparedness

II Sammanfattning

Livsmedelssystemen i Norden står inför kritiska utmaningar gällande resiliens då de till stor del är beroende av import från områden som Sydeuropa. Länder som Spanien drabbas dock i allt högre grad av klimatrelaterade effekter och har nyligen sett en minskning i jordbruksproduktionen. Detta innebär att minskad produktion eller fullständiga skördeförluster kommer att bli vanligare i takt med att klimatförändringarnas effekter förvärras. Denna studie undersöker hur resiliens kan integreras i miljömässigt beslutsfattande genom livscykelanalys (LCA), en metod som vanligtvis prioriterar effektivitet och hållbarhet. Med Stockholms försörjningssystem för sallat som fallstudie mäts resiliens genom att modellera miljöpåverkan under olika störningsscenarier och jämföra dessa med ett föreslaget resilient system, för att identifiera vid vilken punkt det är miljömässigt fördelaktigt att investera i resiliens. Det konventionella systemet antas vara import av sallat från Spanien, då det är Sveriges största importland för sallat, medan Nederländerna och USA modelleras som alternativa källor vid störningar. Det resilienta systemet definieras som ett där 50% av sallaten importeras från Spanien och resterande 50% odlas i vertikala odlingar i Stockholm. Resultaten visar att det resilienta systemet har högre vattenanvändning på grund av Sveriges energimix, men presterar konsekvent bättre gällande global uppvärmningspotential samt erbjuder försörjningstrygghet. Generellt visar resultaten att högre nivåer av störning gör det resilienta systemet till ett alltmer fördelaktigt alternativ, beroende på ursprungsland. Den befintliga metodologin bedöms som otillräcklig för att uppskattamiljöpåverkan vid fullständiga skördeförluster, och nya ekvationer föreslås för att hantera detta. Resultaten bidrar till en förbättrad metod för att beakta resiliens inom LCA, vilket kan stödja strategisk planering och beslutsfattande.

Nyckelord
Livscykelanalys, Resiliens, Störning, Stadsodling, Hållbarhet, Beredskap

III Acknowledgments

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I came back to my original interest of resilience and food systems and feel more inspired than ever to put my passion to good use. For this I have my parents to thank, they inspired my curiosity for the world and supported me through my unconventional academic trajectory. This work would not have been possible without their support or that of the community I have around me in Sweden and in Canada who help me remember to have fun. Especially thanks to Joel for the unwavering support and the zest for life, not to mention the help editing!

IV List of Abbreviations

ALCA	Attributional Life Cycle Assessment
CLCA	Consequential Life Cycle Assessment
FU	Functional Unit
GH	Greenhouse
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
OF	Open Field
RoW	Rest of World
UA	Urban Agriculture
VF	Vertical Farm

Contents

1 Introduction

A growing global population and a changing climate make it important to address anthropogenic impacts to the environment from all angles. Food production presents a significant impact globally. It contributes 26% of anthropogenic greenhouse gas emissions (GHGs), takes up 50% of the globe's habitable land and uses 70% of freshwater withdrawals (Ritchie et al., 2022). Sweden is no exception to this trend. Swedish food consumption accounts for 35% of the country's climate change impact, 54% of the impact on land use, and 72% of the water use (European Commission, 2021), showing that food consumption has a marginally higher share of the country's total impacts than the global average. Additionally, Sweden is a country which mostly imports what it consumes, meaning the environmental impacts of food consumption are often felt in other countries (Fauré et al. 2019, Cederberg et al., 2019), making them less visible and easier to ignore. Sweden is a country which is limited in its ability to produce its own food due to its high latitude and climate and is considered to have the lowest self-sufficiency in Europe, being able to meet only 45% of its food requirements itself (Ryberg et al., 2019). The increased interconnectivity of countries has made it more economically viable in many cases to produce crops in southern Europe or North Africa and import them to northern Europe rather than heat greenhouses locally (Romero-Gámez et al., 2014). Because of the globalised nature of the food system, it can be difficult for consumers or retailers to make environmentally conscious choices, as environmental impacts are hard to account for. Promoting local and/or organic food production and consumption is often seen as the ideal solution for a sustainable food system (Molin et al., 2024). However, several Life-Cycle Assessment (LCA) studies have compared the environmental impacts of local versus imported food (Payen et al., 2015, Canals et al., 2008) and organic versus non-organic production (Meier et al., 2015) and have found that local and organic does not always equate to a system that is more sustainable. These studies have shown that results are often highly context dependent and results can also depend on which environmental impacts are prioritised (Payen et al., 2015).

Assessing sustainability by using LCAs to quantify environmental impacts is an important task but these are not the only important aspects to consider when trying to assess the sustainability of a system. An often-neglected part of sustainability is resilience, which is generally considered to be the ability of a system to withstand disturbance, however this can be difficult to define and quantify and therefore difficult to prioritise (Pizzol, 2015). So far, sustainability assessments and disruptions have not been explored heavily in literature (Larrea-Gallegos et al., 2022). Our food system may seem resilient and robust since grocery stores are stocked with every desirable product all year long, but there are several ways in which our system is quite vulnerable to disturbance. The global food supply network is very homogenous and 85% of countries depend largely on imports (Puma et al., 2015). In the event of food scarcity most exporting countries understandably restrict exports to ensure local food security which leaves many importing countries at risk of food shortages (ibid). The increase in extreme weather events and rising temperatures leaves many countries at risk of decreased agricultural production due to inconsistent yields and crops failures, making it likely that food procurement chains will be faced with increasing numbers of disturbances in the years to come (Masoura, 2024). A recent example like the COVID-19 pandemic exposed how quickly the global supply chain can come to a halt (Pulighe and Lupia, 2020).

Urban agriculture is the act of plant cultivation or animal rearing within cities and their immediate surroundings (Orsini et al., 2020) and it is rising in popularity as an alternative (or supplement) to conventional farming practices to promote sustainability and preparedness. It can take on many different forms such as allotment gardens, rooftop farms and greenhouses, but the majority that is done at a large scale is vertical farming (VF), usually in the form of high-tech systems with controlled environments (Kozai and Niu, 2020). This hyper-local food production system can help to strengthen the local food system by providing a higher yield per unit area and by presenting many opportunities for more tailored solutions or industrial symbiosis (Perambalam et al., 2021, Martin et al., 2019). Other cited benefits of VF include lower usage of water, pesticides and fertilisers compared to traditional farming. However, these systems can also be incredibly energy intensive, requiring significant heating and lighting which can have a very large environmental impact depending on the local energy mix (van Delden et al., 2021). Increased urban food production is often cited as a way to improve the resilience of cities or food systems in general (ibid) but the term is almost always used in a qualitative manner. At a time when decision-making is often guided by the results of LCAs or other quantitative assessments, it is more important than ever to find a way to give resilience a quantitative value so it can compete with other environmental indicators.

2 Aim/Objective

The purpose of this study is to assess the resilience of Stockholm's food system by considering how to give a value to resilience using an LCA. The study will use lettuce as an example to assess the conventional food system and explore how the increased adoption of urban agriculture could make the system more resilient to possible supply-chain disturbance. Having a way to account for resilience in an LCA would make it easier to incorporate into decision-making by providing quantitative results on the environmental benefits, making justification simpler. The study will also visualise to what extent local lettuce production would have to increase in order to fully meet the demand in Stockholm.

2.1 Research Questions

1. How can resilience be integrated into food system LCAs?

2. Can a resilient lettuce-producing system have less negative environmental impacts than a vulnerable one?

3. How can urban agriculture contribute to resilient and sustainable local food systems?

3 Background

3.1 Urban Agriculture (UA) and Vertical Farming (VF)

Urban agriculture (UA) generally refers to any food cultivation occurring within a city or the periurban area (Bousbaine and Bryant, 2020). These can span communal plots, rooftop gardens, personal gardens and others. The goal with many urban agriculture projects skews towards the social impacts, by acting as a communal space for forming social bonds, and as a way to connect people with food growing (ibid). It is generally viewed as a supplement to conventional food production systems which increases its efficiency (Orsini et al., 2020). Most UA faces problems of spatial constraint and land costs as there is generally not much space for agriculture within city limits, additionally, UA has been seen to cause gentrification in some areas as it is seen as a desirable neighbourhood attribute (ibid).

Another form of UA is vertical farming (VF), this refers to a more technological solution which comprises a fully enclosed system where temperature, heat and light are controlled. This type of agriculture is able to produce significant output without competing for urban space as it utilises the vertical space and can operate indoors (Orsini et al., 2020). This type of growing shows promise for creating more resilient food systems as production is less vulnerable to external disturbance.

3.2 Resilience and Sustainability

These terms are used liberally in society and academia but have often been misused and misrepresented. There is a general lack of clarity about their precise definitions, and this can be seen throughout the literature. Resilience especially has proven difficult to form an agreed upon definition. The concept of sustainability has been popular within science and research for many years and resilience has emerged as an important topic more recently, with the largest spike in publications being around 2008 (Pizzol, 2015). Elmqvist et al. (2019) break down the differences in interpretations of the terms sustainability and resilience related to urban settings in both policy documents and recent literature. They cite sustainability in policy as being narrowly viewed as efficiency and optimisation, where social aspects are often overlooked. In literature they acknowledge sustainability having a more nuanced view which considers the importance of a synergistic approach and co-evolution of urban subsystems which are able to develop without harmful impacts on the biosphere. Resilience on the other hand is viewed in policy as simply the ability to recover after disaster events. In literature it is considered to be when an urban system has the ability to maintain or rapidly return to desired functions in the event of a disturbance. In the view of many researchers' resilience is considered to be an essential part of a system for achieving sustainability (Elmqvist et al., 2019).

Over the years the definition of resilience has shifted slightly. Pizzol (2015) identified three integral aspects of resilience that are consistent between authors. The first is that the resilience of a system depends on its structure and architecture, how the different elements are organised and relate to each other. The second is that in ecosystems there is always a fluctuation between resilience and efficiency and that human systems are more likely to consistently prioritise efficiency. Finally, resilience is indeed important for achieving sustainability in a system, requiring the system's ability to maintain its function, or endure change or disturbance (Pizzol, 2015). To understand the resilience of a system one needs to consider what the relevant critical thresholds of collapse are. The further a system can be pushed without collapsing, the more resilient it is (Folke et al., 2010).

An approach to the term which aims to add more nuance is the idea of socio-ecological resilience which takes into consideration the complexity of human and non-human systems and highlights their interdependence on one another (Folke et al., 2010). Using the socio-ecological viewpoint makes it a popular term for use in urban applications where there is a large amount of tension between humans and their environment (Meerow et al., 2016). Resilience is also argued by some authors to be a non-normative term, not inherently referring to a desirable or sustainable state, where it is also possible for an undesirable system to be resilient to change (Elmqvist et al., 2019). This makes it important to be clear about the framing of resilience in its application, considering resilience of *what*, to *what* disturbance, from *whose* perspective, and over *what* time frame (Ingram et al., 2023).

Some studies define different types of resilience, such as climate-resilience, global change-resilience and resource depletion-resilience (Aguilera et al., 2020). Throughout all of these definitions of resilience, adaptability comes out as a very important aspect of a system, showing the importance of complexity and robustness. The importance of this is especially clear when looking at navigating climate change where it is important for systems to be able to withstand both foreseen and unforeseen shocks and relevant thresholds need to be understood (Hunt and Watkiss, 2011).

3.2.1 Food System Resilience

The focus of resilience in this paper is the resilience of the food system (or food supply chain) more so than the resilience of a specific ecosystem or environment, however environmental impacts are what will be used to compare systems. When assessing the resilience of a food system the focus is on the continued functioning of the system. The adaptive capacity of a supply chain is a critical function for resilience and involves preparing for unexpected events and recovering while maintaining continuity of operations at the desired level of connectedness and control over structure and function (Ponomarov and Holcomb, 2009). There is a large body of research on supply-chain resilience, some common strategies that have been suggested for achieving a resilient food system are things such as shorter supply chains, coordinated action between actors, automation or tech solutions, complementing conventional systems with local production and improving processing and waste management (Bakalis et al., 2020). Figure 1 shows a visualisation of a disturbance event to a supply chain and highlights some factors which could improve resilience. An important factor to consider in food system resilience is the importance of decision making in procurement, the main motivation for companies is often financial (Larrea-Gallegos et al., 2022) and if investing in resilient solutions is expensive the only compelling argument may be if a disturbance ends up costing a larger amount.

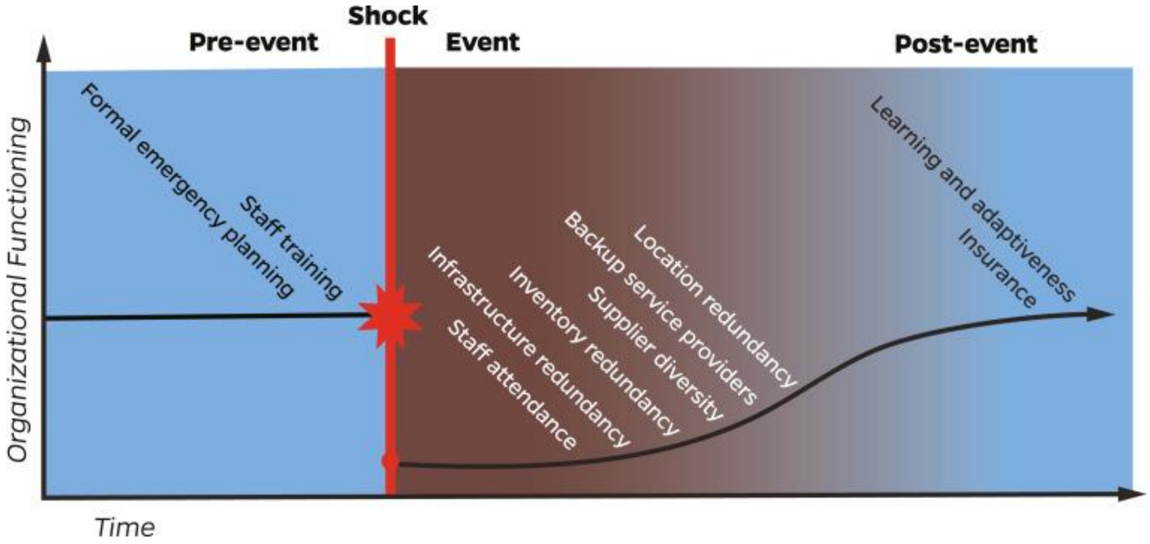


Figure 1: Ten factors identified through semi-structured interviews with food system stakeholders which may affect food system organizational resilience. Mapped along a resilience curve. Source: Hecht et al., 2019

3.3 Current System

As previously outlined, Sweden is a country which imports the majority of its products for consumption and the category of food products is seen to be one of the most polluting in most environmental indicators (Fauré et al., 2019). Efforts are being made to reduce these environmental impacts and increase local resilience, for example Stockholm has a goal of producing 10% of its total food consumption within the city (Stockholm Stad, 2019). Lettuce was chosen as an example for this study as it is a product which is currently being produced in local urban agriculture, but the conventional system still mainly sources lettuce from other countries with warmer year-round climates. The lettuce that is found in stores in Sweden is mainly sourced from Spain, with additional stock coming from Germany, The Netherlands and Italy (see Table 1). In 2019 Sweden imported 17,664 tonnes of lettuce from Spain alone (World Bank, 2019). Spain is one of the largest producers of lettuce in the world and in 2023 produced approximately 865 thousand tonnes (FAOStat-a, 2025) of which 785 thousand tonnes were exported to various countries, equaling 91% of total production (FAOStat-b, 2025). Based on Sweden’s previous imports it can be assumed that only 2% of Spain's exports are going to Sweden. However, Spain is experiencing difficulties in production due to rising temperatures from climate change leading to increased levels of drought (Díaz, 2023). The extent of agricultural production in Spain also poses its own threats to the local environment, as the country is experiencing high levels of fertilizer contamination, when excess nutrients such as nitrogen become overloaded in the soil and accumulate in plants (Romero-Gámez et al., 2014). In addition, the area has been facing increasing levels of soil salinisation due to the proximity to the sea and agricultural irrigation methods (Castañeda et al., 2020).

Table 1. Top four countries exporting lettuce to Sweden, based on data from 2019 (World Bank, 2019)

Export Country	**Lettuce Volume (tonnes)**
Spain	17,664
Germany	2,891
Netherlands	1,926
Italy	1,508

3.4 Disturbance

In this study, disturbance is being considered as it impacts the food supply chain. It can be difficult (or perhaps impossible) to accurately predict the disturbances which will be faced by a system, but looking at trends can allow for some level of anticipation. There is significant research on the predictability of disturbances to general supply chains based on internal disruptions such as machine failure, logistical issues, or ripple effect and these mainly use mathematical projections (Yilmaz et al. 2021, Ivanov, 2022). These types of failures in any part of the system, such as in manufacturing or transportation, have the potential to cause failures to food supply chains (Bakalis et al., 2020), but they are not the main focus of this report.

This report, rather, focuses on disturbances which would lead to potential crop failure in the food supply chain. The most likely related disturbance is climate change, due to increasing temperatures, extreme weather and decreasing and unpredictable water availability. Spain is an important country for food production for the European market and the ESPON (European Observation Network for Territorial Development and Cohesion) has previously identified Spain as one the European countries which will be the most heavily impacted by climate change, in aggregated impacts (ESPON, 2011). Studies using historical and projected data of extreme weather events are becoming more commonplace as a means to anticipate and quantify risks (Hunt and Watkiss, 2011). Figure 2 shows the average surface air temperature in southern Spain over the past 100 years, demonstrating the severity of rising temperatures in the region and showing a trendline indicative of potential future impacts. This makes it clear that there is reason to anticipate disturbance to the current system and that it is likely to increase in severity in the coming years, making the refining of climate projection techniques an important task.

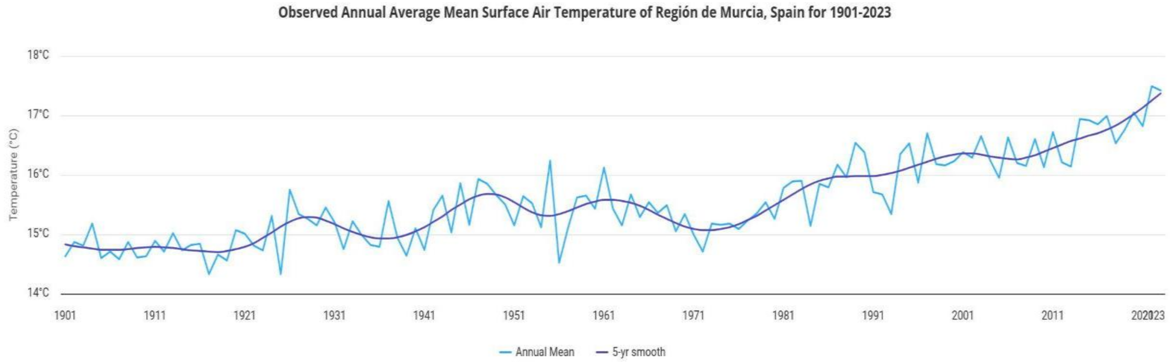


Figure 2. Annual average mean surface air temperature in southern Spain. Source: World Bank Group - Climate Change Knowledge Portal

There are also several other sources of disturbance which may impact crop production or availability and may be unforeseen such as pandemics, natural hazards, operational contingencies, political instability or geopolitical unrest which can also have dramatic implications for global food supply chains (Larrea-Gallegos et al., 2022). An example of how geopolitical unrest can impact the food supply chain is the Ukraine which was previously considered the "bread-basket of Europe" and due to the conflict with Russia has no longer been able to produce or export these staple agricultural products (Masoura, 2024). These supply chain shocks can extend to less violent conflict such as trade embargos, restrictions and tariffs (ibid). Another current example is the newly elected President Trump in the United States imposing tariffs on several countries which will have significant implications for global food supply chains, but these have yet to be fully realised (Coyne, 2025).

4 Life Cycle Assessment - Theory

Life-cycle assessment is a tool which was developed to help improve environmental decision-making by making it easier to understand increasingly complex globalised systems and quantify environmental impacts. One selects a single product or service and systematically maps out all of the products and activities associated with its full life cycle from resource extraction to end-of-life waste (European Commission, 2010). Every component (input/output) is then tied to an environmental impact related to environmental indicators creating numerical impact values. LCAs must abide by the standards set out by the International Organisation for Standardisation (ISO) when designing the study and designating the goal and scope which ensures replicability and reliability of results (ISO 14040:2006). The necessary components of an LCA are shown in Figure 3, below, which consist of (1) Goal and scope definition, (2) Inventory Analysis, (3) Impact Assessment, and (4) Interpretation. As a tool LCAs have been improving and evolving over time. New techniques are being developed such as social LCAs, life-cycle costing, and prospective LCAs where future scenarios are modelled (Finnveden et al., 2009).

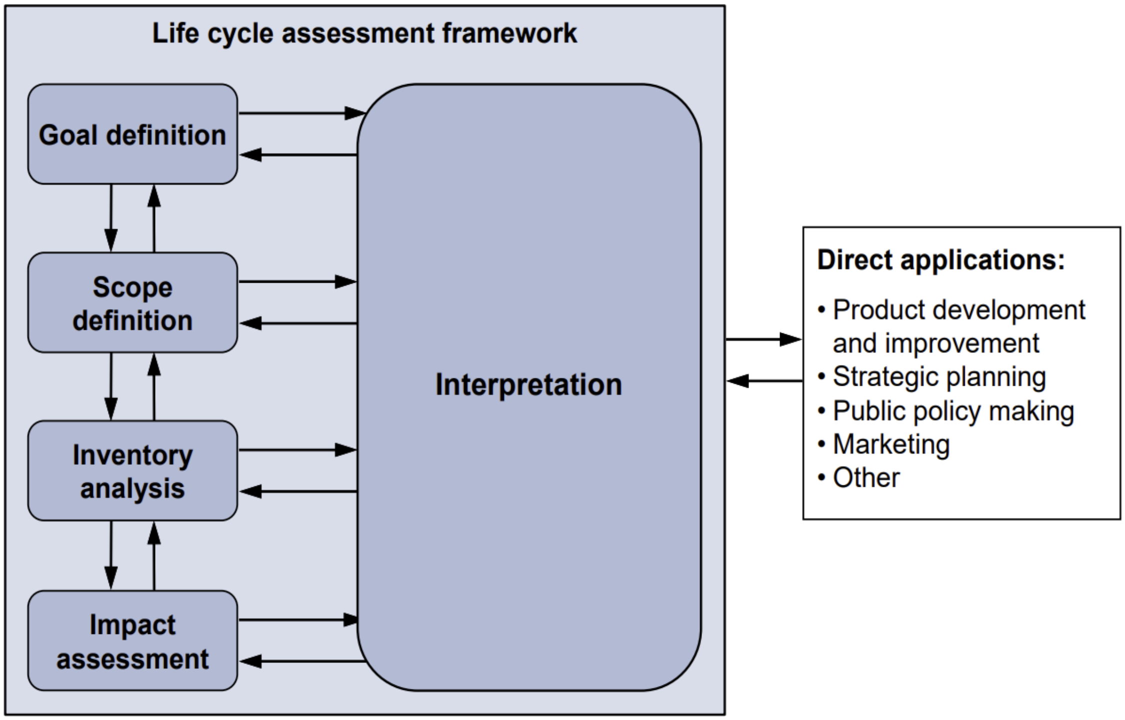


Figure 3. Framework for life cycle assessment based on ISO standards (European Commission, 2010).

4.1 Goal and Scope Definition

This first step in forming an LCA involves defining the aim of the study. It should be made clear why it is being conducted and what the intended uses are of the results, as well as clarify limitations based on the assumptions and the method (European Commission, 2010). Two common forms of LCA are attributional LCA (ALCA) and consequential LCA (CLCA), the former is when one product or service is chosen and assessed and generally uses average data and the latter is a comparison between two systems based on marginal changes within a system (Pizzol, 2015). LCAs allow for minimizing trade-offs between two alternatives of the same functional unit (FU), which is the designated unit of the LCA which fulfils the intended function. It also avoids burden shifting by clearly showing where in a product's life cycle impacts are occurring, referred to as hot spots (Cucurachi et al., 2019). The choices made here depend on the intended outcomes of the study.

The determining of a functional unit (FU) is an important step, as it is what all data will be scaled to as a reference unit. The only time a comparison can be made between LCAs is when the FU and assumptions made are the same for both systems. Another critical aspect is defining the life-cycle boundaries. Studies can choose to focus on different parts of a life cycle such as cradle-to-gate, cradle-to-shelf, or cradle-to-grave. The system boundary should be clearly delineated here showing which are foreground and background processes (European Commission, 2010). Foreground processes are those which are the main focus of the study and will be modelled and background processes are those which are necessary for the function but will not be modelled and rather employ datasets. The goal and scope section should also identify the impact assessment method and the environmental indicators which will be employed in the analysis.

4.2 Life Cycle Inventory (LCI) Analysis

The next phase of an LCA includes the amalgamation of all the data required to represent the chosen product or service and is known as the life cycle inventory (LCI). Data should be as dependable as possible, ideally using first-hand data or reputable sources. The availability and quality of data often poses the largest issue for an LCA, and it is advisable that an iterative approach is used where a base model is created and then improved upon little by little through the addition of more reputable and nuanced data (European Commission, 2010). This data should be scaled to the FU and assumptions and calculations should be tracked during this process to allow for transparency and reproducibility.

4.3 Life Cycle Impact Assessment (LCIA)

This phase translates the data previously acquired into environmental impacts. One can choose between two different types of impact assessment for an LCA, either mid-point or end-point. A mid-point evaluation assesses the environmental impacts of different individual environmental problems while an end-point assessment considers aggregated effects on human health, biodiversity or resource scarcity (European Commission, 2010). End-point results may be more relevant but require a much higher level of data accuracy, thus when using marginal data, it is preferable to use mid-point indicators. One of the main methods for assessing midpoint indicators is the Environmental Footprint method which identifies 15 distinct impact categories with their own units for comparing environmental impacts, listed here in Table 2.

Table 2. The indicators of Environmental Footprint v3.1. Bolded categories will be used as indicators in this report and will be explained further.

Impact Category	**Unit**
Climate Change	**kg CO_2 eq**
Ozone Depletion	kg CFC-11-Eq
Ionizing Radiation	kBq U235-Eq
Fine Particulate Matter Formation	disease incidence
Ozone Formation	kg NMVOC-Eq
Fossil Resource Use	**MJ. net calorific value**
Acidification	**kg mol H^+-Eq**
Freshwater Eutrophication	**kg PO4-Eq**
Marine Eutrophication	kg N-Eq
Human Toxicity, Cancer and Non-Cancer	CTUh

Terrestrial Eutrophication	mol N eq
Freshwater Ecotoxicity	**CTUe**
Land Use	**dimensionless**
Water Use	**m^3 world eq. deprived**
Mineral and Metal Resource Use	**kg Sb-Eq**

4.4 Interpretation

The final step of interpretation aims to understand and convey the results from the LCI and LCIA. This part is crucial for the accurate communication of results as, depending on the goal and scope, these results could be used for decision-making or product labelling. A study may choose to normalise or weight the results to show their relative importance which can be useful when there are trade-offs between indicators (Finnveden et al., 2009) as well as assisting with the communication of results. This section also works as a discussion where limitations and uncertainty should be acknowledged. An optional step to test for uncertainty is a sensitivity analysis which could be conducted here which measures how results change when parameters are changed systematically, allowing you to know if your results are highly dependent on the selection of certain datasets.

5 Methodology

5.1 Life Cycle Assessment

5.1.1 Goal and Scope

The goal of this study is to assess the difference in environmental impacts between a resilient and a vulnerable food system while under disturbance. This presents a more theoretical approach to LCA which aims to test methodology by taking a formula proposed by Pizzol (2015) for accounting for resilience in an LCA. Normally, the focus of an LCA is primarily concerned with sustainability as it was defined in Section 3.2. This is because an LCA represents a system in a static state or only with marginal changes, making it predisposed to value efficiency over resilience, as a system will likely have the lowest absolute environmental impacts when at its most efficient (Pizzol, 2015). However, resilience is often cited as an important aspect of sustainability and should be accounted for in some way, even though it is difficult to quantify. In his paper "*Life Cycle Assessment and the Resilience of Product Systems*", Pizzol (2015) outlines a theoretical framework for how to incorporate resilience into the quantitative assessment tool of LCA. He acknowledges that not all aspects of resilience will be able to be accounted for within the LCA framework as these models are inherently based on modelling partial equilibrium, with constant input/output flows, meaning the aspect of system recovery over time is necessarily omitted. A disturbance to the conventional system would require a change in structure that is likely much less efficient than conventional operation, and these impacts should be considered. The focus is therefore on the disturbance conditions and includes modelling the environmental impacts of the conventional system under disturbance compared to a proposed resilient system. The resilient system will require much larger system boundaries which must include up and down-stream processes which would be impacted by measures employed to prevent disturbance.

To measure the impacts of a conventional system under disturbance, the following formula (1) has been proposed:

$$A * (1 - d) + B * d = Impact\ Total \qquad (1)$$

Where A is the current or vulnerable system with no disturbance and B is the system altered under disturbance which no longer performs its function properly. These letters represent the values of the different environmental indicators of the systems being modelled. The d is the percentage of disturbance days per year which ensures that the correct ratio of impacts is considered.

This allows for calculating the true environmental impact by adding the environmental impacts of the system as it performs under different rates of disturbance. Pizzol (2015) then suggests plotting the environmental impacts under different probabilities of disturbance versus the proposed resilient system which could withstand said disturbance without changing the systems structure. This would show at what point a resilient system is less environmentally impactful than the conventional structure.

The case chosen to evaluate this is the food system, specifically comparing lettuce production and sourcing systems for Stockholm. In the agri-food domain, LCA has been a popular tool which can help to inform the most effective policy measures and assist environmentally conscious decision making (Gava et al., 2019). However, the food system is vulnerable to the increasing streamlining of pathways, bottlenecks of distribution, and its own environmental impacts which may hamper future crop productivity. Many papers conducting LCAs of food products cite resilience as a necessary aspect of improving food systems and as motivation for their work, however they do not actually incorporate any resilience thinking in their methodology (i.e. Martin-Gorriz et al., 2020). When lettuce is no longer available from Spain, it needs to be sourced from elsewhere and for this study both Dutch and American production systems were modelled as alternatives for sourcing during disturbance. The resilient system, which will be used for comparison, was deemed to be 50/50 vertical farming (VF) in Stockholm and open field (OF) in Spain. During the process of this research, the original equation by Pizzol was deemed to not appropriately account for certain scenarios of crop failure, and alternative equations were developed which will be fully explored in the results and analysis sections of this report.

This report employs OpenLCA (v 2.4) for modelling the food system and data is from the Ecoinvent (v 3.10) database. The impact assessment method chosen is Environmental Footprint v3.1.

5.1.2 Functional Unit

The functional unit (FU) was chosen to be: **1kg of edible packaged lettuce supplied by a food system that is able to meet total demand in Stockholm even in the event of supply-chain disruption**. This is based on what Pizzol (2015) outlines in his proposed framework, as he specifies that for a comparison to work, the scope needs to be expanded to include disturbance scenarios in the functional unit. Most studies of lettuce or other agricultural products use a simple FU of 1kg of said product. Making the FU for this study to be 1 kg of lettuce within a disturbance-proof system allows for easier data collection and communicability within the field.

5.1.3 System Boundaries

This study employs a consequential LCA which is best suited for performing comparisons between systems. This means things which are present in all modelled systems can be ignored as part of the system cut off. Therefore, the systems remain quite simple to highlight only the differences; life-cycle stages such as packaging are excluded as they are assumed to be almost identical for all systems. Washing is required for all systems except the VF, but this step was omitted from the model in accordance with source data. The system boundaries are set to be cradle to supermarket shelf as the processes after purchase would also be redundant in a comparison. Two diagrams, in Figures 4 and 5, show the plotted system boundaries for the open field (OF) farms and for the combined greenhouse (GH) and vertical farms (VFs).

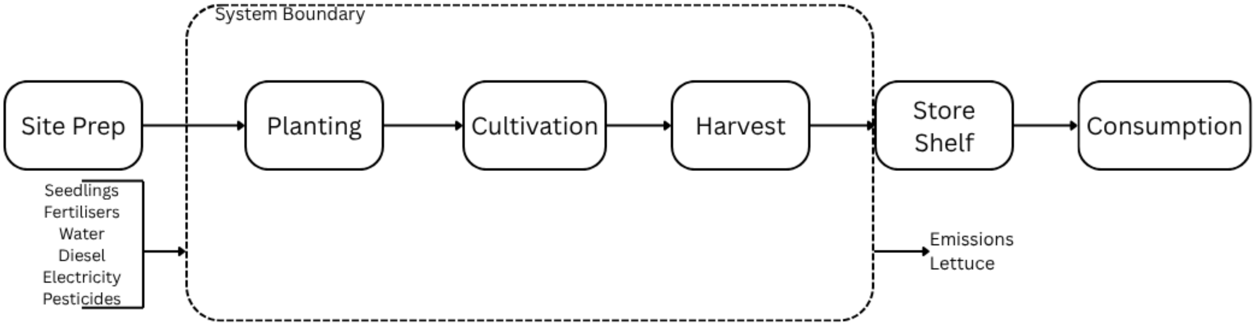


Figure 4. System boundary of OF farm systems, comprising production in both Spain and the USA. Transportation is required for shipping crops from farm to store but is not modelled here.

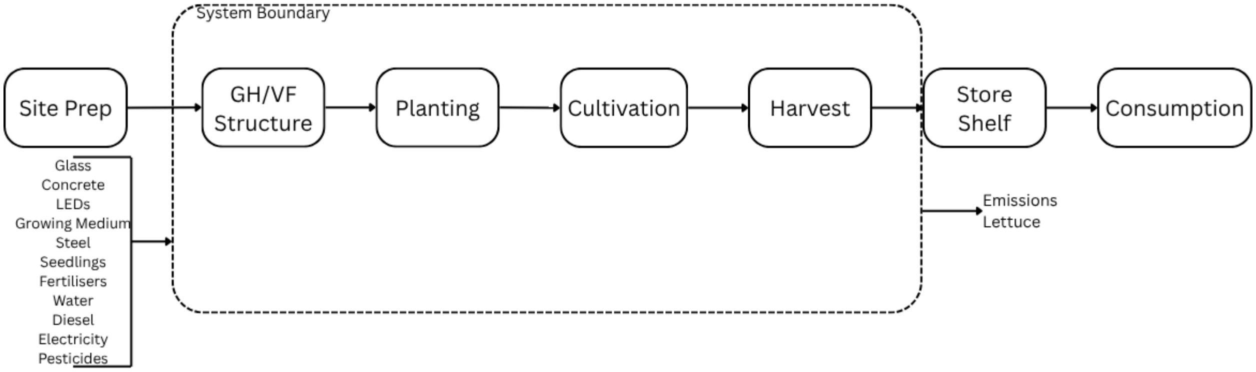


Figure 5. System boundary of semi-closed and closed farming systems, comprising GH production in the Netherlands and VF in Sweden. Transportation is required for shipping crops from farm to store but is not modelled here.

In terms of geographic boundary, Stockholms stad is the boundary as the system under review and the location of the VF scenario. For the conventional production system, the system boundary includes Spain where most lettuce available in Sweden is sourced from, specifically southern Spain (Murcia) where the climate is most favourable (Romero-Gámez et al., 2014). During disruption scenarios the boundary includes both the Netherlands and the USA (Arizona) as the sites of production.

The system is modelled as if all lettuce consumed in Sweden is from Spain, even though it is only the largest of several exporters. Table 3 shows the actual availability of lettuce in all systems being compared. The scenario where lettuce is sourced from the Netherlands during disturbance is not necessarily realistic since they produce at different times of the year, but it still provides a good proxy for European GH lettuce. When choosing an American lettuce to model, the Arizona production was chosen as it has the same growing season as Spanish lettuce and would therefore be available when most needed. In comparison, the lettuce sourced from a Swedish VF would be available all year long.

Table 3. Monthly lettuce availability in all scenarios, Sweden (SE), Netherlands (NL), Spain (ES), and USA and specifying whether production is from open field (OF) greenhouse (GH) or vertical farm (VF). Sources: Martin, Elnour, Siñol 2023, Hofotra nd, HortiDaily 2023, USDA 2023, ibid

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SE-VF	x	x	x	x	x	x	x	x	x	x	x	x
NL-GH					x	x	x	x	x	x		
ES-OF	x	x	x	x							x	x
USA-OF	x	x	x	x							x	x

5.1.4 Impact Assessment Method and Environmental Indicators

For this study the Environmental Footprint v3.1 (mid-point) assessment method was chosen as it represents more accurate results than endpoint indicators and identifies a broader range of categories. Based on similar food systems research (Cabrero Siñol and Martin, 2025), the following 8 indicators were chosen which are the most relevant for agricultural impacts: (1) acidification, (2) climate change, (3) freshwater ecotoxicity, (4) freshwater eutrophication, (5) land use, (6) fossil resource use, (7) mineral and metal resource use and (8) water use.

Perhaps the most pressing category is **Climate Change** (kg CO_2 eq) also referred to here as Global Warming Potential **(GWP)** which measures the extent of greenhouse gas (GHG) emissions to the atmosphere. These emissions are the main drivers of human-caused climate change which work to absorb infrared radiation rather than let it escape, thereby warming the climate (European Commission, 2010-b). This category, while being very important, is also one of the easiest to communicate.

Several of these indicators focus more heavily on the impacts of fertilizers on the environment. Firstly, **Acidification** (kg mol H^+-Eq) measures the extent of change of pH caused by the system in question. The acidification is most often due to nitrogen oxides, sulphur dioxide and ammonia which end up impacting the soil (ibid). Similarly, **Freshwater Eutrophication** (kg PO4-Eq) is due to nutrient overload in aquatic systems from nitrogen and phosphates which lead to imbalances in the environment and can cause algae blooms and oxygen depletion which can be devastating to species composition. **Freshwater Ecotoxicity** (CTUe) on the other hand is about chemicals released into the environment where the long-term effect could lead to bioaccumulation (European Commission, 2010-b). This is a common impact due to processing activities and will be relevant for the production of infrastructure in the system.

The other four indicators all deal with some type of resource depletion. **Land Use** (dimensionless) and **Water Use** (m^3 world eq) are especially relevant for agriculture as food production takes up about half of habitable land and about 70% of the freshwater withdrawals (Ritchie et al., 2022). The systems being modelled should also have dramatically different results for these indicators as vertical farming uses significantly less land and water than traditional farming. Similarly, **Mineral Resource Scarcity** (kg Sb-Eq) and **Fossil Resource Use** (MJ. net calorific value) account for the depletion of resources which are non-renewable and their impact categories are based on the decreased future availability (European Commission, 2010-b).

5.2 Quantifying Disturbance

The premise of this work is seeing how incidents of disturbance would impact the lettuce sourcing of Sweden. Therefore, a critical aspect is in quantifying disturbances. Projections show that Mediterranean climates will experience higher levels of climate change impacts and will likely become arid within the 21st century (Aguilera et al., 2020). Spain struggles, and will continue to struggle with climate change more than many other countries within Europe. Areas such as southern Spain are predicted to experience a rise in temperature 20% higher than the average increase seen by other countries, alongside a reduction in precipitation (Lionello and Scarascia, 2018). For the purposes of this study, disturbance is expressed as days that lettuce is not available from Spain, which is a figure representing the amalgamation of disturbances which span environmental, social/political, supply chain, or disaster (natural or pandemic), however the main focus is on extreme weather-related effects in accordance with Puma et al. (2015).

A paper by Caparas et al. (2021) aimed to project rates of breadbasket crop failures based on temperature, precipitation and atmospheric CO_2 on yields. While lettuce is not a breadbasket crop, their results are considered an adequate proxy. According to Caparas et al. (2021), a crop failure is considered to be when agricultural yield is at least 10% lower than the average yield in the present period. Between the years 2022-2023 agricultural production in Spain fell by -13.6%; significantly higher than any other European country (Díaz, 2023). This change also exceeds the 10% loss which would be considered a crop failure by Caparas et al. (2021). Using 2000-2010 as the baseline of the present period, Spain has experienced three crop failure years in the past 13 years (see Figure 6), and the production is trending down (FAOstat, 2025-a). The results from Caparas et al. (2021) have projected that crop failures will be up to 4.5 times more likely by 2030 and up to 25 times more likely by 2050. In order to calculate disturbance scenarios, different probabilities of overall disturbance leading to crop failure were systematically calculated to see at which point environmental impacts favoured a resilient system. In essence, quantifying disturbance for use in an LCA is a form of prospective LCA as it involves scenario building of possible outcomes.

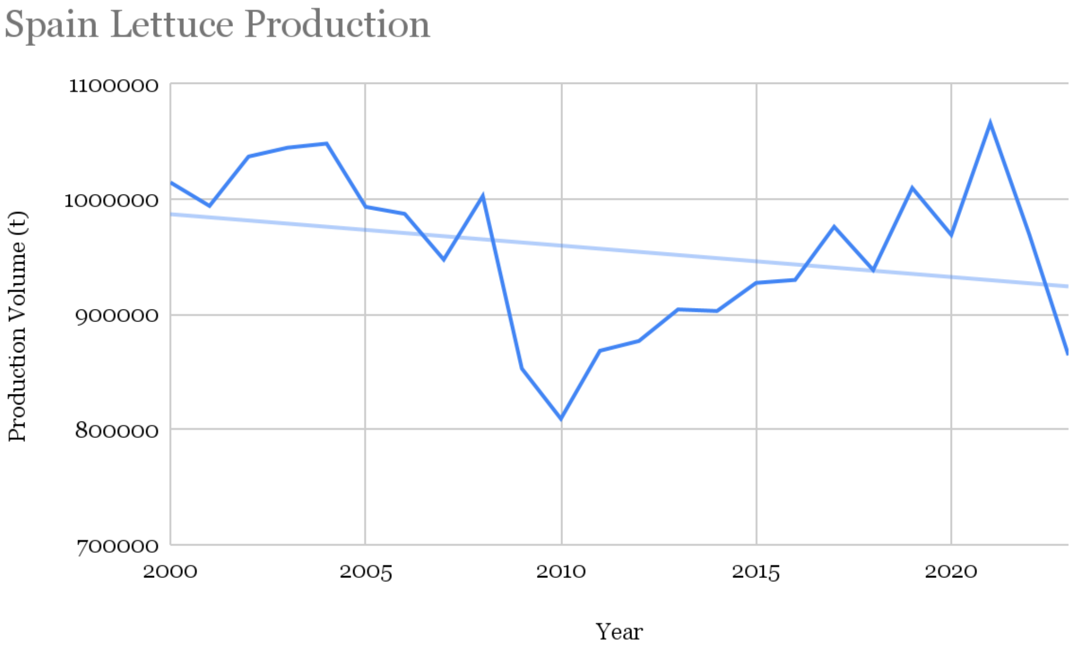


Figure 6. Spain's total lettuce production between 2000-2023, showing a trendline. Source: FAOstat 2025-a

5.3 Life Cycle Inventory (LCI)

The systems modelled here are simplified to allow for a general comparison and do not reflect an in-depth assessment of a single system and therefore results should not be used for other applications. Data was mostly collected from existing LCAs doing similar comparisons, but which do not include considerations of resilience. There are four systems modelled which are involved in the coming resilience calculations. The first is the base model which is the conventional or vulnerable system where 100% of Sweden's lettuce is considered to come from OF farms in Southern Spain. Then there are two disturbance scenarios modelled (disturbance scenario-1) which is the base model supplemented by Netherlands GH lettuce under disturbance, and (disturbance scenario-2) which is the base model supplemented by OF lettuce production in the southern United States which is another sourcing option under disturbance conditions. Finally, a local food system for Stockholm, Sweden in the form of VF lettuce which will be the backbone of the resilient system proposed in Section 6. Data for the Spanish and American production comes mainly from a comparative paper by Casey et al. (2022) who have compared the environmental impacts of lettuce production in different countries using LCA. Their Spanish data is largely based on a study by Canals et al. (2008) which is a primary source. The same paper also provides data on hydroponic vertical farming which was used in part to inform the VF system; however, this was supplemented by a more in-depth primary source of an LCA on an actual VF in Stockholm (Martin, Elnour and Siñol, 2023). Finally, data on the Netherlands GH system comes primarily from Blom et al. (2022) who modelled several types of lettuce farming within the Netherlands.

The Spanish system is set in Murcia, Spain and consists of OF production as it is the most common farm type in that area as it has one of the more appropriate climates for outdoor lettuce production (Romero-Gámez et al., 2014). Several fertilizers are used at relatively high concentrations to account for runoff, a significant amount of manure is also used to supplement the synthetic fertilizers (Casey et al., 2022). Irrigation is assumed to be from drip irrigation using local tap water.

The Dutch system is set in Utrecht as a relatively central location. This is a semi-closed hydroponic GH system which could be operated in any part of the country. A structure is used which is constructed with a metal frame and glass walls, it uses a mixture of passive and mechanical strategies to achieve ideal growing conditions (Blom et al., 2022). Natural light is almost exclusively used for the required light, and it also provides the majority of heating. Any supplementary heat required uses natural gas. Other passive strategies include natural ventilation. As a semi-closed system several fertilizers are required, however runoff is less problematic. Watering is done through a hydroponic structure using local tap water.

The production in the USA is set in the desert of Arizona as this lettuce has the same growing season and availability as Spanish lettuce. This system is an OF farm as that represents the majority of production in the USA. Similarly to the Spanish production, several fertilizers are used to support the growth of lettuce however here only synthetic fertilizers are used, and no manure is added. Watering is assumed to be done using drip irrigation and significantly higher rates of water are required to account for the arid conditions.

In Stockholm, Sweden the production of lettuce is through VF technology which has been steadily gaining in popularity in recent years, this specific system is based on an existing system called Ljusgårda. This is a fully closed system which means it can operate under any weather conditions; however, it requires more significant inputs to replicate ideal growing conditions. Ljusgårda is set up in an old warehouse and required extensive high-tech infrastructure in the construction, for components such as vertical racks and lighting systems. A wider range of different fertilizers are employed to balance soil nutrients. For this system, water is trickled through the vertical racks and kept within the system making it very efficient on water inputs. Using vertical space for growing allows for a higher yield than anything that could be achieved with other forms, even including the space needed for other related activities (Martin, Elnour and Siñol, 2023).

The phases of the LCI have been split into the following categories for all systems: infrastructure, growing media, fertilizers, cultivation, transportation, and emissions. This section will outline the quantities of each input of the different life-cycle stages. Post-harvest processes such as cleaning and packaging for all systems are considered to be done on the respective sites of production and with identical materials and are therefore omitted. Table 4 shows the overview of all systems, and each stage will be explored in further detail. A list of the full names of the Ecoinvent datasets used is available in Appendix I.

Table 4. Life cycle inventory representing 1kg of store grade lettuce produced in each system, not accounting for losses.

Stage	Description	ES-OF	NL-GH	USA-OF	SE-VF	Unit
	Yield	69,100	532,000	40,000	742,800	kg/ha
Infrastructure	Steel Structure	-	1.38E-02	-	1.40E-01	kg
	Aluminium	-	3.52E-03	-	8.70E-03	kg
	Pumps	-	-	-	2.87E-04	unit
	Reinforced Concrete	-	5.70E-06	-	-	kg
	Glass	-	1.49E-02	-	-	kg
	Polyester	-	1.82E-04	-	-	kg
	PVC	-	9.08E-03	-	-	kg
LED lights	Aluminium	-	-	-	1.11E-02	kg
	Diodes	-	-	-	3.57E-04	kg
	HDPE	-	-	-	1.70E-03	kg

	Wire	-	-	-	6.90E-04	kg
Growing Medium	Peat Moss	-	-	-	2.90E-04	m3
	Rockwool	-	1.14E-02	-	-	kg
	Coco Fiber	-	-	-	1.17E-01	kg
Fertilisers	Nitrogen	1.30E-02	1.33E-03	5.00E-03	-	kg
	Phosphate	1.00E-02	8.60E-04	4.00E-03	-	kg
	Potassium	-	1.84E-03	3.00E-03	1.56E-03	kg
	Potassium nitrate	-	-	-	4.30E-03	kg
	Potassium sulfate	-	-	-	1.83E-03	kg
	Calcium	-	-	-	4.27E-02	kg
	Magnesium	-	6.19E-05	-	2.20E-03	kg
	Nitric Acid	-	-	-	4.63E-04	
	Lime	-	-	6.50E-02	-	kg
Cultivation	Electricity	5.90E-02	1.37E+00	3.30E-02	9.92E+00	kWh
	Diesel	2.64E-01	-	8.80E-01	-	MJ
	Natural Gas	-	8.84E-02	-	-	m3
	Carbon enrichment	-	3.52E-01	-	1.04E-01	kg
	Pesticides	3.00E-04	5.92E-05	2.00E-04	-	kg
	Seedlings	1.45E+00	4.72E+00	-	-	unit
	Seeds	-	-	5.99E-03	1.65E-04	kg
	Water	5.82E+01	1.54E+00	9.26E+01	1.06E+01	L
Transportation	Sweden Road Transport	-	-	4.20E-02	5.00E-03	tkm
	Europe Road Transport	3.55E+00	1.42E+00	-	-	tkm
	Air Transport	-	-	8.90E+00	-	tkm
Emissions	N2O to air	1.00E-04	-	1.00E-04	-	kg
	NH3 to air	2.00E-03	-	9.00E-04	-	kg

	CO_2 to air	8.00E-03	-	3.60E-02	-	kg
	N to water	1.00E-03	-	1.00E-04	-	kg
	P to water	1.00E-04	-	-	-	kg

5.3.1 Infrastructure

The infrastructure phase for these systems encompasses the site preparation and building requirements needed for these systems to be able to produce lettuce, see Table 5. The two OF systems require no infrastructural inputs as the farms have been established for some time. The GH system requires building materials to construct the actual structure, which includes metal and glass, as well as polyester and PVC to build the hydroponic structures. The VF operates in a building which was reclaimed from other purposes and therefore the building itself is not included. The infrastructure for this system comprises the materials needed for operations such as hydroponic structures, carts, rollers and irrigation systems. The VF is the only fully closed system, meaning it is the only system to require LED lights, shown separately in Table 6. The modelling of the LED lights is based on modelling by Martin, Elnour, and Siñol (2024). These systems are simplified to show the biggest contributors.

Table 5. Required infrastructure for the production systems with Ecoinvent datasets

Infrastructure	Dataset
Steel Structure	chromium steel 18/8 steel, low-alloyed
Aluminium	aluminium alloy, AlLi
Pumps	40W pump
Reinforced Concrete	normal strength concrete
Glass	flat glass, uncoated
Polyester	polyester fibre
PVC	emulsion polymerised polyvinylchloride

Table 6. Required infrastructure for LED lights with Ecoinvent datasets

Infrastructure	Dataset
Aluminium	section bar extrusion, aluminium
Diodes	light emitting diode
HDPE	high density, granulate polyethylene
Wire	cable, unspecified

5.3.2 Growing Media

The OF systems of Spain and the USA rely only on naturally occurring soils with the later addition of fertilizers, while the GH and VF systems require the sourcing of growing media. The Dutch system uses exclusively rockwool and the Swedish VF uses a combination of peat moss and coco fiber, see Table 7.

Table 7. Required growing media for the production systems with Ecoinvent datasets

Growing Media	Dataset
Peat Moss	market for peat moss
Rockwool	market for packed stonewool
Coco Fiber	market for coconut husk

5.3.3 Fertilizers

The fertilization of crops is a significant aspect of all four systems modelled. The heaviest user of fertilizers is Spain who, on top of synthetic fertilizers, also use a significant amount of manure. The VF system also uses a considerable amount of fertilizer as it needs to make up for being a fully closed system where nutrients cannot be acquired in any other way. The Dutch GH and American OF use fertilizers to a similar extent, while exact inputs differ slightly based on local soil quality. Datasets used for some fertilizers are country specific, while most others are given for Europe or Rest of World (RoW). Table 8 shows the Ecoinvent datasets used.

Table 8. Required fertilizers for the production systems with Ecoinvent datasets

Fertilizers	Dataset
Nitrogen (N)	market for inorganic nitrogen fertiliser
Phosphate (P_2O_5)	market for inorganic phosphorus fertiliser
Potassium (K_2O)	market for inorganic potassium fertiliser
Potassium nitrate (KNO_3)	market for potassium nitrate, agricultural grade
Potassium sulfate	market for potassium sulfate
Calcium	market for calcium nitrate
Magnesium	market for magnesium sulfate
Nitric Acid	market for nitric acid
Lime	lime for soil pH raising agent

5.3.4 Cultivation

The cultivation step includes all the inputs which are necessary to produce lettuce during the growing phase which are not fertilizers, these are listed with their EcoInvent datasets in Table 9. The scenarios differ in how the lettuce is planted, both the Spanish and Dutch systems use seedlings, which are grown in unheated and heated greenhouses respectively, these have been modelled as strawberry seedlings as a proxy in accordance with source literature (Blom et al., 2022, Mìla i Canals et al., 2008). The Swedish VF and American systems both employ direct sowing of seeds which has been modelled here as grass seeds in accordance with similar literature (Martin, Elnour & Siñol, 2023, Tourte et al., 2017). All scenarios require electricity for their general operations but at very different levels, the two OF systems and the Dutch GH which relies on natural sunlight require significantly less than the VF system which uses electricity to generate all of the necessary light for plant growth as well as for heat generation. In the Dutch GH, natural gas is used to generate heat based on the system modelled by Blom et al. (2022). Similarly, water use differs significantly where the VF is the most water efficient since it is a closed system and the OF farms have the highest demand. Pesticides and diesel used in agricultural machinery are only used in both OF systems, whereas carbon enrichment is only required in the GH and VF systems.

Table 9. Required cultivation inputs for the production systems with Ecoinvent datasets

Cultivation	Dataset
Electricity	electricity, medium voltage
Diesel	diesel, low-sulfur
Natural Gas	market for natural gas, low pressure
Carbon enrichment	market for liquid carbon dioxide
Pesticides	market for pesticide unspecified
Seedlings	strawberry seedling in heated/unheated GH
Seeds	market for grass seeds
Water	market for tap water

5.3.5 Transportation

The transportation phase refers to whatever method was used to move the lettuce from these different production systems to central Stockholm; methods used are shown in Table 10. The final destination for all of the lettuce was set to be T-Centralen for simplicity of comparison. The lettuce produced in a VF in Stockholm was considered to have a 5 km distance since it is grown within city limits and is based on the location of an existing VF in the city. Being such a short distance, it is assumed that this transportation would not require a refrigerated lorry. Both the Spanish OF and the Dutch GH lettuce are assumed to be delivered by a larger refrigerated lorry and come directly to T-Centralen rather than stop at a warehouse first, taking 3550 km and 1415 km, respectively. The only system requiring air transport is the American grown lettuce which needs to be moved 8700 km within a short timeframe to preserve product freshness which rules out any transportation by water.

Table 10. Required modes of transportation for the production systems with Ecoinvent datasets

Transport	Dataset
Sweden Road Transport	market for transport. freight lorry 3.5-7.5 metric ton. EURO5
Europe Road Transport	market for transport. freight lorry with refrigeration machine, 7.5-16 ton. EURO5. R134a refrigerant
Air Transport	market for transport, freight aircraft with reefer, cooling

5.3.6 Emissions

This section refers to some other outputs from lettuce production which are detrimental to the environment, shown in Table 11. These are directly linked with the addition of fertilizers and pesticides in the production of lettuce. Due to the different natures of the production systems the majority of these emissions are related to the OF farms in Spain and the USA. Because these systems are in regular agricultural land and not contained in a closed or semi-closed system these additives can seep into the surrounding environment through the water used for irrigation. The Dutch GH has N2O emissions as it is only a semi-closed system and the VF has no direct emissions as it is a fully closed system. These emissions are based on values cited in literature of the LCAs used for system modelling. The emission datasets themselves were created in OpenLCA and linked to the relevant compounds.

Table 11. Emissions related to the production systems with created Ecoinvent datasets

Emissions	**Dataset**
N2O to air	N2O (Nitrogen Oxide) Emissions
NH3 (Ammonia) to air	NH3 (Ammonia) Emissions to air
CO_2 to air	CO2 Emissions "from soil or biomass" to air
N to water	Nitrogen (N) to water
Phosphorus (P) to water	Phosphorus (P) to water

6 Disturbance and Resilience Scenarios

In order to perform calculations of disturbance scenarios, a resilient system is first needed to be defined as a comparison. For the purpose of this research a resilient lettuce producing system for Stockholm is considered to be when 50% of lettuce is produced locally. Since leafy greens like lettuce are a crop that is well-suited for vertical farming, the most sustainable solution would be to have it grown as close as possible to the consumers. The proposed resilient system maintains the other 50% of lettuce as coming from Spanish OF farms. Spain has so far been a reliable source and a significant producer of lettuce and maintaining more linkages is in the best interest of a resilient system which requires redundancies and flexibility in sourcing. VFs often represent a large environmental impact compared to more traditional farming methods, but impacts are often cited as being heavily dependent on the specific design and energy source (Casey et al., 2022). When these two systems are combined in an LCA and compared to disturbance scenarios their impacts may seem less significant.

6.1 Disturbance Scenario 1- Production in the Netherlands

Identifying the most likely alternative source of lettuce for Sweden in the event of a disturbance that would take Spanish lettuce off the market requires making some assumptions. Sweden is a relatively small player in the global food supply chain, with a relatively low population and limited production in comparison with other European countries. Spain is Europe's largest lettuce producer, growing 26% of the total grown in Europe (FAOStat-a, 2025). Even though Sweden imports almost all their lettuce from Spain, there are several countries which import significantly higher quantities of Spanish lettuce, as shown in Table 12. It is assumed here that if Spain had reduced capacity, it would favour their largest importers. The Netherlands was chosen as an alternative source of lettuce as they are one of the next highest exporters to Sweden, as previously shown in Table 1. While the Netherlands also sources lettuce from Spain, the other production and logistics are assumed to be static which would suggest that they would still have the capacity to export to Sweden at a slightly higher volume. The Dutch production also represents a different style of growing using GH systems which are easier to regulate for ideal growing conditions than traditional OF farms. The country is also expected to experience less negative climatic impacts than Spain.

Compared to Spain the Netherlands produces very little and while it had an increase in production in recent years the most recent data shows a sharp decline (see Figure 7). Despite this, the Netherlands still currently produces enough to fulfil Sweden's demand.

Table 12. Top seven countries importing lettuce from Spain, based on 2023 data. (World Integrated Trade Solutions, 2023)

Importing Country (from Spain)	**Lettuce Volume (tonnes)**
Germany	85,793
France	79,806
Italy	25,165
Netherlands	23,842
United Kingdom	23,557
Poland	20,603
Sweden	11,180

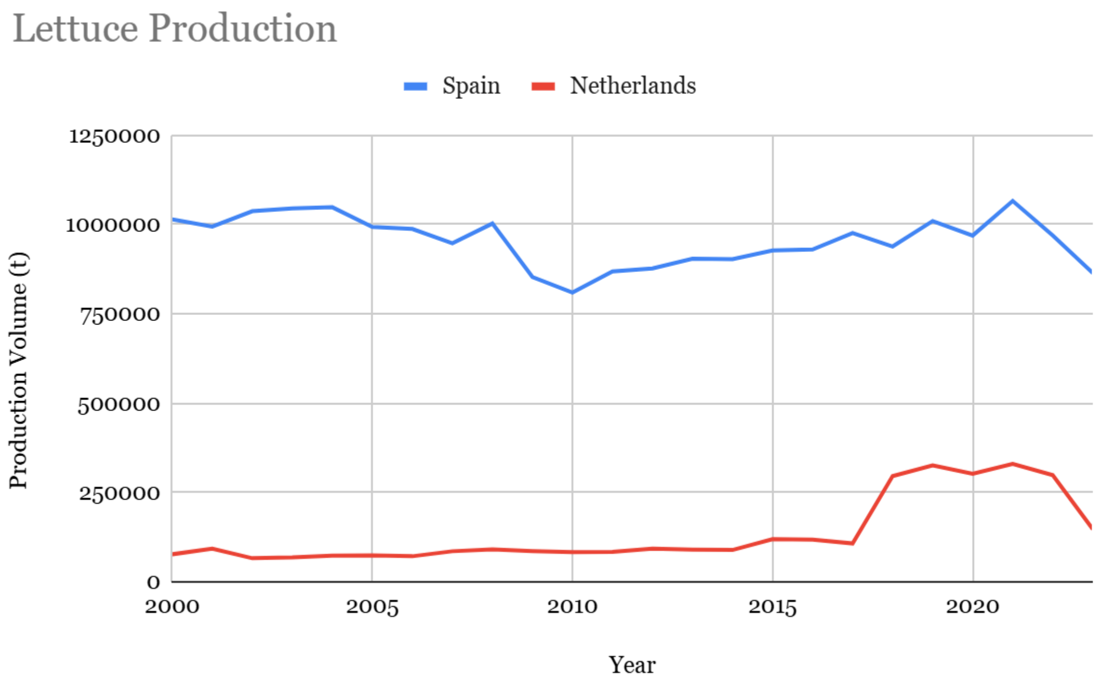


Figure 7. Spain versus the Netherlands lettuce production. Source: FAOstat-a 2025

6.2 Disturbance Scenario 2- Production in USA

Another possible scenario is that if Spanish lettuce was completely removed from the market or severely reduced, European grown lettuce would be in such high demand that it would likely become inaccessible to a small importer like Sweden. This would require Sweden to look further afield for their importing. Sourcing from the United States represents an example of a more extreme situation which may occasionally be necessary with the increasing climatic instability. As was shown in Table 12, the Netherlands is also a large importer from Spain suggesting that if Spain did not have sufficient lettuce to supply even its highest exporters, the Netherlands would no longer have enough lettuce to supply Sweden. In this case, the USA would be a reliable source as it is one of the top three producers of lettuce in the world (FAOstat-a, 2025), and even if it experienced a drastic reduction in production, it would still produce sufficient lettuce. While both Spanish and Dutch lettuce production experienced a sharp downturn in lettuce production in the past year, American production has increased, see Figure 8. The main factor impacting the environmental performance of this scenario is the long flight required to bring this lettuce to Sweden.

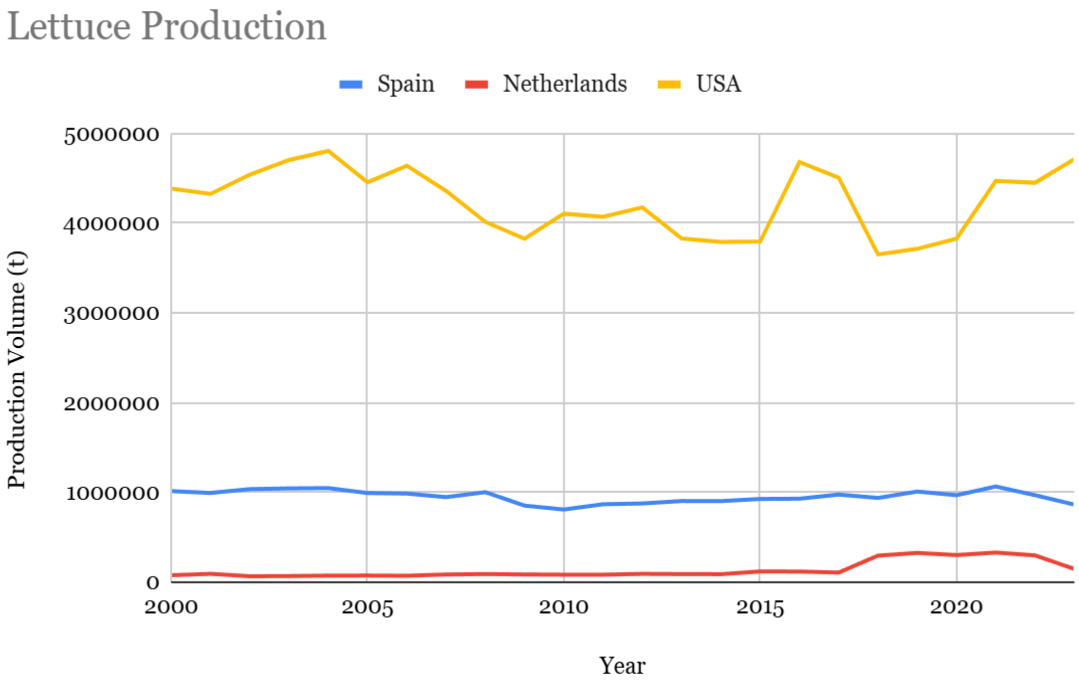


Figure 8. Production volume of USA lettuce compared to lettuce production in the Netherlands and Spain. Source: FAOstat-a 2025

6.3 Assumptions

By necessity this modelling requires making several general assumptions about what disturbance conditions will do to lettuce procurement. Many types of disturbance are very difficult to predict and even if the focus is only on crop failure the extent of the failure may be unclear. It also requires assuming that the alternative country being sourced from under a disturbance scenario is not experiencing its own disturbances, either related or unrelated. Lettuce losses are factored into calculations, the assumption is that any non-Swedish lettuce will experience a 20% loss between cultivation and arrival at central Stockholm, based on supplementary material from Martin et al. (2024). They cite that 10% is lost during processes at the farm, 5% is lost during washing and another 5% is lost before the plate which is here assumed to be from transportation (ibid).

7 Results and Interpretations

7.1 Base System Comparison

When looking at the comparison of the base models of lettuce production, the systems with the most negative impacts are the Swedish VF and the lettuce transported from the USA. Table 13 shows a breakdown of which systems have the highest and lowest impacts on the different environmental impact categories chosen for analysis. The majority of the impacts of the USA grown lettuce are from the air transportation, namely in acidification, GWP, and fossil resource use. The only indicator which performs the worst for the Netherlands is land use, which stems primarily from seedling production and the Dutch electrical mix. Overall, the Swedish VF has the lowest GWP of any scenario. However, it has large impacts in other areas, such as freshwater ecotoxicity and freshwater eutrophication. The biggest contributors to these are the metal building materials and the electricity use. The values for freshwater eutrophication are quite similar in all systems modelled. Similarly, the Swedish system has the highest impact for mineral and metal use although the values are quite close and are primarily caused by the use of metals in the VF's infrastructure. Finally, the results from water use may seem counter-intuitive, as VFs are very water efficient in the cultivation stage which is a significant factor in their appeal. However, the Swedish energy mix accounts for almost all of the water use, corroborating several other studies which cite the importance of energy mix on LCA results of VFs (Casey et al., 2022, Martin, Elnour and Siñol, 2023).

Table 13. The environmental impacts of the base models of lettuce production. The highest impact scenario is highlighted in red and the lowest impact is highlighted in blue

Impact Category	Unit	ES-OF	NL-GH	USA-OF	SE-VF
Acidification	mol H+ eq	1.22E-02	5.17E-03	4.17E-02	5.43E-03
Climate Change (GWP)	kg CO_2 eq	1.59E+00	2.04E+00	9.06E+00	1.03E+00
Freshwater Ecotoxicity	CTUe	7.43E+00	7.47E+00	1.02E+01	1.63E+01

Freshwater Eutrophication	kg P eq	2.53E-04	3.70E-04	2.07E-04	4.10E-04
Land Use	Pt	1.12E+01	1.79E+01	1.40E+01	1.64E+01
Fossil Resource Use	MJ	2.08E+01	3.02E+01	1.20E+02	4.98E+01
Mineral and Metal Resource Use	kg Sb eq	6.13E-06	2.05E-05	4.18E-06	3.88E-05
Water Use	m^3	2.01E-01	3.55E-01	2.49E-01	2.55E+00

Some studies conducting LCAs on lettuce focus primarily on GWP as the main indicator for their findings (e.g. Blom et al., 2022). This is also true of Pizzol (2015) who proposed the resilience calculation for LCA. His theoretical framework was purely based on a resilient system having a lower GWP than the conventional. If we are to only consider GWP then growing all lettuce in VF would be the best option as it has a noticeably lower impact in that category, see Figure 9, as the majority of the GWP impacts come from the transportation of lettuce. However, this would be ignoring the other categories where it has the highest impacts. The feasibility of a primarily VF sourced lettuce system for Stockholm can be imagined based on how much space would be required. The Swedish VF (Ljusgårda) used as source data for this study measures 7000m^2 including necessary space for general operations and has a yield of 520,000 kg per year (Martin, Elnour & Siñol, 2023) which equates to 74.3 kg/m^2. The demand for lettuce is 5.2 kg per person per year (Johansson et al., 2019) and the population of Stockholm was 988,900 at the beginning of 2024 which equals a total demand of 5,142,280 kg of lettuce. To fully meet this demand within the city it would require 10 locations such as Ljusgårda, or approximately the area of 9 soccer fields which would have large impacts on both water use from increased energy demand and freshwater ecotoxicity. A more achievable and resilient strategy is to source lettuce 50/50 from Spain and local VFs. Spain may be facing severe climate projections, but the lettuce produced there is the next lowest in GWP. Additionally, it is already the main source of lettuce for Sweden meaning that the network already exists. The comparison of this resilient system and the conventional system under disturbance will be explored in the following scenarios.

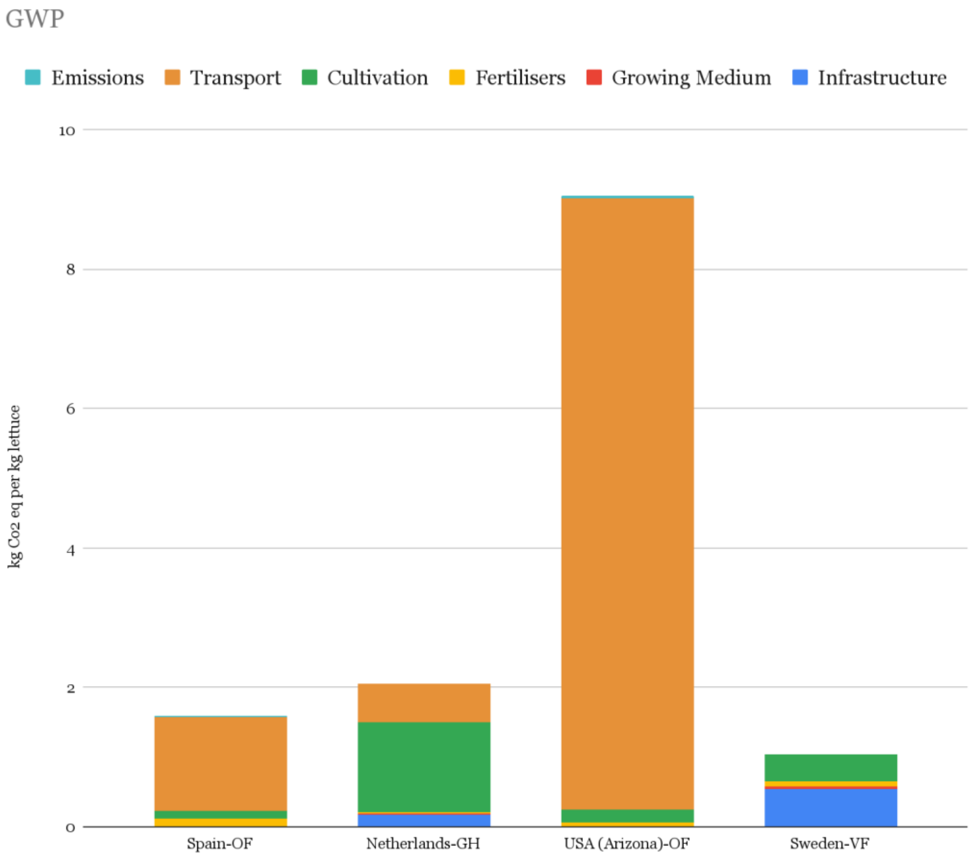


Figure 9. Graph showing GWP impacts of all base scenarios

7.2 Disturbance Scenarios

As previously described, this methodology involves creating alternative scenarios to model under disturbance in a way similar to a prospective LCA. There are four base scenarios which have been modelled, and their standard results are shown in Section 7.1. From here four different scenarios are created: the conventional system under no disturbance, the conventional system under disturbance and sourcing from the USA or NL and the resilient system comprising of 50/50 Spanish and Swedish lettuce (See Figure 10).

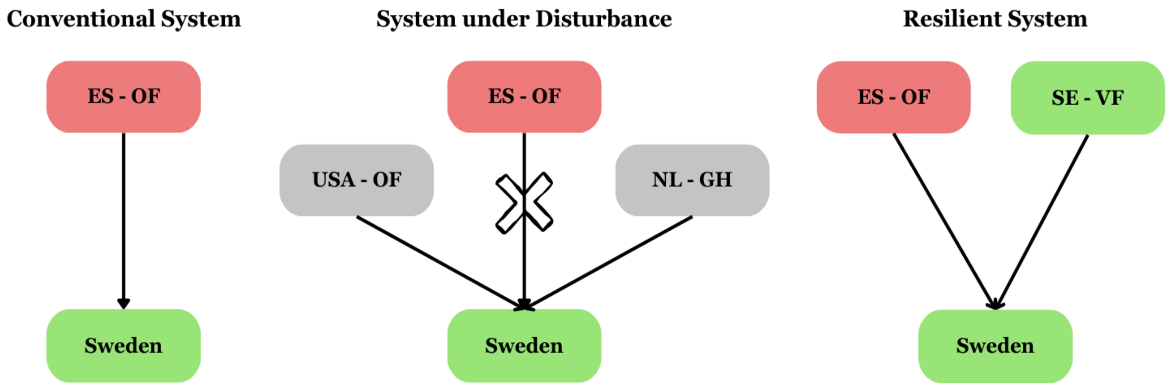


Figure 10. Visual representation of lettuce sourcing scenarios. The conventional system under no disturbance, the conventional system under disturbance and sourcing from the USA or NL and the resilient system of 50/50 ES-OF and SE-VF.

Before considering scenarios of disturbance, a comparison can be made between the conventional system under no disturbance and the resilient system, to act as a basis for analysing the results when accounting for disturbance (Table 14). As shown, the resilient system performs better in GWP, as well as acidification, even without disturbance but is outperformed in all other categories.

Table 14. Comparison of the conventional system where all lettuce is sourced from Spanish OF farms and the resilient system where half of the lettuce is sourced from Spain and the other half is grown in VFs in Stockholm.

Environmental Indicators	**Conventional System - No Disturbance (ES)**	**Resilient system (50/50 ES and VF)**
Acidification	1.22E-02	8.83E-03
Climate Change	1.59E+00	1.31E+00
Freshwater Ecotoxicity	7.43E+00	1.19E+01
Freshwater Eutrophication	2.53E-04	3.32E-04
Land Use	1.12E+01	1.38E+01
Fossil Resource Use	2.08E+01	3.53E+01
Mineral and Metal Resource Use	6.13E-06	2.25E-05
Water Use	2.01E-01	1.37E+00

The source of impacts for the resilient system are shown in Figure 11, below. As the results come half from Spanish production and half from Swedish production there is a wider range of sources of impacts and hotspots vary per indicator. The impact to GWP still primarily stems from the transportation from the half of the lettuce coming from Spain. Cultivation impacts stem from both systems and account for the majority of the impacts for water use, land use, and fossil fuel use.

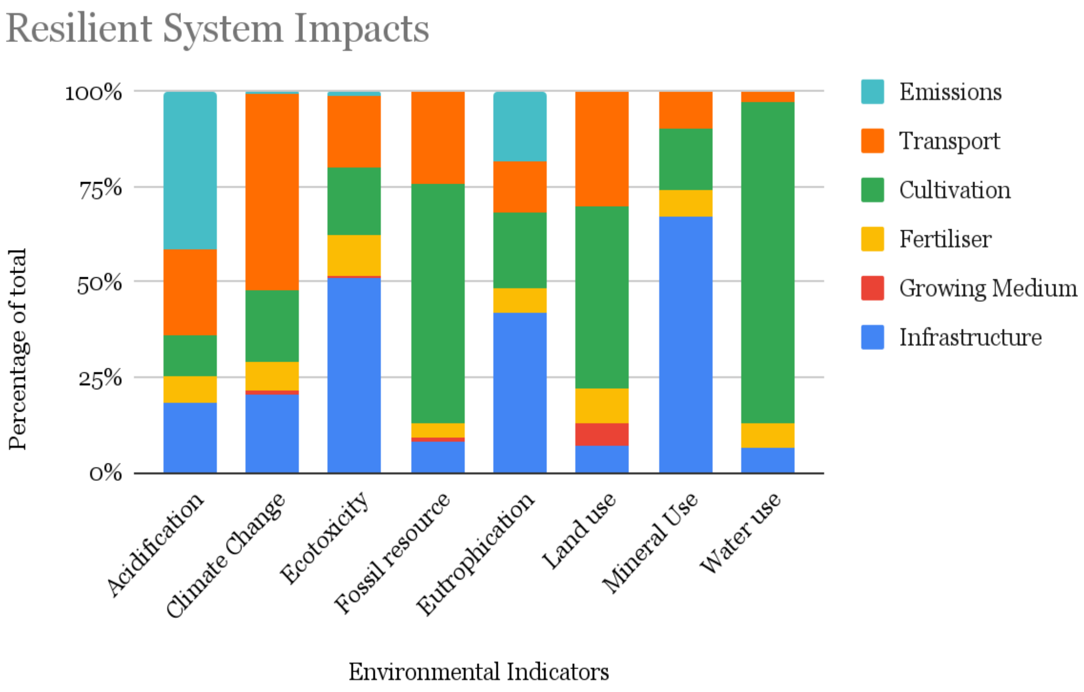
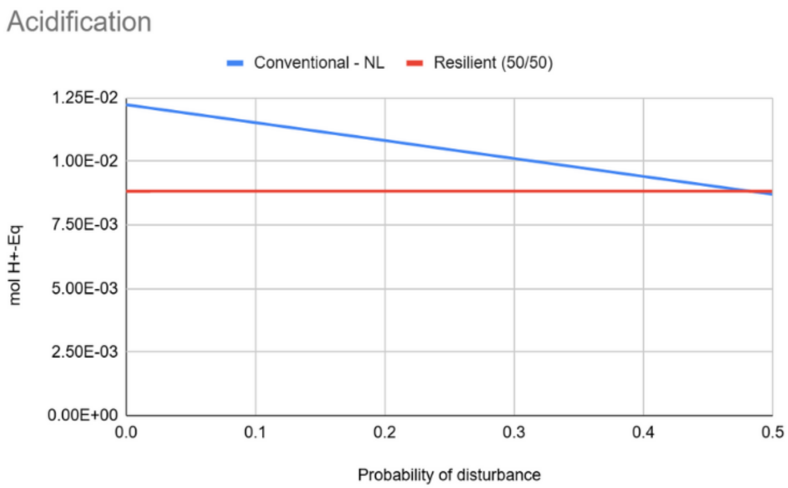
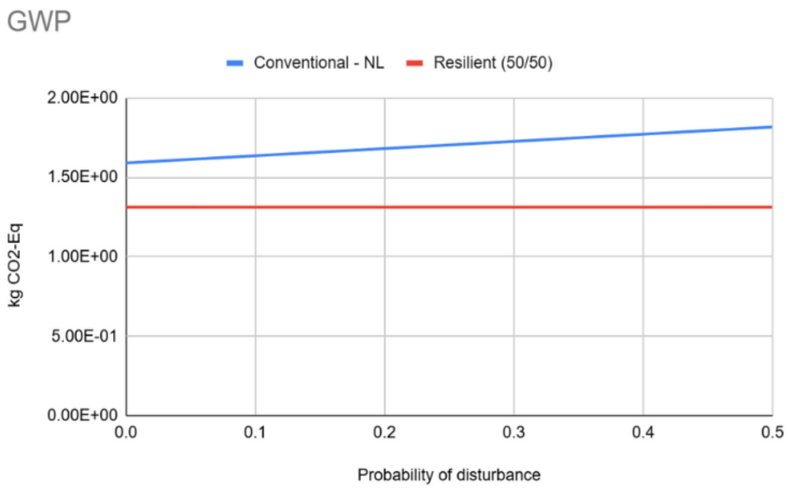


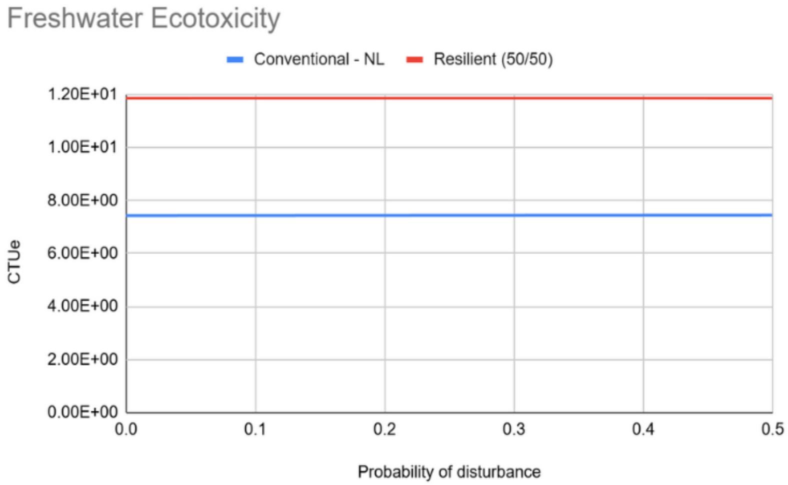
Figure 11. Breakdown of impacts of a resilient lettuce system which includes 50% of lettuce coming from Spain-OF and 50% coming from Sweden-VF.

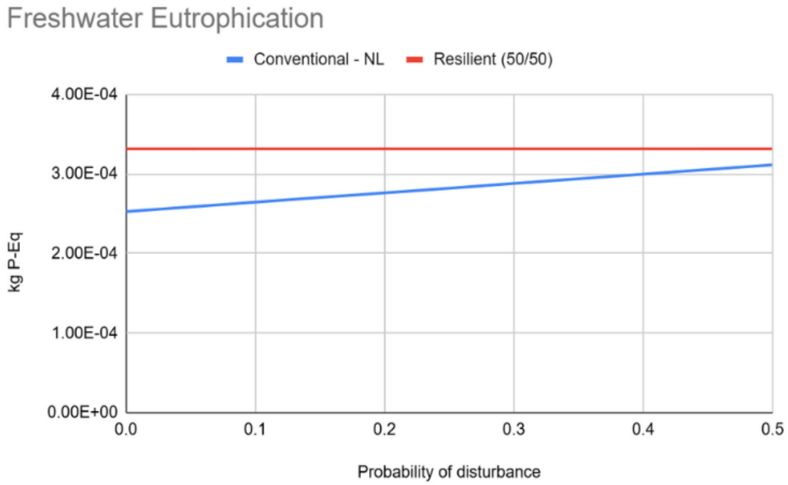
7.2.1 Disturbance Scenario 1 - Netherlands as Alternative

In the event of a disturbance which would require Sweden to source from the Netherlands we can compare at which point it is better environmentally to invest in a resilient system consisting of 50/50 local VF and imports from Spain. Using the equation proposed by Pizzol (2015) to measure total environmental impact, several probabilities of disturbance were modelled. This shows under which probability of disturbance the resilient system would become the preferable option. The following graphs in Figure 12 show the impact categories plotted over disturbance levels, highlighting if or when the resilient system becomes less impactful. As can be seen, GWP is already better for the resilient system and continues to improve. Freshwater ecotoxicity and water use stay almost constant, despite the dramatic shift of up to 50% disturbance, since these indicators show only marginal differences between systems. Under increasing disturbance, freshwater eutrophication, land use, and mineral and metal resource use change in favour of the resilient system, however it is only land use which becomes less impactful, at about 38% disturbance which equates to approximately 139 days of yearly disturbance. Interestingly, acidification improves during the disturbance scenario as the Dutch system performs better in this category and offsets the negative impacts of the Spanish system


Acidification


GWP


Freshwater Ecotoxicity


Freshwater Eutrophication

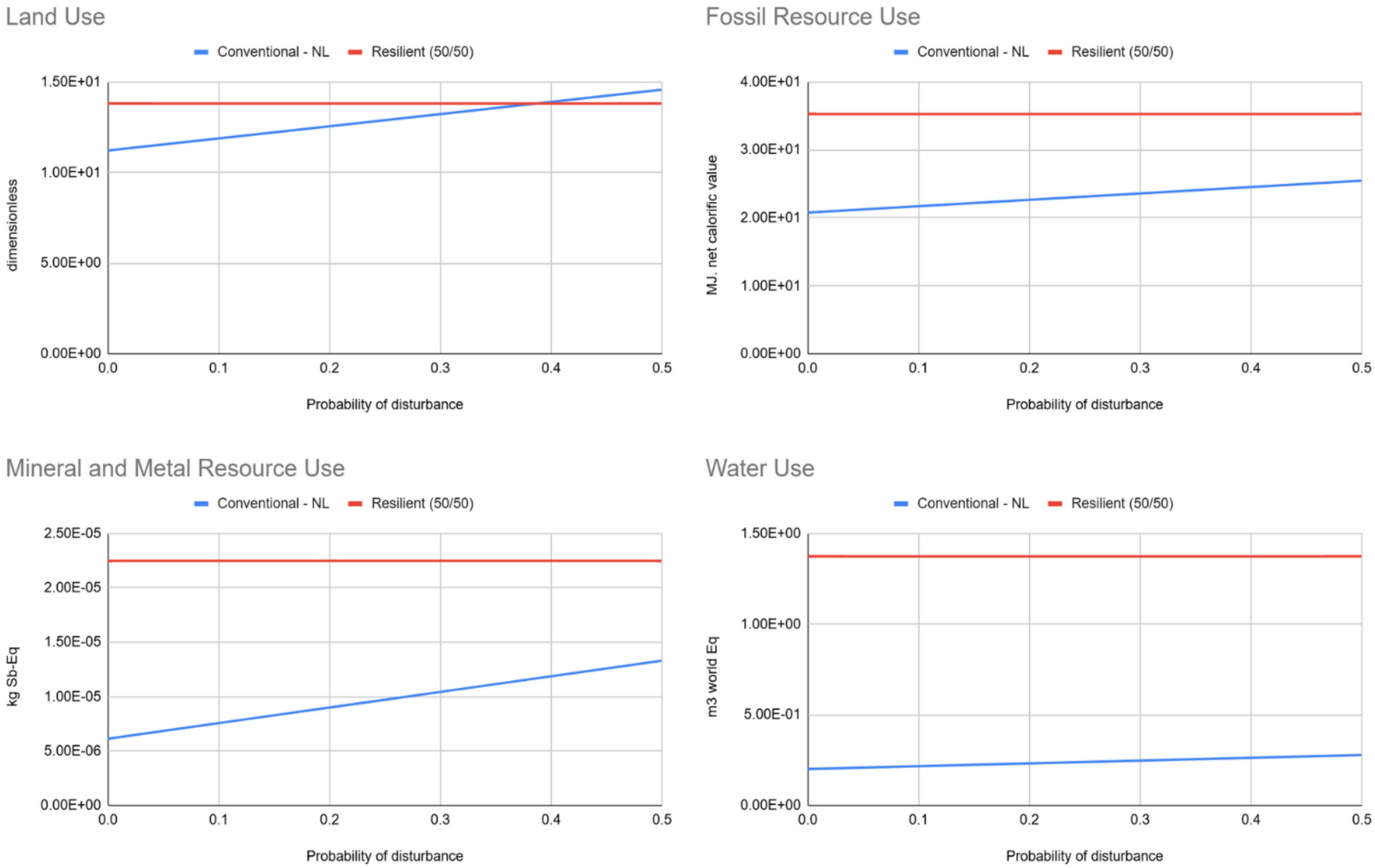
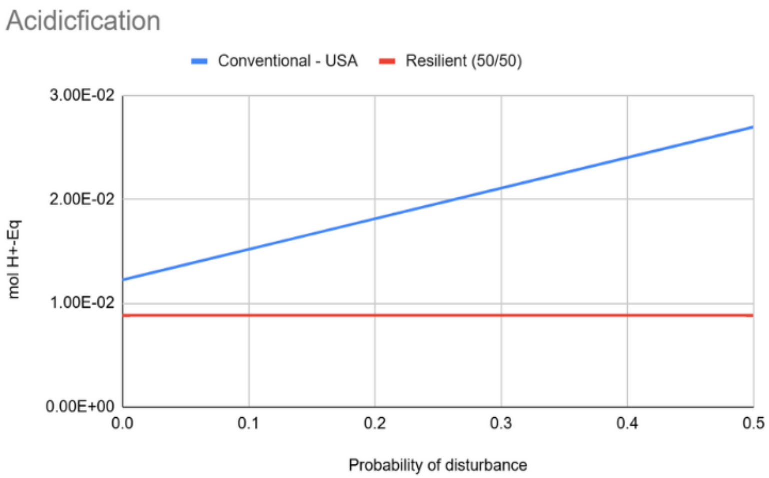


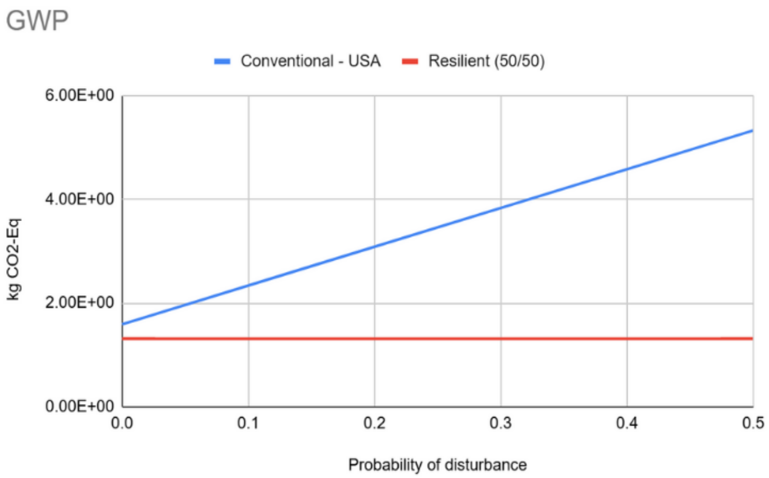
Figure 12. Environmental impacts plotted against increasing probabilities of disturbance (fraction of days) for the conventional system with sourcing from NL and the resilient system of 50/50 ES/VF

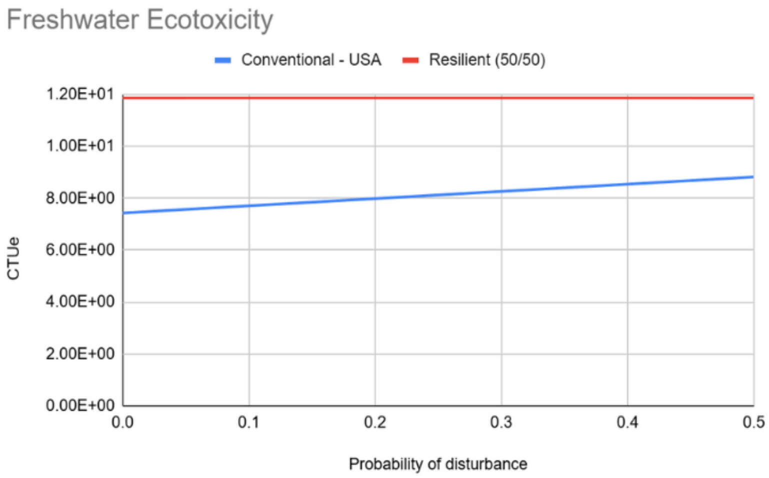
7.2.2 Disturbance Scenario 2 – USA as Alternative

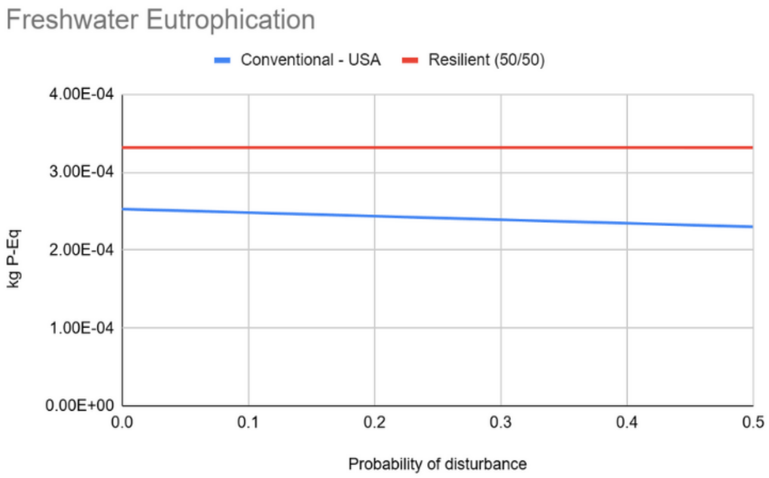
As previously described, a disturbance event that has the potential to take Spanish lettuce off the market would likely have a large impact on all European lettuce and require alternative sourcing. In this scenario the resilient system remains the same mix of 50/50 Spanish OF lettuce and VF grown in Stockholm, with the source under disturbance being the United States. The base system comparison shown in Table 14 is the same for this scenario when there is no disturbance. The following Figure, 13, similarly shows the change in the environmental impacts as the disturbance level increases using the same formula.

The results of these calculations show that freshwater eutrophication, mineral and metal use as well as water use stay mostly constant between a resilient system and the conventional system under disturbance. While a higher quantity of water is used for the growing of lettuce in Arizona, USA, the water use impact from the Swedish energy mix makes the results remain in favour of the conventional system in that category. Both the acidification and GWP categories are better in the resilient system with no disturbance and are seen to become increasingly preferable under disturbance. The categories of freshwater ecotoxicity, land use, and fossil resource use all change towards favouring the resilient system as the disturbance level increases. However, it is only fossil resource use where the impact of the conventional system surpasses the resilient one, which occurs at approximately 15% disturbance, equating to approximately 55 days of disturbance.


Acidicfication


GWP


Freshwater Ecotoxicity


Freshwater Eutrophication

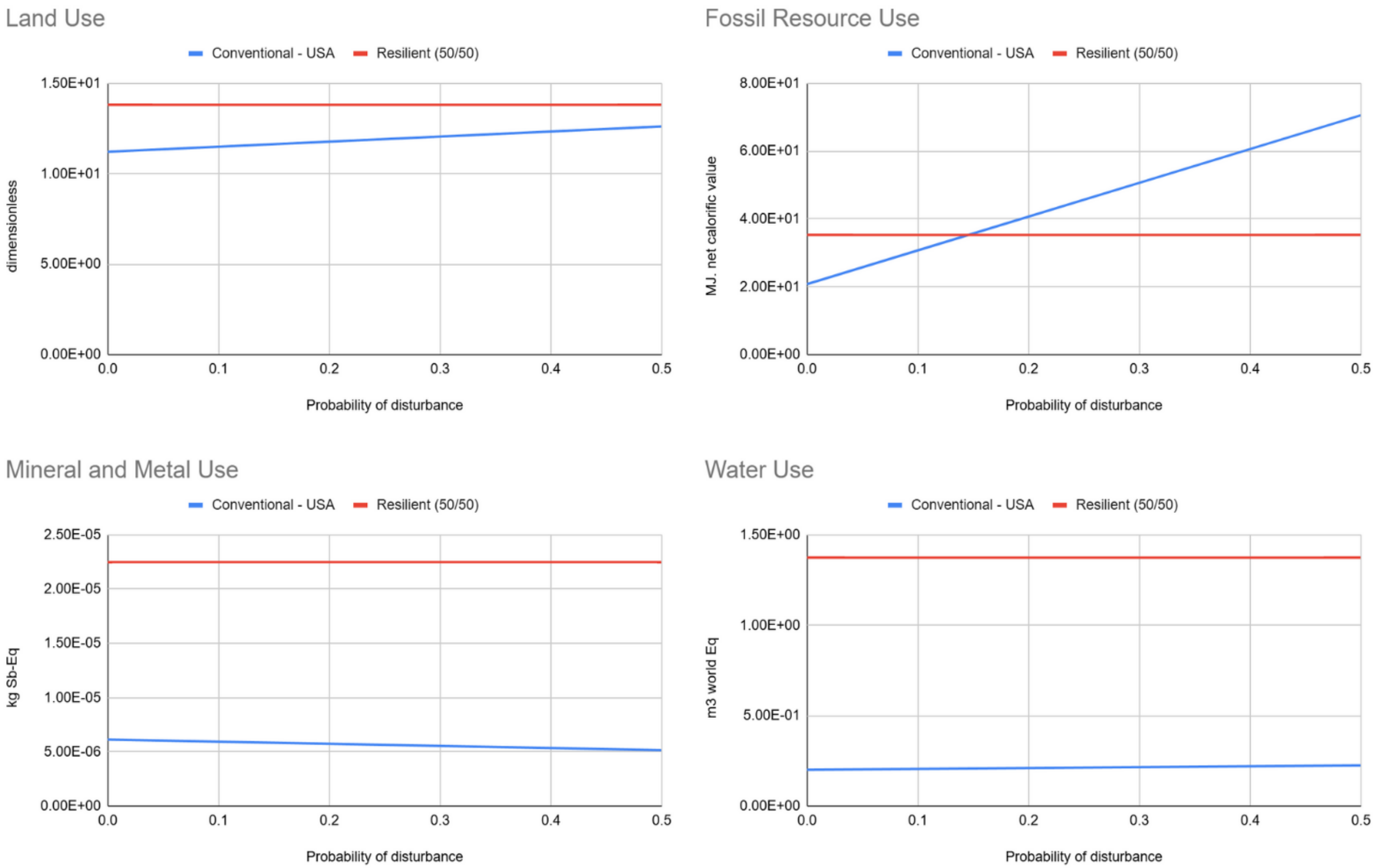


Figure 13. Environmental Impacts plotted against increasing probabilities of disturbance (fraction of days) for the conventional system with sourcing from the USA and the resilient system of 50/50 ES/VF

7.4 Accounting for Full Crop Failure

A crop failure in literature refers to a decrease in production of only 10% of the recent average (Caparas et al., 2021). However, increasing temperatures and climatic instability are making it more likely to see entire crop failures due to heat waves, droughts, floods or other extreme weather. Currently, relevant literature does not consider scenarios of complete crop failures in the framework of an LCA, and these impacts seem to be ignored. If all, or even the majority, of inputs are still going into the system before it fails, these impacts should be accounted for in some way. I argue here that the fairest way to account for these impacts is to allocate them to the intended exporting purchaser and add the production impacts to the product they source from another country. If there is an intent to purchase lettuce from Spain (for example) and the crop fails, even if the purchase was not officially made, the intended purchaser should have to account for the inputs of the lost crops in an LCA of their lettuce sourcing. This means they would have to add the results of the Spanish production to the impacts of the alternative source, in this case either Dutch or American. Having the impacts allocated to the intended purchaser rather than roll over to the next crop of lettuce produced puts the responsibility on those choosing to source from a country struggling with climate impacts. For simplicity's sake to visualise this theoretical scenario, it is assumed that the full crop failure occurred when the lettuce was fully matured and ready for harvest, meaning that all inputs had gone into the system except post-harvest processes. To calculate this, I propose another version (2) of the equation by Pizzol (2015), which would be relevant in any LCA considering disturbance scenarios when the entire source fails:

$$(A - p) + B = Total\ Impact \tag{2}$$

As with the original formula, A refers to the primary, conventional scenario and B to the alternative scenario used under disturbance. The values used for these are the results from environmental impacts categories of the base models. For example, the A could be the total GWP of Spanish lettuce and the B would be the GWP of either lettuce grown in the USA or the Netherlands. The p refers to post-harvest inputs which could be ignored as they occur after the crop fails, in this case only referring to transportation. For this calculation the disturbance level does not need to be considered as the entire crop failing equates to 100%

disturbance. These impacts are then added to the alternative source, accounting for both the intended and actual sources of production.

In the case of this study, Spain has a lettuce production rate of three harvests per year (Martin-Gorriz et al., 2022). One of these failing would equate to a full harvest failure and would account for ⅓ or ⅔ of production rather than the entire yearly production. In this alternative scenario the production of the failed crop is still accounted for, but now the variable of disturbance is re-added for proper allocation. This would require another more detailed formula (3) to calculate:

$$A_1 * (1 - d) + (A_2 - p) * d + B * d = Total\ Impact \qquad (3)$$

Written like this the equation still considers the impacts of 100% of lettuce as coming from Spain where A_1 represents the actual lettuce acquired and A_2 represents the lettuce intended to be acquired from Spain but subtracts the post-harvest processes (p). The d represents the disturbance level being experienced by the system where the B similarly indicates the alternative source of production. These two equations are summarised in Table 15.

Table 15. Overview of crop failure scenarios with their definition and equation

Full Crop Failure	When the entire yearly production fails	(A-p)+B=Total Impact
Harvest Failure	When one of the yearly harvests fails	A_1*(1-d)+(A_2-p)*d+B*d=Total Impact

7.4.1 Entire Crop Failure

Using equation 2 we see the environmental impact of accounting for the total lettuce produced in Spain, excluding post-harvest processes, plus the impact of the alternate source, the Netherlands. In Figure 14 these results are compared to the resilient system using a radar chart with logarithmic values, so it is clear which system has a larger impact. This shows that using this methodology, the resilient system outperforms the conventional in acidification, climate change, freshwater eutrophication, and land use. The fossil resource use, mineral and metal use and ecotoxicity are almost the same. Water use is the main indicator which is still notably in favour of the conventional system though as previously indicated this is largely due to the energy source.

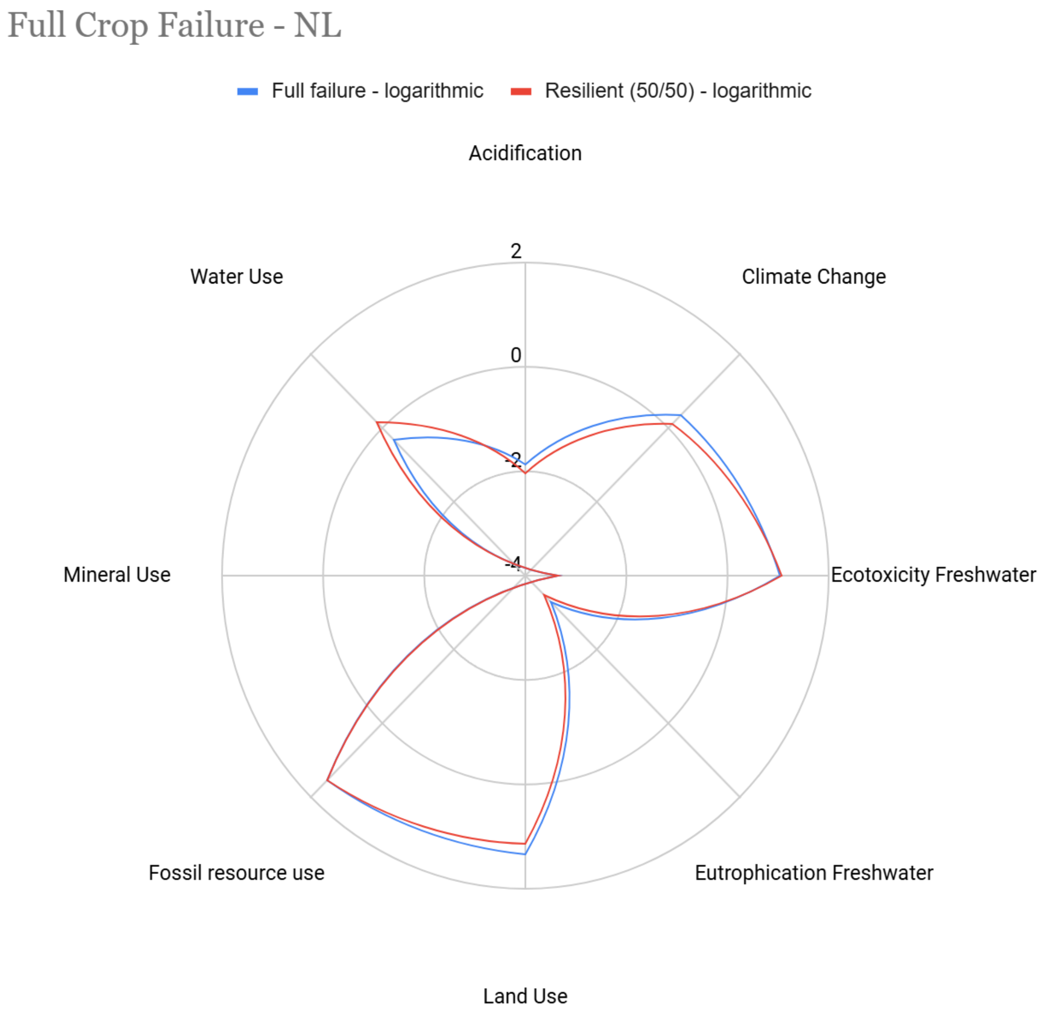


Figure 14. Comparison of impacts of accounting for a full crop failure plus sourcing from the Netherlands with a resilient system.

Results in Figure 15 show the same logarithmic comparison for the USA as the alternative source. Where acidification, climate change, and fossil resource use are all substantially in favour of the resilient system. Freshwater eutrophication and ecotoxicity and land use are all around equal whereas water use and mineral and metal use still favour the conventional.

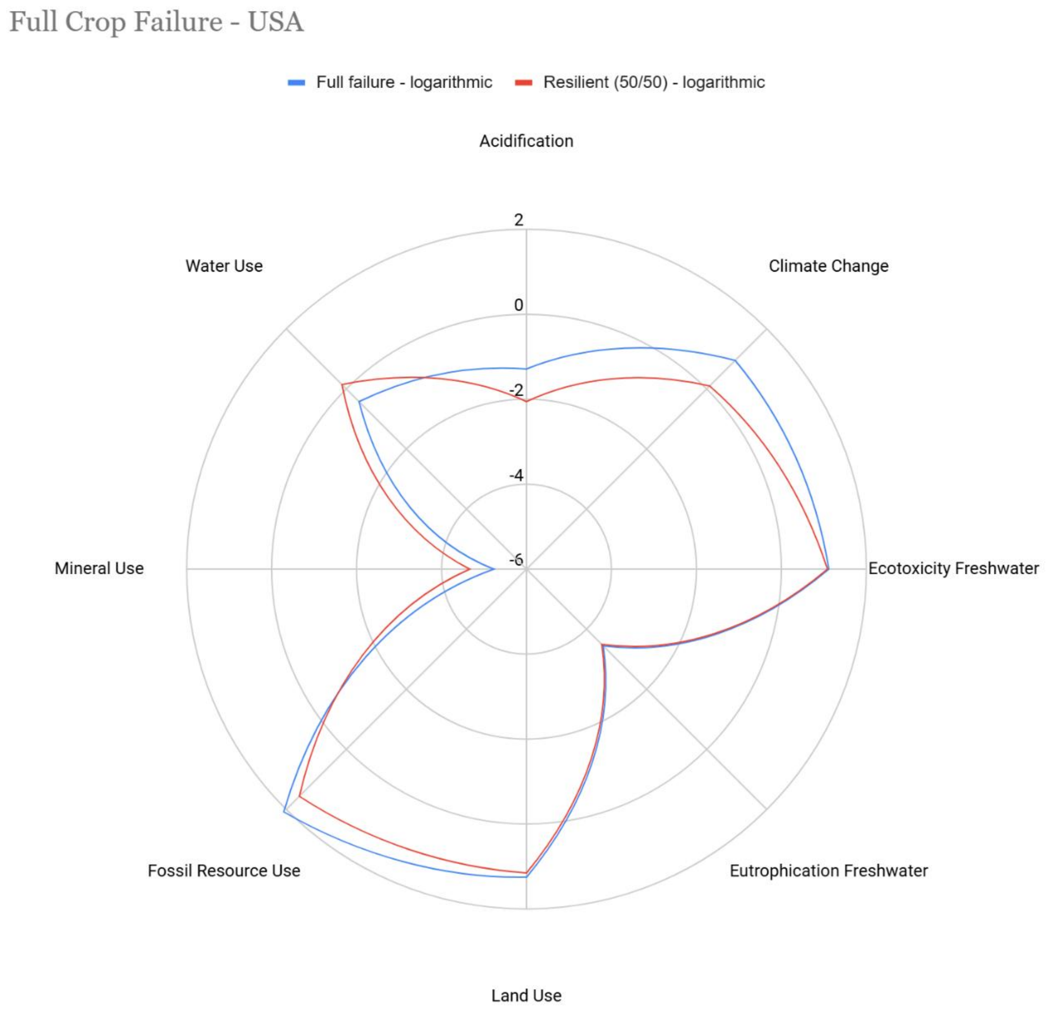


Figure 15. Comparison of impacts of accounting for a full crop failure plus sourcing from the USA with a resilient system.

7.4.2 Individual Crop Failure

Because Spain has three crops of lettuce per year the other possible scenarios of crop failure are 33.33% and 66.66% disturbance which would account for one and two of three crops failing. Accounting for this can be done by employing equation 3; comparisons shown in Tables 16 and 17 represent the results of a system comparison if a Spanish crop fails entirely and is sourced instead from the Netherlands or the USA. These results account for the percentage of lettuce that failed, what was successfully sourced from Spain as well as what was sourced from an alternative country. The results of this are not dramatically different from the calculations of the regular disturbance scenario as the impacts of the Spanish production are quite low when excluding transportation, however margins are smaller. Even if results do not differ significantly, this is an important consideration to make in results when faced with an entire crop failure and the marginal change in values does not diminish the applicability of the methodology itself.

Table 16. Comparison of environmental impacts of full individual crop failure in Spain with alternative sourcing from the Netherlands to a resilient system

Environmental Indicators	Units	ES→NL 33.33%	ES→NL 66.66%	Resilient (50/50 ES/VF)
Acidification	mol H^+ eq	1.27E-02	1.31E-02	8.83E-03
Climate Change	kg CO_2 eq	1.82E+00	2.05E+00	1.31E+00
Ecotoxicity, Freshwater	CTUe	8.47E+00	9.51E+00	1.19E+01
Eutrophication, Freshwater	kg P eq	3.46E-04	4.38E-04	3.32E-04
Land use	Pt	1.46E+01	1.80E+01	1.38E+01
Fossil Resource Use	MJ	2.52E+01	2.96E+01	3.53E+01
Mineral and Metal Use	kg Sb eq	1.15E-05	1.68E-05	2.25E-05
Water Use	m^3	2.96E-01	3.90E-01	1.37E+00

Table 17. Comparison of environmental impacts of full individual crop failure in Spain with alternative sourcing from the USA to a resilient system

Environmental Indicators	Units	ES→USA-33.33%	ES→USA-66.66%	Resilient (50/50 ES/VF)
Acidification	mol H^+ eq	2.48E-02	3.74E-02	8.83E-03
Climate Change	kg CO_2 eq	4.16E+00	6.73E+00	1.31E+00
Ecotoxicity, Freshwater	CTUe	9.38E+00	1.13E+01	1.19E+01
Eutrophication, Freshwater	kg P eq	2.91E-04	3.30E-04	3.32E-04
Land use	Pt	1.33E+01	1.54E+01	1.38E+01
Fossil Resource Use	MJ	5.52E+01	8.97E+01	3.53E+01
Mineral and Metal Use	kg Sb eq	6.03E-06	5.93E-06	2.25E-05
Water Use	m^3	2.60E-01	3.20E-01	1.37E+00

8 Analysis

When considering all scenarios even in an undisturbed state, the GWP has the lowest impact in the Swedish VF, which means that the resilient scenario of 50% Spanish OF and 50% Swedish VF lettuce also performs better than the other base scenarios. As previously mentioned, even though a strictly VF system has the lowest GWP it is preferable to maintain other linkages to ensure continued performance under various disturbances by being more adaptable. GWP is often the most heavily used indicator because it represents one of the most pressing environmental issues. The resilient system of 50/50 Spanish OF and Swedish VF still performs better in GWP in every scenario presented, which is also true of acidification. The majority of the other indicators only prefer the resilient system under certain disturbance conditions and based largely on which country is the alternative source of lettuce. For example, freshwater eutrophication is only better in the resilient scenario when the proposed equation for full crop failure is used, accounting for intended purchase (for both NL and USA), as well as when employing equation (3) when the Netherlands is the alternative. When considering land use, the resilient system is preferable when the Netherlands is the alternative starting at 38% disturbance as well as when full crop failure is taken into consideration. Another example is fossil resource use, the scenario with the USA as the alternative uses considerable fossil fuel inputs for intercontinental travel and the resilient system becomes preferable under only 15% disturbance and under all scenarios modelling full crop failure. However, when the Netherlands is the alternative, the resilient system only becomes narrowly preferable under full crop failure. On the other hand, water use performs consistently worse for the resilient system in every scenario even with full crop failure due to the Swedish energy mix. Even if decision making is largely done based on GWP it is important to have transparency on the trade-offs between a larger number of indicators.

To accurately understand the impacts of the different systems it is important to view them not just at a FU scale but also at the system level. In Stockholm lettuce is consumed at 5.2kg per person equalling a demand of roughly 5.1 million kg. Table 18 shows the breakdown of total lettuce quantities associated with their GWP per kg and compares the resilient system and conventional systems with sourcing from the Netherlands or the USA under a 20% disturbance. The difference in GWP is almost 25% (24.56%) higher for the conventional system with supplementation from the Netherlands and 81% (80.79%) higher when the USA is the alternative. The disturbance level of 20% equates to 73 days per year of disturbance. When shown at scale, the difference in impact is considerable and provides a more accurate assessment of the impacts of the entire system.

Table 18. System totals showing the total GWP for the resilient system versus the conventional system under 20% disturbance and sourcing from the Netherlands or USA

Resilient (50/50)	**ES-OF**	**NL-GH**	**USA-OF**	**SE-VF**	**Life Cycle**
Spain Production	-	-	-	-	2,571,140 kg
Netherlands Production	-	-	-	-	-
USA Production	-	-	-	-	-
VF Stockholm Production	-	-	-	-	2,571,140 kg
GWP (kg CO_2 per kg lettuce)	1.59	2.04	9.06	1.03	**6,750 tonnes**

Vulnerable (NL) d: 0.2	**ES-OF**	**NL-GH**	**USA-OF**	**SE-VF**	**Life Cycle**
Spain Production	-	-	-	-	4,113,824 kg
Netherlands Production	-	-	-	-	1,028,456 kg
USA Production	-	-	-	-	-
VF Stockholm Production	-	-	-	-	-
GWP (kg CO_2 per kg lettuce)	1.59	2.04	9.06	1.03	**8,640 tonnes**

Vulnerable (USA) d: 0.2	**ES-OF**	**NL-GH**	**USA-OF**	**SE-VF**	**Life Cycle**
Spain Production	-	-	-	-	4,113,824 kg
Netherlands Production	-	-	-	-	-
USA Production	-	-	-	-	1,028,456 kg
VF Stockholm Production	-	-	-	-	-
GWP (kg CO_2 per kg lettuce)	1.59	2.04	9.06	1.03	**15,900 tonnes**

When it comes to seasonality, more accurate results should consider actual availability from different systems as these calculations assume year-round production. Figure 16 shows the total GWP of the resilient system and the conventional systems with disturbance sourcing from the Netherlands and the

USA divided over the months that lettuce is available. It is set at 20% disturbance and highlights the stability of the resilient system in lettuce availability and GWP, however it should be repeated that lettuce from the Netherlands is not available during the same period as Spanish lettuce and this scenario is for illustrative purposes only. The inability of an LCA to account for time is a shortcoming of the methodology for assessing resilience, as noted by Pizzol (2015). These results highlight the stability of the resilient system and show significant impacts for the conventional systems.

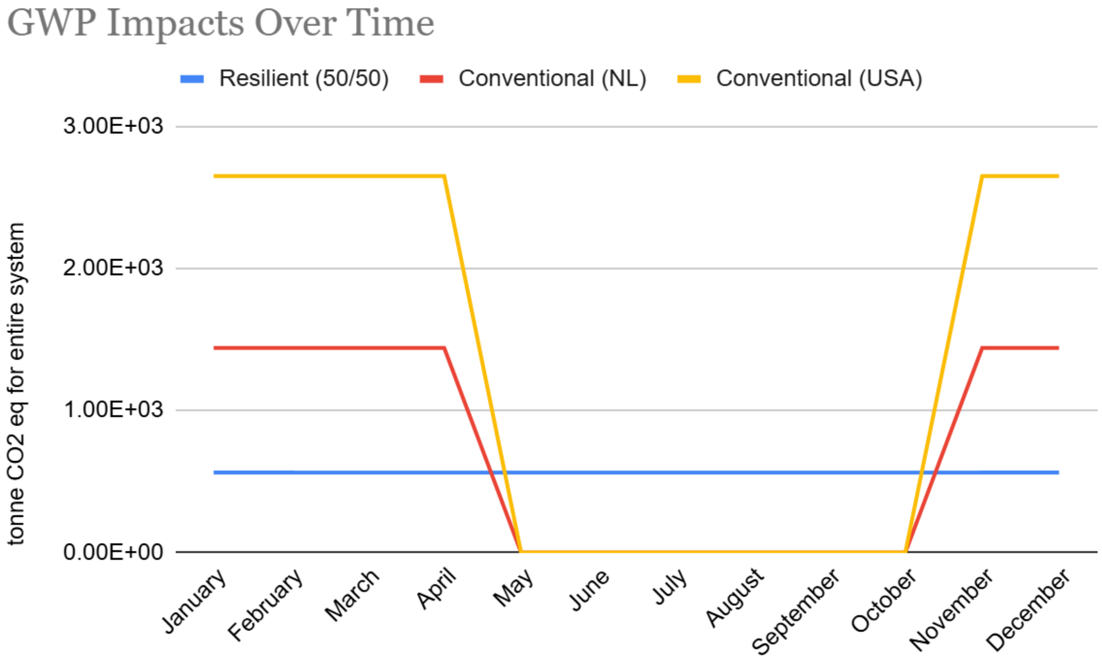


Figure 16. Actual GWP impacts of the conventional lettuce sourcing system from Spain with alternative sourcing from the Netherlands and the USA under 20% disturbance, compared with the resilient system showing actual monthly availability of lettuce

9 Discussion

This study shows that LCA results can more accurately represent the real environmental impacts of a system by taking into account disturbance scenarios which should reasonably be expected. The comparison of the base lettuce-producing systems is consistent with findings by Martin et al. (2023), where it was found that a commercial VF in Stockholm had lower GHG emissions than conventional sources. The creation of the resilient system, which averaged the impacts of the Swedish VF and Spanish OF lettuce, still shows lower impacts than any other single source. Several indicators consistently show that environmental impacts can be lower in a resilient system, which provides significant incentive to research and invest in these resilient alternatives further.

This work brings up important questions about how to prioritise indicators, especially in relation to resilience assessments in LCAs. Climate change and therefore GWP is a significant issue in the world today and it is one of the most commonly used indicators in LCAs which measures the extent of GHG emissions. In fact, the paper by Pizzol (2015) only considers GWP when defining a resilient system. Pizzol cites that this preference is due to proxy datasets being used in calculations (chosen based on their GWP) which would cause all other indicators to be irrelevant, and further suggests its high level of importance. An optional step in an LCA is normalisation, which assigns a value of relative importance to different indicators, allowing for comparison between indicators. This would be a useful step when considering different options with several indicators, however these weightings are subjective and have no “correct” set of weighting factors (Finnveden et al., 2009). In can be inferred, due to the fact that resilience is not yet commonly integrated into LCAs, that the standard weightings do not assign as much importance to resilience. Additionally, LCAs are not able to account for the actual state of environmental impacts in the country they are based in. These tensions have been seen within LCAs for some time, with Finnveden et al. (2009) highlighting several issues of subjectivity with weighting and making normalisation more accurate. In the case of this report, Spain struggles with eutrophication due to excessive nutrients (Romero-Gámez et al., 2014), suggesting that more exploration should be done regarding case-specific weighting of environmental indicators. When considering the lettuce sourcing system under disturbance, neither scenario prefers the resilient system in all categories, thereby requiring some prioritisation of indicators.

The aspect of seasonality is an important component when discussing agriculture and supply chains which has been greatly simplified in this report. As previously mentioned, the Netherlands' lettuce is available during the opposite months as Spain's (Martin, Elnour, Siñol 2023, Hofotra nd, HortiDaily 2023, USDA 2023), however in calculations they have been treated as both being available for the entire year. The proposed resilient system has great potential as an alternative, as lettuce would be available all year. The equations do not specify any timeframe for sourcing from different systems, meaning that in practice Sweden could focus a larger share of its lettuce production during May-October when lettuce is not available from Spain. This also contributes to the desired aspect of responsiveness for resilience, where reorganisation can occur strategically in supply networks, as recommended by Larrea-Gallegos et al. (2022). These months may also require less energy inputs for the VFs as temperatures are warmer, however this would depend on the construction of the farm. The fact that VFs are not season-dependent (Martin et al., 2023) improves the resilience of them as a solution as climate change and extreme weather events would not impact production unless they affected energy sources. However, VFs can still experience some disturbance scenarios such as upstream supply chain disturbances, although the largest risk is to the supply of energy.

The increasing level of international trade has improved regional food security in many countries by making them more resilient to local disturbance, however disturbances at a systems level could still have drastic consequences (Puma et al., 2015). This also depends on how critical the region is for food sourcing, for example, if regional disturbances occur in high export areas such as Spain, consequences could be far reaching as it is relied on by many other countries. In these cases, export restrictions are likely applied which impacts the whole food system, a term referred to as self-propagating trade disruption. This underlines the need to balance globalised food sourcing with local solutions. Puma et al. (2015) also highlight the importance of increasing redundancy as part of the solution for handling supply-chain disturbances, supporting the design of the resilient system proposed in this paper. The ideal "resilient" solution will, however, look different depending on what food item is being considered and may not include VF when assessing other goods.

Within our current system it is not seen as an option to decide not to source a product even if there are significant disturbances in production or supply chains, we are accustomed to always having access to any food we want. In the case of lettuce, it is not a critical item per se; it does not provide a significant amount of nutrients or calories and is easily replaceable with other vegetables or greens. However, similar situations could arise with products which could have a higher impact on people's lives such as wheat, maize or rice which are often the chosen crops in food supply studies (Puma et al., 2015, Caparas et al., 2021, Masoura, 2024). In addition, more accurate disturbances could be modelled by using historic disturbance scenarios to project future disturbances and test the methodology as was done by Puma et al. (2015). Various mathematical models could also be applied which have aimed to project disturbances and create more viable models (Ivanov, 2022). Additionally, assessments could be done with data directly taken from procurement to more accurately model the supply-chain disturbances. Models could also assess upstream disturbances by using alternative upstream products to represent disturbances to background materials.

The addition of impacts from a fully failed crop would help to incentivise more thoughtful purchasing or the consideration to forego the product rather than source from great distances. In practice, allocating failed crops to intended purchasers may prove a difficult task as it would require a confirmed intent to purchase from the country in question. This could also become an issue where a country experiencing extreme weather conditions suddenly has no demand for their products, as importing countries could fear the unpredictability, and not want to be responsible for their crop failure. Another possible method would be in having the impacts of a failed crop carry forward to the next successful crop. However, this would further compound the problem on the country experiencing extreme weather. This methodological decision is a similar consideration to that of an allocation problem which can often occur in LCAs, where one must decide how to allocate certain impacts when causation is not direct (Finnveden et al., 2009). Using the proposed equations is more illustrative of the interactions of the food system and supply chain network. Caparas et al. (2021) wrote about the increasing probability of crop failure in their work and consider in their discussion how to identify a point of no return regarding failing crops. These consideration of a point of no return is not account for within these equations, but they can provide some transparency regarding the extent of crop failures and thereby aid decision-making in this regard.

Many papers have attempted various methods for assessing how disturbances will impact a supply chain. For example, Puma et al. (2015) looked at trade network connections and how those changed during historic disturbances. Another example is Pulighe and Lupia (2020), who assessed the impacts of the COVID-19 pandemic and how it impacted our food supply system. Both papers have supported a more careful balancing of global trade with local production to combat uncertainties which is in line with the methodology used in this report. However, Larrea-Gallegos et al. (2022) who conducted a review of research which connects resilience, disturbance and sustainability, conclude their paper by reinforcing the importance of the aspect of change over time for resilience. In practice, a disturbance scenario necessarily involves a dynamic system, and LCAs were created to show a product or system in a static state. This means that the dynamic aspects of disturbances must be manually added through scenario building which adds a level of uncertainty to results and ignores the ability of systems to recalibrate over time. Nonetheless, these LCA results are still informative by providing a snapshot of the actual environmental impacts when including disturbance. This type of scenario building could be viewed as a type of future or prospective LCA as it considers “what if” scenarios.

Information in the form of quantitative data can be a powerful tool for assigning importance to environmental issues and guiding investment (Hummel and Hörisch, 2020). This work has aimed to provide a concrete justification for the investment in resilient systems. Overall, accounting for resilience within an LCA shows promise as a new tool which could be improved over time, despite limitations to what it can achieve. It also proves that resilient systems can be just as, if not more, environmentally conscious than conventional systems.

9.1 Limitations

As previously mentioned, the goal of this study is to provide a real-world example of accounting for resilience in an LCA. The food system as it is represented here has been simplified to allow for efficient illustration of the concept proposed by Pizzol (2015). There is significant room for expansion of this model to account for system complexity, but conclusions can still be drawn from the findings, and it can be used as a blueprint for future studies that aim to incorporate resilience into their assessments. However, it is important to acknowledge which aspects of the food system have been left out and may be limiting factors.

One of the main limitations for this work, which makes it not representative of the entire food system, is that urban agriculture cannot be the resilient solution for the majority of crops. Lettuce represents one food item which is predisposed for VF, but many staple crops either cannot be efficiently grown in VF or other urban farming, or not in large enough quantities to meet demand (Bakalis et al., 2020). Therefore, other products would require different designs of a resilient system. In addition, other forms of urban farming which already exist in Stockholm, such as allotment gardening have an important impact on resilience and should be accounted for in some way, even if they have shorter growing seasons and cannot provide as high of quantities as VF.

The choice of a mass-based FU with disturbance prevention added was the appropriate choice for measuring resilience, however there are other considerations to be made when setting a FU. There is a growing idea of food-related LCAs switching or adding other measurements such as calorie content as there are other reasons to eat food rather than its mass. In this case, it was deemed not relevant for the systems level view of lettuce sourcing systems. However, another aspect which could be an important addition to an assessment of resilience using an LCA is economic aspects. In this case, accessibility can be impacted by the price of lettuce where lettuce may be available on the market but at a much higher cost. For example, Spanish exports decreased between 2022 and 2023 as previously described but total export value increased (Díaz, 2023). If products become unaffordable that is also a way in which they may become unavailable and decision making in supply chain management is often largely based on costs and not environmental standards. Puma et al. (2015) take costs into consideration in their study by accounting for the financial capacity of different countries and assuming that countries with higher financial resources will have improved access to limited resources. Properly measuring resilience should in some way incorporate some kind of cost analysis to account for accessibility.

In regard to the assessment of full crop failure scenarios, these could be tailored in practice to actual circumstances. Here the crop failure was modelled as being once the lettuce had reached full maturity for illustrative purposes, but crops could fail at any point and therefore inputs could be capped to include only inputs used until the point of failure.

10 Conclusion

This research has explored what resilience looks like through the lens of an LCA. Using scenario building, it has shown that results can vary significantly when accounting for the impacts of disturbance and that resilient system can have a lower environmental impact during these disturbance scenarios.

The way we produce and consume food has a large impact on many environmental indicators and the increasing interconnectedness of the world is making it more difficult than ever to track what impacts our actions have. In this regard LCA is an invaluable tool to provide quantitative information on environmental impacts. It can prevent burden-shifting and target hotspots to show how best to improve a product or system. However, resilience is a crucial part of sustainability according to many, and there has so far been no way to appropriately account for it within the framework of an LCA. The equation proposed by Pizzol (2015) sets an excellent starting point for understanding and communicating the role of resilience in these assessments. When applying the equation to real world cases it requires determining the likely disturbance scenarios and based on those, the design of a resilient system which could withstand such disturbances. However, when applied to agriculture a new concern arose regarding the environmental impacts of failed crops due to disturbance. In the case of 100% disturbance, or full crop failure, a new equation was deemed necessary to adequately allocate impacts. This ensures that any inputs used in the failed crop are accounted for by allocating them to the intended purchaser. These newly proposed equations are an important addition to the existing methodology which help to visualise possible future scenarios and add a level of nuance to calculations of resilience. Overall, results from this report corroborated the findings and claims of Pizzol (2015) that a resilient system does not always equate to a more negatively environmentally impactful system if disturbances are accounted for. This is a topic of increasing importance as disturbances from climate change will become more extreme as we continue to not meet emission reduction targets. Emissions from food systems are a large contributor to climate change but food production can also be part of the solution if we take more care in designing systems which are not only efficient but can withstand an unpredictable future.

Recommendations for further research on this topic are to supplement it by relating it to procurement decision making using a mix of qualitative and quantitative work including interviews and decision analysis. This would further ground the results by adding a more real-world basis of understanding. Another opportunity for further work is to differentiate more between types of disturbances which may have different impacts. Here only a blanket disturbance is used which covers mainly crop losses due to weather conditions and is intended as a catch-all for other possible disturbances. These can be looked at more on a case-by-case level and include upstream disturbances to the sourcing of various inputs such as fertilisers and other consumables used by different farming systems, more fully incorporating the method of prospective LCA. Additionally, this methodology could be used to model past circumstances of disturbance or crop failure to assess accuracy.

The target audience for this LCA is predominantly academics in the field of resilience, food-systems or LCAs as part of the discussion around how to add nuance to the decision-making process based on LCAs. Additionally, these results could be used to help inform consumers about which products have the lowest environmental impacts and inform about which have been produced within a resilient system. This research would also be relevant for city planners and urban farmers as justification for investing capital and energy into expanding the urban farming sector. Another possible target group is grocery distributors who would be able to get an improved understanding of the environmental implications of their sourcing decisions. This research is also affiliated with IVL Swedish Environmental Research Institute and their project called FOCUSE (Food production and provisioning through circular urban systems in European cities) exploring the sustainability and resilience of urban food systems. These results can provide an improved framework for considering resilience when conducting food-related LCAs for any LCA practitioner.

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Appendix I: Data

Table S1. LCI datasets used for system modelling, Ecoinvent v 3.10

Stage	Description	Dataset
Infrastructure	Steel Structure	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S
	Aluminium	market for aluminium alloy, AlLi | aluminium alloy, AlLi | Cutoff, S
	Pumps	market for pump. 40W | pump. 40W | Cutoff. S
	Reinforced Concrete	market group for concrete. normal strength | concrete. normal strength | Cutoff. S
	Glass	market for flat glass. uncoated | flat glass. uncoated | Cutoff. S
	Polyester	market for fibre. polyester | fibre. polyester | Cutoff. S
	PVC	market for polyvinylchloride, emulsion polymerised | polyvinylchloride, emulsion polymerised | Cutoff, S
LED lights	Aluminium	section bar extrusion, aluminium | section bar extrusion, aluminium | Cutoff, S
	Diodes	market for light emitting diode | light emitting diode | Cutoff, S
	HDPE	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, S
	Wire	market for cable, unspecified | cable, unspecified | Cutoff, S
Growing Medium	Peat Moss	market for peat moss | peat moss | Cutoff. S
	Rockwool	market for stone wool, packed | stone wool, packed | Cutoff, S
	Coco Fiber	market for coconut husk | coconut husk | Cutoff. S
Fertilisers	Nitrogen	market for inorganic nitrogen fertiliser. as N | inorganic nitrogen fertiliser. as N | Cutoff. S
	Phosphate	market for inorganic phosphorus fertiliser. as P2O5 | inorganic phosphorus fertiliser. as P2O5 |

		Cutoff. S
	Potassium	market for inorganic potassium fertiliser. as K2O | inorganic potassium fertiliser. as K2O | Cutoff. S
	Potassium nitrate	market for potassium nitrate, agricultural grade | potassium nitrate, agricultural grade | Cutoff, S
	Potassium sulfate	market for potassium sulfate | potassium sulfate | Cutoff, S
	Calcium	market for calcium nitrate | calcium nitrate | Cutoff. S
	Magnesium	market for magnesium sulfate | magnesium sulfate | Cutoff. S
	Nitric Acid	market for nitric acid, without water, in 50% solution state | nitric acid, without water, in 50% solution state | Cutoff, S
	Lime	lime to generic market for soil pH raising agent | soil pH raising agent, as CaCO3 | Cutoff, S
Cultivation	Electricity	market for electricity. medium voltage | electricity. medium voltage | Cutoff. S
	Diesel	market for diesel. low-sulfur | diesel. low-sulfur | Cutoff. S
	Natural Gas	market for natural gas. low pressure | natural gas. low pressure | Cutoff. S
	Carbon enrichment	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, S
	Pesticides	market for pesticide. unspecified | pesticide. unspecified | Cutoff. S
	Seedlings	strawberry seedling production, in heated greenhouse, for planting | strawberry seedling, for planting | Cutoff, S
	Seeds	grass seed production. organic. for sowing | grass seed. organic. for sowing | Cutoff. S
	Water	market for tap water | tap water | Cutoff. S
Transportation	Sweden Road Transport	market for transport. freight. lorry 3.5-7.5 metric ton. EURO5 | transport. freight. lorry 3.5-7.5 metric ton. EURO5 | Cutoff. S
	Europe Road Transport	market for transport. freight. lorry with refrigeration machine. 7.5-16 ton. EURO5. R134a refrigerant. cooling | transport. freight. lorry with refrigeration machine. 7.5-16 ton. EURO5. R134a refrigerant. cooling | Cutoff. S

	Air Transport	market for transport, freight, aircraft with reefer, cooling | transport, freight, aircraft with reefer, cooling | Cutoff, S
Emissions	N2O to air	N2O (Nitrogen Oxide) Emissions
	NH3 to air	NH3 (Ammonia) Emissions to air
	CO2 to air	CO2 Emissions "from soil or biomass" to air
	N to water	Nitrogen (N) to water
	P to water	Phosphorus (P) to water

Appendix II: System Totals

Table S2. System total of Spanish OF lettuce production scaled to 1 hectare

Stage	Description	Amount-ES	Unit	Dataset
	Yield	69,100.00	kg/ha	
Fertilisers	Nitrogen	716.00	kg	market for inorganic nitrogen fertiliser
	Phosphate	692.00	kg	market for inorganic phosphorus fertiliser
Cultivation	Electricity	4,076.90	kWh	market for electricity, medium voltage
	Diesel	414.60	kg	market for diesel. low-sulfur
	Pesticides	20.72	kg	market for pesticide. unspecified
	seedlings	100,195.00	units	strawberry seedling production, in unheated greenhouse, for planting
	Water	4,021,620.00	L	market for tap water

Transport	Europe Road Transport	3,550.00	km	market for transport. freight. lorry with refrigeration machine. 7.5-16 ton. EURO5. R134a refrigerant. cooling
Emissions	N2O to air	6.91	kg	N2O (Nitrogen Oxide) Emissions
	NH3 to air	138.20	kg	NH3 (Ammonia) Emissions to air
	CO2 to air	552.80	kg	CO2 Emissions "from soil or biomass" to air
	N to water	69.10	kg	Nitrogen (N) to water
	P to water	6.91	kg	Phosphorus (P) to water

Table S3. System total of Netherlands hydroponic GH lettuce production scaled to 1 hectare

Stage	**Description**	**Amont-NL**	**Unit**	**Dataset**
	Yield	570,000.00	kg/ha	
Infrastructure	Steel Structure	7,866.00	kg	market for steel, chromium steel 18/8
	Aluminium	2,006.40	kg	market for aluminium alloy, AlLi
	Reinforced Concrete	3.25	kg	market group for concrete. normal strength
	Glass	8,493.00	kg	market for flat glass. uncoated
	Polyester	103.74	kg	market for fibre. polyester
	PVC	5,175.60	kg	market for polyvinylchloride, emulsion polymerised
Growing Medium	Rockwool	6,498.00	kg	market for stone wool, packed
Fertilisers	Nitrogen	758.10	kg	market for inorganic nitrogen fertiliser. as N
	Phosphate	490.20	kg	market for inorganic phosphorus fertiliser. as P2O5
	Potassium	1,048.80	kg	market for inorganic potassium fertiliser. as K2O

	Magnesium	35.28	kg	market for magnesium sulfate
Cultivation	Electricity	780,900.00	kWh	market for electricity. medium voltage
	Natural Gas	50,388.00	m3	market for natural gas. low pressure
	Carbon enrichment	200,640.00	kg	carbon dioxide production. liquid
	Pesticides	33.74	kg	market for pesticide. unspecified
	Seedlings	2,690,400.00	unit	strawberry seedling production, in heated greenhouse, for planting
	Water	877,800.00	L	market for tap water
Transport	Sweden Road Transport	100.00	km	market for transport. freight. lorry 3.5-7.5 metric ton. EURO5
	Europe Road Transport	1,415.00	km	market for transport. freight. lorry with refrigeration machine. 7.5-16 ton. EURO5. R134a refrigerant. cooling

Table S4. System total of OF lettuce production in the United States of America, scaled to 1 hectare

Stage	Description	Amont-USA	Unit	Dataset
	Yield	40,000.00	kg/ha	
Fertilisers	Nitrogen	120.00	kg	market for inorganic nitrogen fertiliser. as N
	Phosphate	160.00	kg	market for inorganic phosphorus fertiliser. as P2O5
	Potassium	120.00	kg	market for inorganic potassium fertiliser. as K2O
	Lime	2,600.00	kg	lime to generic market for soil pH raising agent
Cultivation	Electricity	1,320.00	kWh	market for electricity. medium voltage
	Diesel	800.00	kg	market for diesel, low-sulfur

	Pesticides	8.00	kg	market for pesticide. unspecified
	Seeds	239.60	kg	grass seed production. organic. for sowing
	Water	3,704,000.00	L	market for tap water
Transport	Sweden Road Transport	42.00	km	market for transport. freight. lorry 3.5-7.5 metric ton. EURO5
	Air Transport	8,695.00	km	market for transport, freight, aircraft with reefer, cooling
Emissions	N_2O to air	4.00	kg	N_2O (Nitrogen Oxide) Emissions
	NH_3 to air	36.00	kg	NH_3 (Ammonia) Emissions to air
	CO_2 to air	1,440.00	kg	CO_2 Emissions "from soil or biomass" to air
	N to water	4.00	kg	Nitrogen (N) to water

Table S5. System total of Swedish VF lettuce system, scaled to 1 hectare

Stage	**Description**	**Amount-VF**	**Unit**	**Dataset**
	Yield	742,800.00	kg/ha	
Infrastructure	Steel Structure	103,992.00	kg	market for steel, low-alloyed
	Aluminium	6,462.36	kg	market for aluminium alloy, AlLi
	Pumps	213.18	unit	market for pump. 40W
LED lights	Aluminium	8,245.00	kg	section bar extrusion, aluminium
	Diodes	265.00	kg	market for light emitting diode
	HDPE	1,262.75	kg	polyethylene production, high density, granulate

	Wire	512.50	kg	market for cable, unspecified
Growing Medium	Peat Moss	215.40	m3	market for peat moss
	Coco Fiber	86,662.50	kg	market for coconut husk
Cultivation	Potassium	1,158.80	kg	market for inorganic potassium fertiliser. as K2O
	Potassium Nitrate	3,194.00	kg	market for potassium nitrate, agricultural grade
	Potassium sulfate	1,356.40	kg	market for potassium sulfate
	Calcium	31,717.60	kg	market for calcium nitrate
	Magnesium	1,634.20	kg	market for magnesium sulfate
	Nitric Acid	343.90	kg	market for nitric acid, without water, in 50% solution state
Cultivation	Electricity	7,370,804.40	kWh	market for electricity. medium voltage
	Carbon enrichment	77,251.20	kg	carbon dioxide production. liquid
	Seeds	122.60	kg	grass seed production. organic. for sowing
	Water	7,873,680.00	L	market for tap water
Transport	Sweden Road Transport	5.00	km	market for transport. freight. lorry 3.5-7.5 metric ton. EURO5

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