CHALMERS
UNIVERSITY OF TECHNOLOGY

Pesticide and water footprints of fruits and vegetables imported from Spain

Master’s thesis in Industrial Ecology

LÖFGREN Matilda
VÅNGELL Johanna

DEPARTMENT OF Space, Earth and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se

Master's thesis 2023

Pesticide and water footprints of fruits and vegetables imported from Spain

Matilda LÖFGREN
Johanna VÅNGELL

Department of Space, Earth and Environment,
Physical Resource Theory
Sustainable Land Use and Bioeconomy
Chalmers University of Technology
Gothenburg, Sweden 2023

Pesticide and water footprints of fruits and vegetables imported from Spain
MATILDA LÖFGREN, JOHANNA VÅNGELL

Supervisor: Christel Cederberg, Chalmers University, Department of Space, Earth and Environment
Examiner: Christel Cederberg, Chalmers University, Department of Space, Earth and Environment

Master's Thesis 2023
Department of Space, Earth and Environment
Division of Physical Resource Theory
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Citrus fruits from Spain.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2023

Pesticide and water footprints of fruits and vegetables imported from Spain
MATILDA LÖFGREN, JOHANNA VÅNGELL
Department of Space, Earth and Environment
Chalmers University of Technology

Abstract

Spain is one of the most important food producers in Europe, exporting a large share of their fruit and vegetable production to northern Europe. This makes them an important actor from a Swedish food supply perspective as Sweden is heavily dependent on imports. Agricultural practices such as irrigation and crop protection with pesticides are necessary to pertain high yields, two things that possibly could cause negative effects on ecosystems and human health.

The aim of this thesis is therefore to evaluate the water and pesticide use in Spain and quantify the impact by defining water and pesticide footprints. For this purpose, two crop groups were selected, citrus fruits and vegetables. The evaluation follows a life cycle methodology, starting with an inventory analysis of water use for irrigation and pesticide use, followed by an impact assessment where input data is transformed into impacts using characterisation factors. The water footprint uses regional characterisation factors according to AWARE which weights results depending on the local water scarcity situation. The pesticide footprint on the other hand is created by retrieving characterisation factors for each active substance from the USEtox-model. This results in a comparative factor of the freshwater ecotoxicity for the pesticides.

The results from the inventory analysis showed that there are large differences in both water use and pesticide application between citrus fruits and vegetables. The impact assessment further distinguishes these differences. Considering the freshwater ecotoxicity of pesticides, the impact of vegetables was much higher than the impact of citrus. Furthermore, it could be seen that the pesticide group insecticides contributed most to the pesticide footprint. A conclusion from the impact assessment is that the indicator "applied mass of pesticide" does not represent the impact on freshwater ecotoxicity correctly. The water scarcity footprint on the other hand was in general significantly higher for citrus, but with larger regional variations for the vegetables.

The results of this thesis raise great concerns for the agricultural sector in the future. There are challenges due to pesticide use such as resistance, as well as increased water scarcity risks with a changing climate. Therefore, it is important to further evaluate these two aspects and develop efficient and sustainable methods to maintain high yields.

Keywords: Pesticides, Water Scarcity, AWARE, USETox, Sustainable Agriculture, Spain, Citrus Fruits, Vegetables

Acknowledgements

First of all we would like to thank our involved and enthusiastic supervisor, Christel Cederberg. Your support as well as your eager to share your deep knowledge and opinions with us have been truly inspiring. Furthermore, we would like to acknowledge Ylva Ran at the Swedish University of Agricultural Sciences for your input and feedback within the water and irrigation area. Lastly, we would like to mention our fellow master thesis friends at the SEE department. Our daily lunches and coffee breaks have brought a lot of joy to our days.

Matilda Löfgren & Johanna Vångell, Gothenburg, May 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AS	Active Substance
AWARE	Available Water REmaining
CF	Characterisation Factor
ECOTOX	The ECOTOXicology Knowledgebase.
EFSA	European Food Safety Authority
ESYRCE	Encuesta Sobre Superficies y Rendimientos de Cultivos en España
F	Fungicide
FRAC	Fungicide Resistance Action Committee
H	Herbicide
HRAC	Herbicide Resistance Action Committee
I	Insecticide
INE	Instituto Nacional de Estadística
IRAC	Insecticide Resistance Action Committee
IS	Impact Score
LCIA	Life Cycle Impact Assessment
MAPA	Ministerio de Agricultura, Pesca y Alimentacíon
MoA	Mode of Action
PestLCI	Pest Life Cycle Inventory
PF	Pesticide Footprint
PPDB	Pesticide Properties Data Base
SCB	Statistiska Centralbyrån
WF	Water Footprint
WSF	Water Scarcity Footprint
WSI	Water Scarcity Index

Contents

List of Figures

List of Tables

1

Introduction

The agricultural sector is completely fundamental in order to meet the global food demand. Some studies have even projected that fruit and vegetable production will need to increase by 50 - 150% to satisfy the nutritional needs for the expected 10 billion people by 2050 [1]. To meet this increasing demand it is essential for farmers to transition into more sustainable farming systems to tackle challenges such as climate change, environmental degradation and reduced water supplies [1]. Two resources that are key for optimized crop yields and for fulfilling the growing food demand are water and pesticides. Currently, the agricultural sector is causing a high pressure on both current and future water supplies by utilizing approximately 70 - 80% of the global water resources [2]. Furthermore, the use of pesticides provides many benefits but several negative impacts follow, such as risks for human health, contamination of surface and groundwater, disturbance in community structure and ecosystem functions [3]. Managing pesticides and water more sustainably will hence be necessary to minimize adverse risks for humans and nature, but also to deal with increasing water scarcity risks that follow with the rapidly changing climate.

Sweden is a country that is heavily dependent on food import, especially fruits and vegetables, due to for instance unfavourable climate conditions for farming. Statistics from Jordbruksverket, indicate that during the last 10 years, Sweden has imported approximately 70% more food products than we have exported [4]. This further implies that the Swedish food consumption which heavily relies on import from other countries, is causing significant environmental impacts and resource pressures outside the national borders. This fact was also proven in the PRINCE project (Policy Relevant Indicators for National Consumption and Environment) in 2018, whose purpose was to analyse both the national and international environmental impacts of Swedish consumption [5]. The PRINCE project also showed that the Swedish pesticide footprint, as well as the impact on water resources, is mainly due to import from other countries.

One country that is of specific interest in order to evaluate the Swedish footprints of both pesticides and water, is Spain. According to the latest report by Jordbruksverket on Swedish foreign trade with agricultural products and foods, Spain is one of our most important exporters when it comes to fruit and vegetable categories [4]. This in combination with the fact that Spain is also one of the largest consumers of pesticides in the European Union and prone to high water scarcity risks in the future [6, 7], makes the food import from Spain to Sweden an interesting case to analyse. This thesis will therefore investigate pesticide and water footprints due to

Swedish food consumption, specifically from imported fruits and vegetables from Spain, to evaluate environmental impacts and possibilities for implementing more sustainable farming.

1.1 Aim and scope

The aim of this master's thesis is to investigate the use and potential impacts of pesticides and water in the cultivation process of major crops that are imported to Sweden from Spain. Based on available data, the thesis will examine the possibilities of calculating pesticide and water footprints. If there is sufficient data, LCA and the USEtox model will be used to examine freshwater ecotoxicity impacts due to pesticide use in agriculture. The thesis will also analyse the water footprint and the correlation to water scarcity risks in Spain. These analyses on pesticide and water footprints are necessary to increase knowledge on possible harmful effects and water scarcity risks, and how to manage these resources more sustainably to preserve a long-term, prospering agricultural sector.

To address the topics of pesticide and water footprints, the thesis will answer the following research questions:

- *What data and statistics are available on pesticide and water use in Spanish agriculture, and what are the uncertainties of the data?*
- *Based on available data, is it possible to calculate a pesticide- and water footprint due to the cultivation of major crops in Spain?*
- *Based on the above, how can the calculated pesticide and water footprints be related to Swedish food consumption and how will the Swedish import be affected in the future?*

1.2 Limitations

The thesis will be focused on Spain and will not include import to Sweden from similar countries in the Mediterranean area such as Italy and France. Other large export countries of agricultural products will also be excluded from this analysis. Furthermore, the thesis will only study the largest groups of imported fruits and vegetables from Spain. For the analysis of pesticides, only the three pesticide groups of fungicides, herbicides and insecticides will be included.

2

Theory

This section aims to give a brief background to essential concepts used in this study. To start with, the agricultural system of Spain and the major crops will be introduced, then the import of Spanish crops for the Swedish food supply. Lastly, the effects of intensive farming due to pesticide use and irrigation will be introduced by presenting useful tools to evaluate their impact.

2.1 Crop production and Swedish import

Within the European Union there are a few countries producing a large majority of the food. The largest agricultural countries are France, Germany and Italy followed by Spain [8]. More than 50% of the total land area in Spain is dedicated to agricultural land and they are the second largest producer of fruits and vegetables in the EU and sixth globally [9]. In the southern and south-east of Spain, there are large cultivation areas of fruits such as citrus and apricot, and vegetables like tomatoes, lettuce and peppers [10]. Out of the total production of fruits and vegetables, around 50% is exported. Furthermore, Spain is the leading producer of olive oil and table olives globally, and they are also at the forefront of wine production with Rioja as a famous wine district [9, 10]. In Figure 2.1, the top produced agricultural crops in 2021 are presented.

From a Swedish perspective, the two main trading partners in regard to fresh fruit and vegetables are the Netherlands and Spain [4]. In 2021 Sweden imported goods in the category of fresh and chilled vegetables from Spain to a value of 1658,6 million SEK. That could be compared to the total export from Sweden the same year, in the same category, which was around 660 million SEK [4]. If also considering the import of fresh fruit to Sweden, Spain is again the second largest exporter.

According to Jordbruksverket, some of the largest goods of fruits and vegetables imported to Sweden, independent of export country and in terms of weight, are *citrus fruits, tomatoes, cucumber, lettuce, peppers, bananas and apples*[4]. In Figure 2.2 the total import to Sweden of these fruits and vegetables, is presented together with the share that Spain stands for of the total import. As can be noticed in the figure, Spain stands for a rather large share of many of the imported goods. Thus, considering the importance of Spain for the Swedish food supply it is of great interest to investigate the environmental effects of the agriculture.

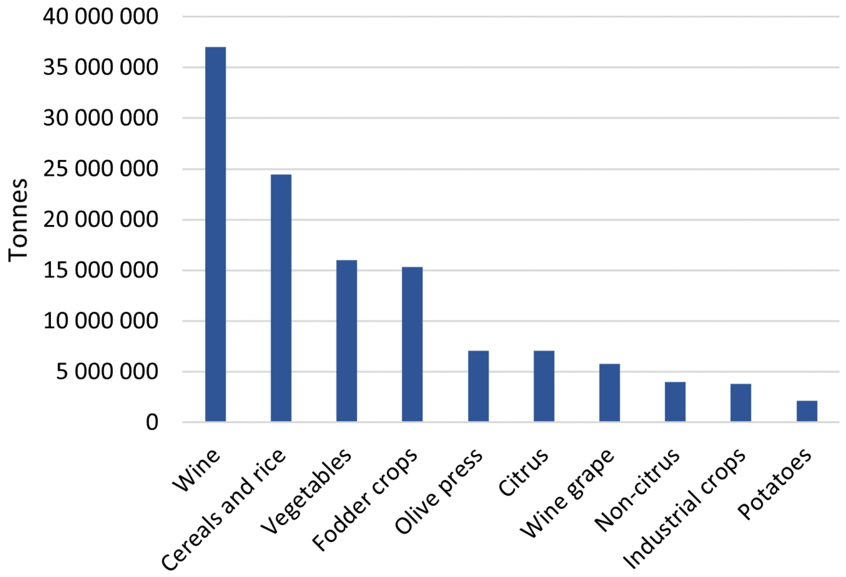


Figure 2.1: Production of the ten most produced agricultural products in Spain 2021, based on data from Statista [11].

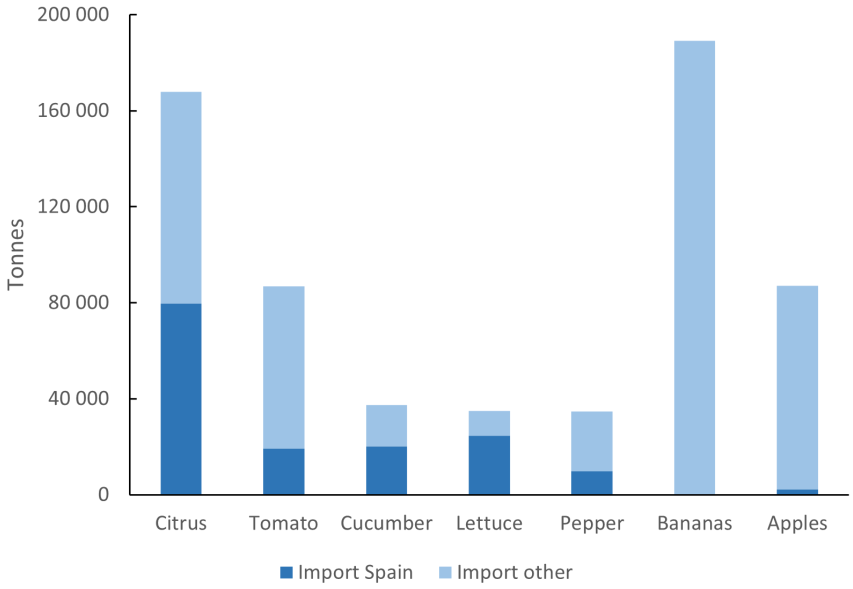


Figure 2.2: Average import to Sweden between 2019-2021 of some of the largest imported goods in the category fruits and vegetables. Statistics retrieved from Jordbruksverket [4] and Eurostat [12].

2.2 Pesticides

Pesticides are substances used to prevent weeds and damage to crops caused by pests. There are different types of pests that can degrade the final harvest, for instance fungus, insects or other types of plants interfering in the fields. Pesticides can therefore be distinguished into different subgroups depending on what type of pest it aims to control. The three largest groups are *fungicides, herbicides and insecticides* but there are also others. As of 2022 around 4 million tonnes of pesticides were used globally [13]. Of this value around 50% were herbicides, 30% insecticides and 17% fungicides [13]. In Spain the total amount of pesticides used in 2020 was around 76 000 tonnes, of which 66 500 tonnes count as fungicides, herbicides or insecticides [14].

It is clear that extensive use of pesticides in agriculture can cause biodiversity loss and degradation of ecosystems [15]. In Europe many substantial effects have been seen the last decades as a result of intensified agriculture. The effects of pesticides are not limited to biodiversity loss but also affect the environmental quality at large, eventually reaching humans. Pesticides can spread in air, soil and water, contaminating areas far from the original application spot [15]. From a human perspective, residues of the substances can be found in the final crop, causing health effects while being consumed.

2.2.1 Difficulties in quantification

There are large difficulties in evaluating the effects of pesticide use due to several reasons. Primarily, there is no standardised methodology of reporting pesticide use and therefore large data gaps exist [13]. The efforts to quantify the use have therefore looked at sales numbers, but this lead to uncertain conclusions that are aggregated to a national level and do not discern local varieties or certain effects on the environment or human health [13]. Moreover, there are large differences between types of pesticides and certain products on the market. Every pesticide consists of one or more active substances, and the specific chemical with a certain mode of action (MoA) that counteracts the pest [16]. The MoAs can have quite diverse pathways and affect the pest in different ways. Some of the more advanced substances could for instance inhibit essential metabolic processes in the pest and in that way prevent infestation [17]. On the other hand, some more fundamental substances can provide physical protection for the crop [18]. These differences in chemical structure and MoA create a variation in efficiency. Some pesticides need to be applied in large quantities while others can be highly effective in a low dose. These differences make it hard to distinguish the toxicity of the substance, as well as the effect it has on human health and the surrounding environment. There is clearly a great need for more accurate methods of evaluating the effects of pesticide use in agriculture.

2.2.2 Future threats

With a globalization of the world, regarding the movement of people and goods due to travel and trading, there is an increased spreading of diseases and invasive species. This has led to the introduction of new pests in areas where the species lack natural enemies. A specific example of this in the context of citrus fruits is the African citrus psyllid, an insect that can act as a vector for the citrus disease *Huanglongbing* (HLB), also called citrus greening disease [19]. The insect has recently been found in Europe, in the corner of Spain and Portugal, and there are great concerns that the disease heavily will affect the citrus industry in Spain [20]. The HLB-virus was spread to the North American continent (Florida) in 2005 and has since then caused large losses in the yearly productions [21].

Another alarming development is the increasing pesticide resistance [22]. In an article by Hawkins et al. a parallel is drawn to the emerging antibiotics resistance in bacteria [23]. Extensive use of pesticides with the same mode of action poses an increased risk of extended resistance [24]. The Insecticide Resistance Action Committee (IRAC) recommends a few strategies, closely correlated to their MoA-classification, to restrict emerging resistance [22]. The main strategy is to continuously change the type of pesticide that is used and select substances with different mode of actions. Furthermore, the use of specific pesticides should be prioritized over broad spectrum substances.

The European Union offers a service via their pesticide database [25]. The database contains most active substances used within the union as well as regulations for each substance. As a consequence of the regulations some active substances have become banned within member countries on a union level. Nevertheless, it is interesting that these substances sometimes are getting exception at national level. One reason for this could be lack of effective pesticides or resistance problems. To bring up an example, the insecticide thiamethoxam (a substance within the group neonicotinoids) was banned in the European Union in 2019 [25], partially due to the threat the substance poses to pollinating insects. Despite this, the sugar beet industry in England received an exemption after a claim that a high percentage of their yield was infected by a virus spread by aphids [26]. The exemption was justified by the lack of other efficient pesticides [27].

2.2.3 Fungicides

From a Spanish perspective, the group fungicide (and bactericides) are the dominating pesticide type, counting for 50% of the total pesticide use in 2020 [14]. Fungicides aim, as the name reveals, to control the growth of fungus on the plants. The Fungicide Resistance Action Committee (FRAC) is an organisation working with questions regarding fungicides and resistance. They also make a classification of different fungicides based on the mode of action of the active substance. The majority of the subgroups have mode of actions affecting the functioning of the fungus cells and therefore preventing growth [17].

2.2.4 Herbicides

Herbicides are the group of pesticides that aim to prevent or inhibit the growth of unwanted vegetation such as weeds and invasive species [28]. In 2020, the herbicide group contributed to about 27% of the total amount of applied pesticides in Spain [14]. Most herbicides are considered to be non-toxic to humans and animals, but the herbicide can on the other hand affect and kill plants in the surrounding environment that other species depend on [28].

The potential effect of the herbicide is heavily dependent on the mode of action (MoA) and application method. The herbicides can be grouped based on their MoA where the Herbicide Resistance Action Committee (HRAC) provides comprehensive information about weed resistance and how to classify and chemically group herbicides [29]. Herbicides have been used for a very long time and the development was revolutionized in 1945 with the introduction of 2,4-D, 2,4,5-T and IPC (isopropyl-N-phenylcarbamate), which were highly toxic and could be applied with 1-2 kg/ha [28]. Since then, other efficient herbicides have been developed, where glyphosate is one of the most used herbicides globally.

2.2.5 Insecticides

Insecticides are the group of pesticides counteracting insects. The use of insecticides in Spain 2020 reached 8 381 tonnes, corresponding to 11% of the total pesticide use in Spain [14]. This makes insecticides the smallest group out of the three in regard to the quantity used. Insects do not only harm the plants themselves but can act as a vector for diseases and spread harmful viruses as in the example in previous sections [19]. The Insecticide Resistance Action Committee (IRAC), classifies insecticides into different groups based on their mode of action [18]. Two interesting groups in this classification are the pyrethroids and the neonicotinoids. The neonicotinoids are a group of substances that were introduced at large scale during the 1990s, standing for around 30% of the global insecticide use in 2018 [30, 31]. The active substances are highly effective and interfere with the insect's nervous system, causing palsy or death, while being less dangerous to other types of animals [31]. Due to the effectiveness only small amounts need to be sprayed on the fields to protect the crops, i.e. being a so-called low-dose pesticide. However, during the 2010s studies showed severe negative effects on pollinator insects which led to a ban of three active substances in the European Union in 2018 [31].

The second group, the pyrethroids, are insecticides used since the 1940s and in 2019 standing for around 25% of insecticides use globally [32]. Pyrethroids are said to have a significantly larger toxic effect towards insects compared to higher animals [32]. However, studies have shown negative effects also for aquatic invertebrates and fish which makes this group interesting from an ecotoxicity perspective. In Sweden the pyrethroids are used for several different crops and resistance has been found in some insects, especially in rapeseed and potato fields [33].

2.3 Evaluating pesticide impacts with LCA

Life cycle assessment (LCA) is a commonly used method to evaluate the impact of a process or a product throughout its whole life cycle. The process consists of several stages such as an inventory analysis where data of emissions, in-going raw material and energy is determined. In the context of this thesis the inventory analysis would mainly focus on data related to pesticides used in Spain. Thereafter the impact assessment (LCIA) is performed in which data is treated and translated into impact categories by using characterisation factors associated with each substance.

Commonly used impact categories are global warming potential (GWP), acidification, eutrophication, water use and resource depletion to mention a few. Both human toxicity and ecotoxicological impacts are included as impact categories in LCA to evaluate emissions of toxic compounds, such as pesticides. However, analysing health impacts and toxicity effects on humans and ecosystems due to pesticide emissions, are seldom included in LCA studies [34, 35]. Yet, these impact categories are of great importance to include due to the harmful effects pesticides can have on human health and the surrounding environment, from where they are initially intended to give the effect. This thesis will therefore address at least one of these impact categories and evaluate ecotoxicological effects in freshwater ecosystems.

Two models that are particularly useful in the context of pesticides are Pest LCI and USEtox consensus models which will be presented in the coming sections. Pest LCI stands for Pest Life Cycle Inventory and is a certain methodology of performing the inventory analysis for pesticides. USEtox on the other hand will be used as a part of the impact assessment.

2.3.1 Pest LCI

A methodology specifically developed for the evaluation of emissions of pesticides is the *Pest LCI.* The model is trying to quantify the amount of pesticide emitted to the environment and the fractions in each compartment [36]. The formula describing the spreading is presented in equation 2.1.

$$f_{em} = \frac{m_{em}}{m_{appl}} = f_{air} + f_{sw} + f_{gw} \tag{2.1}$$

f_{em} is the total fraction of pesticide released into the environment, calculated as the emitted mass over the applied mass. The fraction is then divided into sub-fractions corresponding to different compartments in the environment which are air, surface water and groundwater. Several factors such as wind speed, type of application method or crop size can affect the spreading of the pesticide and the fraction in each compartment.

2.3.2 USEtox

In 2005 a group of researchers experienced issues with different impact results depending on what chemical impact assessment model was used. They initiated the creation of the consensus model USEtox based on principles from, and in collaboration with, the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC) [37]. The main focus of this model is to provide standardized and easy-to-use characterisation factors within the impact categories human health and freshwater ecotoxicity [37], where this thesis focuses on the latter.

When a chemical is released into the environment, the toxicological effects are assessed by analysing the cause-effect chain. This chain describes the environmental impacts caused by the emitted chemical through the three factors; environmental fate, exposure, and effects [37]. Consequently, the characterisation factors in the USEtox model are derived from the product of these three factors [38]. The fate factor illustrates the concentration of the chemical substance in the compartment of interest after solving a set of mass balances, where processes such as degradation and sedimentation lead to the removal of the substance. Then, the exposure factor represents the bio-availability of the substance, i.e. the fraction of dissolved chemical and lastly, the effect factor estimates the relationship between the dose of exposure and severity of an effect, often expressed in EC50 values [38]. In the end, characterisation factors (CFs) in USEtox are representing Potentially Affected Fraction of species (PAF) at mid-point level for freshwater ecotoxicity, expressed in the unit Comparative Toxic Unit (CTUe) per kg emitted substance (1 CTUe = PAF*m^3*day/kg emitted substance). PAF can be interpreted as the fraction of species that is exposed above the EC50 benchmark, i.e. the concentration where 50% of the species are exposed to a certain effect such as mortality, growth and reproduction behaviours [34].

2.4 Evaluating impacts of water use

Freshwater is a natural resource that is vital both for human health as well as for industrial and production processes, where the agriculture sector is the largest user of the global freshwater [2, 39]. However, ecosystems are also dependent on water to sustain vital ecosystem services [40]. With the increasing demand for food, the agricultural sector will continue to put a large pressure on freshwater supplies which also can be problematic due to climate change and undeniable issues with increasing water scarcity risks, and over-exploitation [39]. It is therefore of great importance to implement a more mindful and sustainable water use to be able to continue supporting vital ecosystem services and at the same time meet the growing food demand.

To increase the knowledge on water use, the water footprint (WF) concept was developed in 2002 by Hoekstra and the Water footprint network [40, 41]. The WF was first developed as a volumetric indicator for freshwater use and the focus was put on water productivity. However, since 2009 the LCA community increased their interest in including water use as an impact category [41]. Since the purpose of a LCA is to assess environmental impacts, there was a need for a new methodology to assess water use. Therefore, the LCA community has proposed a weighted water footprint based on water scarcity [42] and hence, a LCA-based water footprint does not necessarily report the volume of consumed water, but it is the caused impact that is of importance [41]. Thus, there are different methodologies when evaluating water use and both methods will be presented next.

2.4.1 Volumetric water footprint by Hoekstra

The WF by Hoekstra [40], is an indicator of the amount of freshwater used, both indirect and direct use throughout the entire supply chain. This means that the volumetric WF does not only consider the direct consumption through the water tap in households, but the water used throughout the supply chain to produce a certain product. Traditionally, only direct consumption is considered by consumers and companies, but the general recommendation is to include both direct and indirect water use which would provide a more complete picture. Furthermore, with the volumetric WF, three different types of water are considered:

- ***Green water*** - the consumption of rainwater along the supply chain, as long as it does not become run-off water [40].
- ***Blue water*** - the consumption of surface and groundwater along the supply chain. Consumption refers to the loss of water in a surface or groundwater source, where losses occur through water evaporation, incorporation in a product or movement to another water body [40].
- ***Grey water*** - the volume of freshwater that is needed to assimilate the pollutants that have been generated during production and restore the water to standard quality. It is thus an indicator of freshwater pollution [40].

The total volumetric WF is then the sum of the green, blue and grey water, commonly expressed as the water volume to produce a unit of product (m^3/tonne) [39]. Calculating water volume requirements in a supply chain can then be used to for instance assess efficiency of water use and compare water usage between products. But also how to fairly allocate water resources globally and how to make supply chains more sustainable from a water perspective [42]. Therefore, according to this methodology, the volumetric unit is key.

2.4.2 LCA-based water footprint with water scarcity index

Due to the purpose of LCA, the potential environmental impact of water use is put in focus, rather than the water consumption itself [42]. In contrast to the volumetric methodology, the LCA community focus on the blue water and takes it one step further and includes a water scarcity index. A framework for the LCA-based water footprint has been formalized in an ISO 14046 standard, but no standardized methodology has existed for applying this standard [43]. On behalf of the UNEP-SETAC Life Cycle Initiative, a group called Water Use in Life Cycle Assessment (WULCA), has worked to reach a consensus-based methodology for assessing water use in LCA.

In 2018, WULCA presented a recommended model for characterisation factors in order to calculate a *water scarcity footprint*. These characterisation factors are based on Available WAter REmaining (AWARE) in a watershed after human and environmental water demands have been met, relative to the world average [43]. The AWARE factor is first calculated as water availability minus the sum of human and environmental water demand (AMD) per unit area and time (m^3/m^2*month). In a second step, AMD is inverted and normalized against the world average result (0.0136 (m^3/m^2*month). The inversion, 1/AMD is limited to a range between 0.1 and 100 where a value of 10 for instance, can be interpreted as a region with 10 times less available water compared to the world average.

2.4.3 Hoekstra vs LCA water footprint

The two methodologies that have been presented, differ in how to assess the water use and there are both pros and cons with each method. On the one hand, Hoekstra and the Water Footprint Network (WFN) mean that the WF should be measured as a volumetric indicator to be able to analyse possibilities for increasing the productivity and efficiency of water use. On the other hand, the LCA community means that it is the environmental impact of the water use that is of importance, where using water from a water abundant basin can be seen as less problematic than exploiting a water scarce source. Hoekstra expresses his critique on the water scarcity based footprint [42], for overlooking several important aspects such as inconsistency with other footprints, the fact that green and blue water are connected and that water is a global resource and every drop of water counts, regardless of the water source, and the question is more about how to make the water use as efficient as possible to achieve "more crop per drop". The LCA community answers to this critique [41]. But the main point that can be made in their answer is to be aware of the differences and that both communities serve different purposes but can potentially be used in synergy to contribute to the common goal of mitigating global water stress [41].

2.5 Irrigation techniques in Spain

One important technique to guarantee sufficient food production in agriculture is irrigation. This technique is of special importance in regions with irregular rainfalls and dry climate conditions. Spain has a historical tradition of using irrigation as a water use technique. In Spain, approximately 23% of the total cultivated hectares are irrigated [44]. Even if this number can seem rather small, the irrigated areas contribute to 65% of the total vegetable production [45]. The Spanish agricultural ministry has also in a survey evaluated and compared crop yields across different Spanish regions, where it can be concluded that irrigated crops have higher crop yields than non-irrigated [46]. Consequently, irrigation is, without doubt, a fundamental technique for the agricultural sector to satisfy the demands for national consumption but also for exports of fruits and vegetables to meet international demands.

The regions in Spain that are the most dependent on irrigation are *C. Valenciana*, *R. de Murcia*, *Cataluña* and *Andalucía* which irrigate approximately 46%, 39%, 33%, 32% respectively, of their total crop area [46]. The Spanish Institute of national statistics estimated in 2018, that the total water used for irrigation was primarily from surface water (74%), followed by groundwater (24%) and then other sources (2%), such as desalinated water or treated waste-water [47].

2.5.1 Types of irrigation

There are several different techniques to irrigate agricultural land and the three most common ones in Spain will be introduced. These are aggregated groups of irrigation techniques and there are several sub-techniques and adaptions that could be implemented.

- ***Gravity irrigation*** - (also called surface irrigation) is globally the most commonly used irrigation method and has been used since ancient times. The technique is simple and irrigation is performed by overflowing the fields with water that infiltrates the soil, eventually reaching the roots of the crops. It can be controlled by creating dykes and furrows, but the spreading of water occurs due to gravity [48].
- ***Sprinkler irrigation*** - Spray or sprinkler irrigation is a methodology where water is spread over the fields from above [48]. Compared to other techniques there are quite high water losses, mainly due to evaporation but also dislocation of the water since the technique is wind sensitive [49].
- ***Drip irrigation*** - A method where pipes are used and placed like a network on the fields or in greenhouses. It is a more expensive technology due to the material needed, but effective and precise when in use. This technology is the most efficient one in regard to water losses since it is easy to control the flow, where water is added and since it has a low evapotranspiration [48]. The system is easily automatized which can be seen as an advantage compared to other techniques [48].

In Spain all three methods are commonly used but there are differences between regions. In the northern parts of Spain there is a smaller variations and a mix of all three types. In the south and eastern regions along the coasts, drip irrigation is dominating [50].

Another interesting aspect while talking about the different irrigation techniques is the water use and the efficiency. Different techniques have, as described above, diverse application methods. Aspects like application method and weather, such as wind and temperature, can affect the efficiency of irrigation. If looking historically over the last two decades the irrigated land in Spain has increased from around 3.4 to almost 4 million hectares [51]. In the meantime, the water consumption due to irrigation has remained stable or even decreased a little [51]. This is due to the gradual change of irrigation techniques where drip irrigation is becoming more and more implemented [52].

3

Methods

This section aims to present the procedure for calculating the pesticide- and water footprint. First, the data collection and data sources will be presented, followed by the methodology behind the selection of crops to calculate footprints for. Then, the equations required to obtain a pesticide- and water footprint will be explained, to at last, present the impact due to the Swedish food import.

3.1 Data collection

The data needed for calculating pesticide and water footprints was retrieved from various data sources. The required data was statistics on agricultural areas and production, data on pesticide and water use and lastly, statistics on the Swedish import. The data sources where this statistics were retrieved from are presented in this section.

3.1.1 Agricultural areas and production

Ministerio de Agricultura, Pesca y Alimentación (MAPA)

Ministerio de Agricultura, Pesca y Alimentación, with the abbreviation MAPA, is the Spanish ministry of agriculture, fisheries and food. MAPA collects all kinds of national data related to agriculture and food production. For the production of the crops of interest in Spain, data was collected from Statistical Yearbooks [53]. In these yearbooks, statistics on total national production in tonnes can be found for all cultivated crops in Spain, as well as production on a regional level.

The data of agricultural hectares was retrieved from both Statistical yearbooks [53], and from a survey on crop surfaces and yields, called ESYRCE [50]. These two data sources provide data on agricultural land in hectares for all cultivated crops in Spain, divided into both "dry land" where rainwater is the only water source needed, and "irrigated land" where irrigation is required. The data on agricultural hectares is available on both national and regional levels.

3.1.2 Swedish import

Jordbruksverket

The Swedish ministry of agriculture, Jordbruksverket is responsible for reporting statistics and publishing reports about the Swedish agriculture and water use for agricultural purposes. In one of their reports on the Swedish foreign trade between 2019-2021, the total import to Sweden of several food categories can be found, where the fruit and vegetable categories were of interest for this study [4].

Eurostat

Eurostat is a department in the European Commission, responsible for reporting high-quality data and statistics within Europe. In one of their databases called *EU trade since 1988 by HS2-4-6 and CN8*, the foreign trade between European countries of several food categories can be found. Consequently, more detailed statistics on the amounts of fruits and vegetables of interest, imported specifically from Spain to Sweden, could be found in this specific database [12].

Statistiska Centralbyrån

Statistiska Centralbyrån (SCB) is the Swedish governmental statistical agency. At SCB, detailed statistics can be found on the Swedish trade and how much Sweden imports from a specific country [54]. Hence, the data found in Eurostat for the import of fruits and vegetables to Sweden from Spain, was compared against the statistics reported by SCB.

In the database, certain codes were needed to search for specific crops. In this report the combined nomenclature (Kombinerade Nomenklaturen, KN) was used [54]. The codes used for searches in the statistical database can be found in Appendix B.

3.1.3 Pesticides

Ministerio de Agricultura, Pesca y Alimentación (MAPA)

All pesticide data was gathered from MAPA, as they provide detailed data on the national pesticide use. MAPA has since 2011 up until 2021, performed an annual Marketing survey and reported the total national use of pesticides in agriculture, also divided into the different classes where fungicides, herbicides and insecticides are included [55].

Furthermore, MAPA has also reported detailed data of the specific active substance (AS) applied on different crops [55]. This data source has been the base for the thesis when calculating the pesticide footprint. MAPA has provided two detailed pesticide reports, one in 2013 and 2019, where the latter was chosen for this thesis. In these reports, the amount of kg applied AS of fungicides, herbicides and insecticides can be found for different crop groups such as citrus, vegetables, olives, grapes and barley.

Furthermore, the total area in hectares that the AS has been applied on is reported. These detailed data are given at national level only.

Food and Agriculture Organization of the United Nations

The data on pesticide use was validated by comparing the statistics provided by MAPA, against reported data from FAOSTAT. They are an organisation by the United Nations that provides all kinds of statistics related to food and agricultural systems for more than 245 countries [56]. To mention a few categories, the database of FAOSTAT includes yearly production of crops and livestock, inputs to agricultural systems such as fertilisers and pesticides, land use and emissions.

FAOSTAT collects data from countries around the world on the national yearly pesticide use, including sub-categories of fungicides, herbicides and insecticides. Consequently, the data provided by MAPA could then be validated by comparing it with the statistics on pesticide use from FAOSTAT.

3.1.4 Irrigation and water use

Ministerio de Agricultura, Pesca y Alimentación (MAPA)

MAPA annually execute a survey of crop areas and yields within the agricultural sector of Spain, ESYRCE [50], including data on irrigated areas categorised per region and irrigation technique; gravity, sprinkler and drip irrigation (Table 3.7.1) [50].

Based on the annual ESYRCE-survey a report analysing irrigation operations in Spain was released, *Análisis de los regadíos en España* [57]. This report evaluates irrigation operations for different crops such as citrus or vegetables. From this report, specified shares of irrigation techniques used for different crop types have been retrieved and used in calculations of water use.

Instituto Nacional de Estadística

Instituto Nacional Estadística (INE), the national Spanish agency for statistics provide data of irrigation volumes per technique in Spain in their database [52]. Both at national and regional levels. The data is an estimation of water consumption per hectare, based on the ESYRCE-reports, conducted annually by MAPA. Besides the database, INE also presents two detailed reports, based on the same data as the database. These are for 2016 and 2018 and have been used as a complement to the database [47, 58].

WULCA

The organisation WULCA, Water Use in Life Cycle Assessment, is a working group designated to create consensus on water use assessments and water footprinting within the life cycle community [43]. WULCA has developed the AWARE methodology of assessing water footprints. AWARE-factors can be obtained on a national level and on a more specified regional level. For this study the regional AWARE factors for Spain have been collected. These factors originally come from the article *Sub-national regionalisation of the AWARE indicator for water scarcity footprint calculations* by Boulay and Lenoir [59]. The full data set can also be found on the WULCA webpage [60]. The AWARE-factors for each region are divided monthly and have one average over the year. Furthermore, the yearly factors are separated into factors for agricultural use (mainly used for irrigation), non-irrigation use and unknown use. The factors implemented in this thesis are the AWARE Sub-national factors, agricultural at regional level.

3.2 Selection of crop groups

This thesis calculated a pesticide and water footprint for a selection of crops. The selection has been based on import statistics and how important Spain is for the Swedish import, as well as the available pesticide- and water data. In the background and specifically in Figure 2.2, it was shown that Spain was rather important for the Swedish import of citrus fruits, tomatoes, cucumbers, lettuce and peppers. This became the primary selection of crops to evaluate. As described in Section 3.1.3 though, the pesticide data provided by MAPA was given for "citrus fruits" and "vegetables" among other crop groups. The citrus group included *clementines, oranges, tangerines* and *lemons*, whereas the vegetable group included *tomatoes, lettuce, melons, broccoli and cauliflower, onions, garlic* and *celery.* It was consequently, not possible to evaluate individual vegetables as desired due to this aggregation. Therefore the final selection of crops to do footprints for was:

- ***Citrus fruits*** - seen as an aggregated group of clementines, oranges, tangerines and lemons
- ***Vegetables*** - seen as an aggregated group of tomatoes, lettuce, melons, broccoli and cauliflower, onions, garlic and celery

This selection was based on the aggregated pesticide data, but even though more detailed data could be obtained in regard to the water use for specific crops, it was decided to evaluate the same selection of fruits and vegetables for both footprints.

3.3 Pesticide footprint

The pesticide footprint calculation can be divided into three steps. First, an inventory analysis was performed, where the pesticide data was analysed in detail. This was followed by the derivation of new characterisation factors to be able to perform the final step of the environmental impact assessment, where emissions of pesticides are translated into impacts. These three steps will be presented in the following sections.

3.3.1 Pesticide inventory analysis

To calculate a pesticide footprint, data of pesticide application in Spain was needed. This data was retrieved from MAPA [55], as described in Section 3.1.3. The documentation in 2019 of applied active substances (AS) has been the base for the pesticide calculations. With the provided pesticide data on kg applied AS of fungicides (F), herbicides (H) and insecticides (I) for different crops, the following result was obtained:

- Total amount of applied AS within each pesticide class (F, H, I)
- Top 10 AS in kg among all pesticides for the crop groups (citrus and vegetables) analysed, regardless of pesticide class
- Top 10 AS in kg within the classes F, H and I for the crops of interest

In order to perform the impact assessment in the next step, the amount of AS emitted to freshwater systems was required. Due to lack of data, it was decided to do a simplified estimation of the released AS to freshwater, instead of using the model Pest LCI, described in Section 2.3.1. This model would have required information about for instance weather conditions, wind speed, soil type, crop size and application method, which was deemed to be too complicated to obtain, especially on a regional level. Therefore, a simplification was made according to a report published by Joint Research Centre (JRC)[61]. JRC has worked with developing a methodology for calculating product environmental footprints (PEF). In this report, JRC has suggested a simplified, default modelling of pesticide emission where 90% AS is assumed to be emitted to the soil compartment, 9% to air and 1% to freshwater. Consequently, in this thesis, it is assumed that 1% of the applied AS on agricultural land is emitted to freshwater. By multiplying this factor with the applied AS [kg AS], an estimation could be made of the released amount of AS to freshwater.

3.3.2 USEtox

In order to perform the last step of assessing the environmental impacts, characterisation factors (CF) for each AS applied were needed. Most CFs for the active substances could be found in the USEtox® model version 2.12, and were retrieved. Some substances were however, not included and new CFs needed to be calculated manually and the process for this will be described in the following section.

3.3.2.1 Missing characterisation factors in USEtox

In a first step, some of the missing CFs in the pesticide data have previously been derived in a report by Nordborg et al. in 2014 [62], which were added to the list in this thesis. However, even after this addition, it was noticed that too many pesticides were still missing to calculate new CFs for and a prioritization was required. The selection process will therefore be described next, followed by a detailed description of how new CFs were derived manually.

I) Selection of pesticides

The selection of active substances to derive new CFs for was done according to three principles and if a CF was missing for an active substance according to these principles, they were added to the list to calculate new CFs for. The principles were:

- Top 10 active substances applied in kg
- Top 10 active substances applied in hectares
- Pesticides used in Spain, but prohibited in the European Union

It is possible that the active substances applied with the highest mass are not the most toxic ones. However, they can still cause a high impact in nature if the dose is high enough, and in a worst case the pesticide is both toxic and applied in large amounts. This is why the top ten pesticides applied in kg are included in the selection. Furthermore, it is also of interest to study the pesticides that are being applied on the largest areas, which is why the top ten pesticides applied in hectares are included. This can indicate that the active substance is more toxic. For instance, an active substance that is being applied in an extremely low dose but is sufficient for a very large area, would indicate a highly toxic active substance. At last, it was also of interest for the selection to include pesticides that are still used in Spain but prohibited in the EU. Most likely, these pesticides are highly toxic and hence, banned to be used.

II) Derivation of new characterisation factors

For the selected active substances that were not included in USEtox® version 2.12, characterisation factors were calculated. This was done according to the methodology used in USETox®, described in the manual *USEtoxTM Chemical-specific database: organics* [63]. The software EPISiuite (EPIWEB 4.1) was used to derive physical and chemical parameters for each substance. This is in line with the recommendations presented by Huijbregts et al. [63]. If experimental data for a substance was lacking the priority order and approach described by Nordborg et al.(Appendix 2) was used [62]. The collected parameters are presented and explained in Table 3.1.

Table 3.1: Explanation of physico-chemical parameters from EPISUITE.

Physico-chemical properties	**Annotation**	**Unit**
Molecular weight	MW	$g * mole^{-1}$
Octanol-water partition coefficient	K_{OW}	
Organic carbon- water partition coefficient	K_{OC}	$l * kg^{-1}$
Henry's law constant	$K_{H,25}$	$Pa * m^3 * mole^{-1}$
Vapour pressure (at 25° C)	$P_{VAP,25}$	Pa
Water solubility (at 25° C)	Sol_{25}	$mg * l^{-1}$
Degradation rate in air	$kdeg_A$	s^{-1}
Degradation rate in water	$kdeg_W$	s^{-1}
Degradation rate in sediment	$kdeg_{SD}$	s^{-1}
Degradation rate in soil	$kdeg_{SL}$	s^{-1}
Measure of ecotoxic effects	$avlog_{EC50}$	

The parameter $avlogEC50$ cannot be found in EPISuite but needed to be calculated manually. This was done according to Equation 3.1 where an average of multiple logarithmised EC50 values for different species are calculated.

$$av_{logEC50} = \frac{\sum_{i=1}^{N} log(x_i)}{N} \tag{3.1}$$

x_i corresponds to the EC50 value for the species. N is the number of unique species used for in the calculations. *av* stands for average.

EC50 values, the concentration at which a species experiences negative effects of a chemical, were collected from three different databases.

- EFSA - European Food Safety Authority
- ECOTOX - The ECOTOXicology Knowledgebase
- PPDB - Pesticide Properties DataBase

EC50 values can be found as either acute or chronic. For the calculations according to Equation 3.1 the chronic value was used. If only acute data was found in the databases the value was treated as in Equation 3.2 below, in line with the methodology described by Norborg et al. [62].

$$Chronic\,EC50 = \frac{Acute\,EC50}{2} \tag{3.2}$$

There are two different levels of avlogEC50 values according to Huijbregts et al., these are *recommended* and *interim* [38]. The difference is the coverage of different species in the avlogEC50 calculations. To be considered *recommended* ecotoxic data at least three different trophic levels were needed. This was done for all the active substances that were calculated manually in this study.

If several experimental data for one species, with the same duration time, were found a geometric mean was calculated, see Equation 3.3

$$Geometric\,mean = \sqrt[n]{x_1 x_2 ... x_n} \tag{3.3}$$

The geometric mean was then treated together with the other chronic EC50-values to form the avlogEC50 for a certain active substance. Lastly, all physical, chemical and ecotoxic parameters were inserted in the USEtox version 2.12 template. The inbuilt equations in the template calculated a characterisation factor for the Midpoint Ecotoxicity Potentials for freshwater with the unit $[CTU_{eq} * kg^{-1}_{emitted}]$.

In general, the final CF can be either interim or recommended not only because of the quality of the *avlogEC50*. It could also be classified as interim due to uncertainties in physical data or properties of the substance. In this thesis no distinction is made between CFs marked interim or recommended, meaning the available CFs in USEtox are used regardless of classification.

3.3.2.2 Comparative AI-methodology

Due to the uncertainties in the conventional avlogEC50 calculations described above, an alternative methodology for retrieving the EC50 values was tested. The AI-driven ecotoxicological predictor *Trident* was used to obtain EC50 values for the three trophic levels of fish, aquatic invertebrates and algae [64].

These values were then used to calculate an avlogEC50 as before according to Equation 3.1. Later on, this avlog was compared to the conventional avlog value to see the effect the methodology has on the result of the characterisation factor.

3.3.3 Freshwater ecotoxicity impact assessment

In order to evaluate the ecotoxicity impact on freshwater ecosystems, the estimated mass of emitted AS to freshwater (1% of kg applied AS) was multiplied with the corresponding toxicity mid-point CF generated by the USEtox model, including the newly calculated CFs in the thesis. This resulted in a freshwater toxicity Impact Score (IS) according to Equation 3.4:

$$IS_{freshwater} = CF_{i,j} * m_i * 0,01 \quad [CTU_{eq} = PAF * m^3 * day] \tag{3.4}$$

Where *CF = characterisation factor, m = applied mass in kg, i= AS of interest* and *j=compartment of interest, in this case freshwater.*

The IS will illustrate how many species that can potentially be affected above the EC50 concentration, in a given compartment (PAF*m^3*day). The IS was illustrated in a similar way as the inventory results to be able to compare the applied mass of AS against the impact the AS generates once released in the environment. As described in Section 2.2 about pesticides, the different AS vary in toxicity and efficiency to counteract the pests. Thus, only evaluating the total mass applied of the AS will not provide the full picture. For example, an AS that is being applied in low doses and on many hectares can still be among the highest IS according to Equation 3.4 if the CF is high enough. Therefore, it was of interest to compare the inventory results of kg applied AS against the impact analysis that was illustrated in the following ways:

- Total IS within each pesticide class (F, H, I)
- Top 10, highest IS among all pesticides for the crops of interest, regardless of pesticide class
- Top 10, highest IS within the classes F, H and I for the crops of interest

3.4 Irrigation and water scarcity footprint

In this thesis, a Water Scarcity Footprint (WSF) was calculated, which was based on available data on the blue water use, in contrast to the green and grey water that was not available. Due to this reason, and the fact that the overall methodology of this thesis is a life cycle assessment, led to a decision of using the LCA-based water footprint.

The concepts of water scarcity, water footprints and water stress are commonly used, but not explicitly defined. The methodology of making a water footprint might therefore change from study to study. In this thesis the definition used by Boulay et al. (2017) has been applied [43]. The two concepts used here are therefore water use (WU), which simply means the quantity of water used per tonne crop, and the Water Scarcity Footprint (WSF), which is the weighted WU by AWARE characterisation factors.

3.4.1 Inventory analysis

Data on blue water use was initially collected from several data sources described above. Regionalised irrigation data was summarised and can be found in Appendix C. Table C.1 contains data of amounts of water used per irrigation technique in each region, while table C.2 summarises the areas irrigated with each technique per region.

Irrigation data provided by MAPA makes a distinction within the irrigation technique sprinkler and separates it into fixed or mobile sprinkler system. To achieve consensus in regard to other data sources these two values have been added together and are to be found in Table C.2 as sprinkler irrigation, along with gravitational and drip irrigation.

The obtained data of water quantities and irrigated areas were then treated to distinguish the efficiencies of each irrigation technique in every region. This was done according to Equation 3.5.

$$\frac{(Water\ quantity)_{i,j,k}}{(Irrigated\ land)_{i,j,k}} = (Irrigation\ efficiency)_{i,j,k}\ [\frac{1000m^3}{ha}] \tag{3.5}$$

i= total-, gravity-, sprinkler- or drip- irrigation. j=region. k=year. This means that four different values of irrigation efficiency were obtained for each region and for several different years.

The total water use (WU) for the crops was then calculated for each region. This was done, for each irrigation technique, by multiplying the total area of irrigated land for the crop in one region, with the share of each irrigation technique used for the crop, and finally the efficiency of that technique in the region (calculated in the previous step).

$$WU_i = Irrigated\ land * share_i * efficiency_i\ [m^3] \tag{3.6}$$

Where *i= gravity- , sprinkler- or drip irrigation.* To obtain the total water use of the crop in the region the water use of all techniques were added together according to Equation 3.7.

$$WU_{tot} = WU_{gravity} + WU_{sprinkler} + WU_{drip}\ [m^3] \tag{3.7}$$

Finally, the total water footprint (WF) was calculated by dividing the total water use by the yearly production of the crop in the region, either total citrus or the vegetable group, see Equation 3.8. This generated a value with the unit $[m^3/tonne]$ that later on could be used for the water scarcity footprint calculations in the impact assessment.

$$WF = \frac{WU_{tot}}{Yearly\ production}\ [\frac{m^3}{tonne}] \tag{3.8}$$

3.4.2 Impact assessment

The results from the calculation on the total blue water footprint in Equation 3.8 were used in a further step to evaluate the environmental impact of the water use according to the LCA-based water footprint (Section 2.4.2). This was based on the methodology presented by WULCA [65], where a water scarcity footprint (WSF) could be obtained by multiplying the water footprint for each crop $[m^3/tonne]$ with the AWARE characterisation factors $[m^3{}_{eq}/m^3]$ by WULCA (Equation 3.9). This generates a yearly water scarcity footprint (WSF) of each crop with the unit $[m^3{}_{eq}/tonne]$ for each region [65].

$$WSF = WF_{i,j} * CF_{AWARE,j} \quad [\frac{m^3_{eq}}{tonne}] \tag{3.9}$$

Where i = *crop of interest* (i.e. citrus or vegetables) and j = *region of interest.*

3.5 The impact of Swedish import of fruit and vegetables from Spain

In order to allocate a reasonable share of the total impacts in Spain to Swedish consumption of fruit and vegetables, import data was needed. This was taken from SCB and Eurostat. SCB has reported a deviant import value from Spain for broccoli and cauliflower that exceeds the total import to Sweden of these vegetables and hence, import statistics from Spain to Sweden were taken from Eurostat.

After the inventory analyses and impact assessments of water and pesticides, footprints were obtained. These will be used in this section to allocate a reasonable share of the environmental impacts in Spain to the Swedish import of food.

3.5.1 Pesticides

The Swedish pesticide footprint was illustrated both for each pesticide class, but also for the total amount of applied fungicides (F), herbicides (H) and insecticides (I). The Swedish pesticide footprint will be illustrated for 2019, as the reported pesticide data by MAPA was provided for that year. As a first step, the total impact score (IS) within each pesticide class, i.e. the sum of IS for all chemicals applied in each class, was divided by the national production of citrus or vegetables in 2019. Hence, a total pesticide footprint of Spain could be obtained by taking the sum of IS/tonne crop for each pesticide class. Then, a Swedish pesticide footprint was calculated by multiplying the Spanish pesticide footprint with the total amount of imported citrus and vegetables to Sweden (see Equation 3.10). The Swedish pesticide footprint was illustrated for each pesticide class individually and as a total impact.

$$Swedish\ \ pesticide\ \ footprint = \frac{\sum IS_{i,j,k}}{tonne\ \ produced\ \ crop} * import_i\ \ [CTU_{eq}] \qquad (3.10)$$

Where *i = citrus or vegetables*, *j = the three pesticide classes F, H or I*, *k = active substance.*

3.5.2 Water

As for the impact on water scarcity of Swedish import the calculations need to be extended. The first step was to create a weighted water scarcity footprint of the four regions that could symbolise an approximated average of Spain on a national level. This was done by multiplying the water scarcity footprint (WSF) of each region with the annual production in that region, see Equation 3.11. The weighted WSFs were summed up and divided by the total annual production in the four regions. This generates a weighted value of Spain, based on the average of the years 2013-2016 and 2018.

$$WSF_{Spain,j} = \frac{\sum_{i=1}^{4} WSF_i * yearly\ \ production_i}{\sum_{i=1}^{4} yearly\ \ production_i,}[\frac{m3, eq}{tonne}] \qquad (3.11)$$

Where i= the four regions of interest for citrus and vegetables respectively

The water scarcity footprint of Spain was then multiplied with the average Swedish import of citrus fruit or vegetables during the same years (2013-2016, 2018).

$$WSF_{Sweden,j} = WSF_{Spain,j} * Swedish\ \ import_j \qquad [m^3, eq] \qquad (3.12)$$

4

Results

4.1 Production of citrus and vegetables

The production of citrus and vegetables is illustrated in Figure 4.1, which is based on average values between 2013 and 2019 provided by MAPA. As can be seen, Spain produces more vegetables compared to citrus, with a production of approximately 10 million tonnes and 7 million tonnes respectively. An interesting aspect is that even though Spain produces less citrus, the agricultural land dedicated to citrus cultivation is larger than for vegetables (Figure 4.2), where the land for citrus is 300 000 ha and for vegetables roughly 200 000 ha.

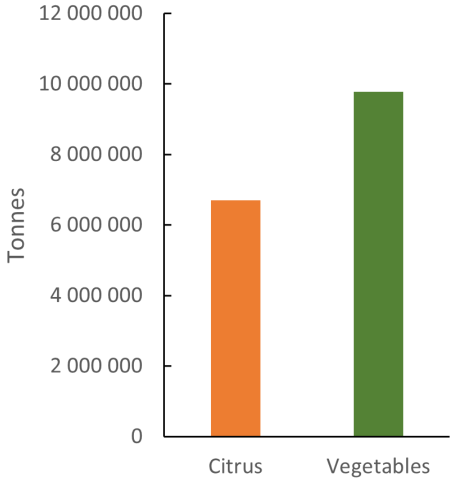


Figure 4.1: Average yearly production (tonnes) of citrus fruits and vegetables during the period 2013-2019.

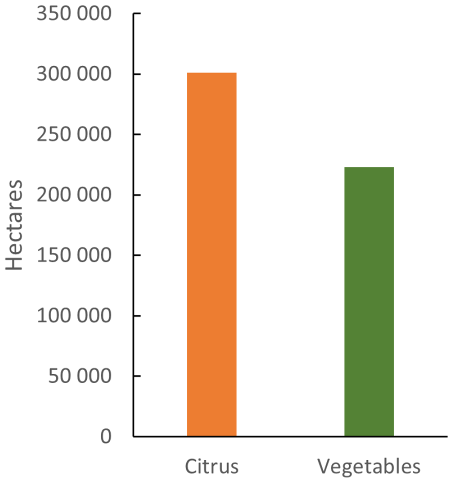


Figure 4.2: Average yearly agricultural land use (ha) for citrus fruits and vegetables, during the period 2013-2019.

When looking at a regional level, the four regions in the east both produce and hold the majority of the land when it comes to citrus production (Figure 4.3-4.4). These numbers are again for the average yearly production and agricultural land between 2013 and 2019. It is clear though, that *C. Valenciana* and *Andalucía* stand out with 85% of the production and 81% of the land use. More detailed data on yearly and regional production and land areas can be found in Appendix A.1 - A.2.

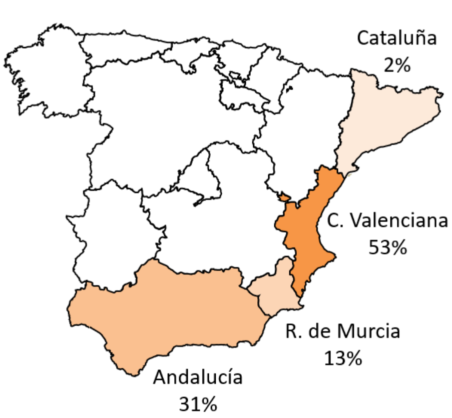


Figure 4.3: Share (%) of national citrus production per region. Based on an average between 2013-2019.

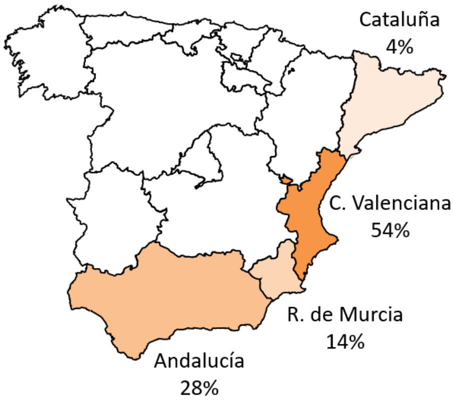


Figure 4.4: Share (%) of national citrus cultivation areas per region. Based on an average between 2013-2019.

For vegetables, the distribution of the production is more evenly spread compared to citrus where the majority of the production is allocated to two regions. As can be seen in Figure 4.5-4.4, the four regions marked are contributing to 84% of the production and hold 79% of the agricultural land dedicated to vegetables. For detailed data on yearly and regional production and land areas, see Appendix A.3 - A.4.

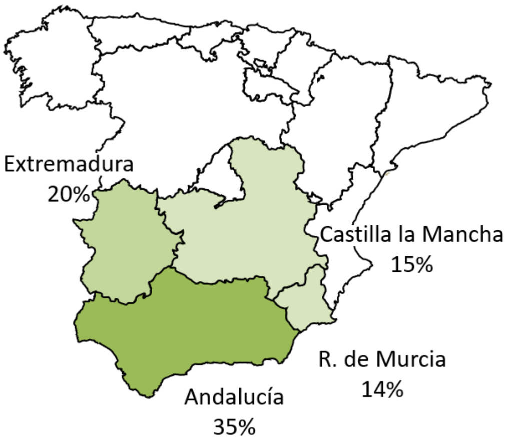


Figure 4.5: Share (%) of national vegetables production per region. Based on an average between 2013-2019.

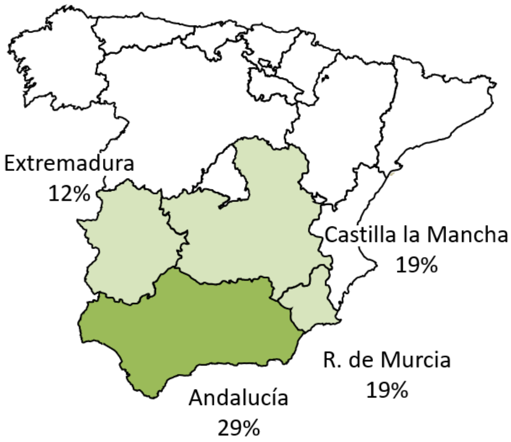


Figure 4.6: Share (%) of national vegetables cultivation areas. Based on an average between 2013-2019.

4.2 Pesticide footprints

In this section, the results for the pesticide footprint will be presented. First, the total use of pesticides in Spain will be illustrated, followed by the pesticide use on citrus and vegetables and at last the freshwater ecotoxicity impact assessment.

4.2.1 Comparison of national pesticide use data

In Figure 4.7, the national pesticide use of the three common classes fungicides (F), herbicides (H) and insecticides (I) given by MAPA [55], is compared against reported data from FAOSTAT [56]. Until 2017, the reported statistics is the same for the two databases, while MAPA reported a higher pesticide use in all classes in 2018 and 2019. By using statistics from MAPA, Spain has applied in average 59 497 tonnes per year of F, H and I between 2013 and 2019.

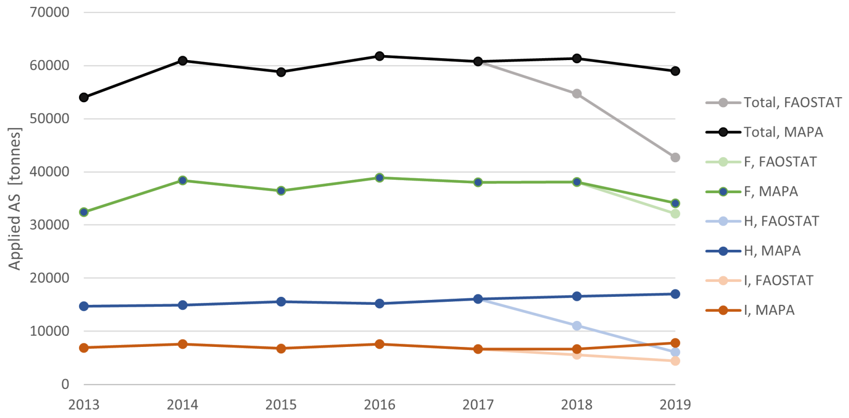


Figure 4.7: Comparision of the national use of pesticides between 2013 and 2019, reported by FAOSTAT and MAPA, where $F = fungicides$, $H = herbicides$, $I = insecticides$ and the *Total* is the sum of the three.

4.2.2 Pesticide use on citrus and vegetables

Detailed statistics of active substances (AS) used per crop group are reported in two surveys by MAPA [55], one in 2013 and another in 2019. In this thesis data from 2019 has been chosen to be analysed. MAPA has reported a use of 103 different AS on citrus fruits when considering the three common classes F, H and I. For vegetables, a use of 201 different AS has been reported. The distribution of the number of AS applied within the different pesticide classes, F, H and I is illustrated below in Figure 4.8.

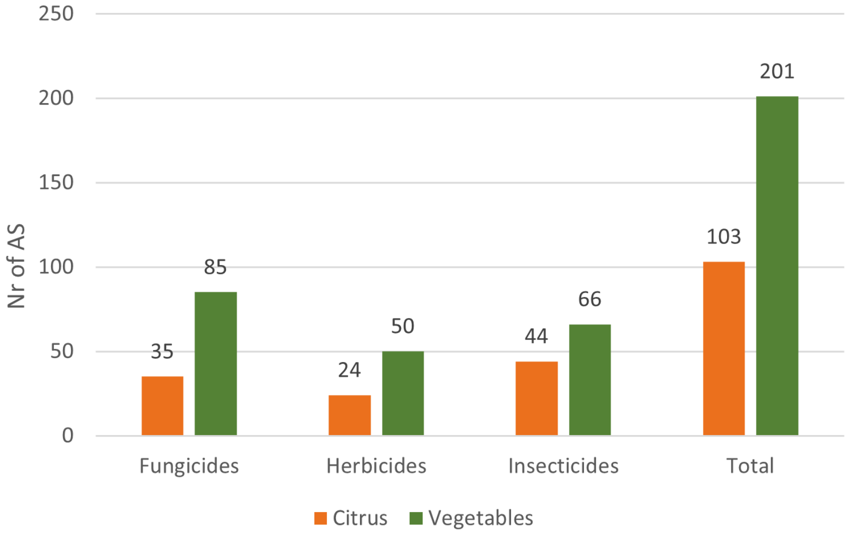


Figure 4.8: Number of active substances applied on vegetables and citrus in 2019.

The amount applied of each AS in kg was reported. Table 4.1 illustrates the total applied amount of F, H and I on vegetables and citrus in 2019. As can be noticed, the total amount of pesticides applied on vegetables is much higher than for citrus. The dominating class of pesticides applied for vegetables is clearly fungicides, whereas for citrus it is insecticides that are the largest group.

Table 4.1: Total amount of applied fungicides, herbicides and insecticides [kg] in 2019 for citrus and vegetables.

Crop	Fungicides	Herbicides	Insecticides	Total
Citrus	370 724	197 333	1 058 896	1 626 953
Vegetables	4 290 261	252 528	241 390	4 784 179

The total amount of applied AS within the classes F, H and I, was divided with the production of citrus and vegetables in 2019 [kg AS/tonne crop], which is illustrated in Figure 4.9, followed by the AS applied per hectares cultivated land, presented in Figure 4.10.

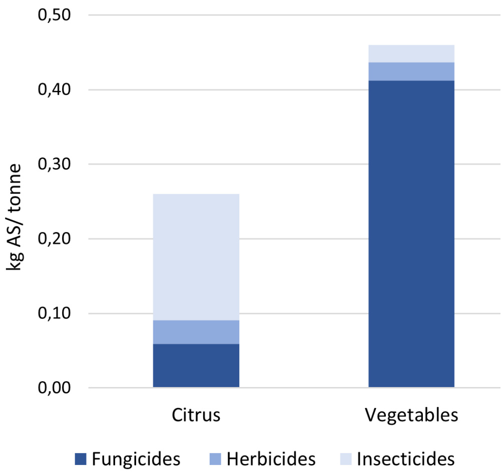


Figure 4.9: Pesticide use presented as kg AS/tonne for citrus and vegetables.

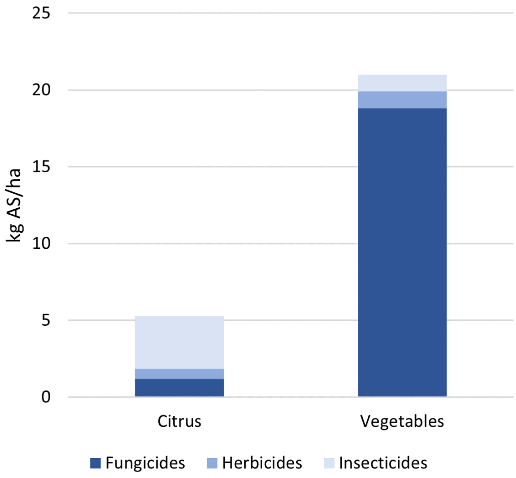


Figure 4.10: Pesticide use presented as kg AS/ha for citrus and vegetables.

4.2.2.1 Top ten applied active substances on citrus and vegetables

When considering the top applied pesticides, they could be illustrated as I) Top ten applied AS among all applied pesticides, II) Top ten applied AS within each pesticide class (F, H and I). Starting with the former, Table 4.2 represents the results for citrus fruits. Among the top ten, it is an even distribution of F, H and I where *Parrafin* is the one dominating with 789 699 kg applied.

Table 4.2: Top ten applied pesticides on citrus fruits in 2019 [kg] as well as which class and share the pesticide represents.

Active substance	**Pesticide class**	**kg applied**	**% of pesticide class**
Parrafin	I	789 699	75
Fosethyl-Al	F	214 812	58
Parrafin oil	I	156 440	15
Glyphosate	H	153 856	78
Mancozeb	F	80 412	22
MCPA	H	28 957	15
Chlorpyrifos methyl	I	27 945	3
Sulfur	F	23 896	7
Copper oxychloride	F	23 836	7
Sulfuryl fluoride	I	15 838	2

In Table 4.3, the ten most used pesticides on vegetables are illustrated. The dominating class of pesticides among the top ten is fungicides, where *Fosethyl-Al* is the most used with 1 629 531 kg applied.

Table 4.3: Top ten applied pesticides on vegetables in 2019 [kg], as well as which class and share the pesticide represents.

Active substance	Pesticide class	kg applied	% of pesticide class
Fosethyl-Al	F	1 629 531	38
Folpet	F	851 360	20
Sulfur	F	835 753	20
Dimethomorph	F	202 958	5
Cyprodinil	F	179 352	4
Mancozeb	F	125 482	3
Fludioxonil	F	119 640	3
Spinosad	I	80 885	34
Copper oxychloride	F	72 368	2
Prosulfocarb	H	64 803	26

The pesticide use is also presented for each pesticide class. Starting with the fungicides, the top ten applied fungicides on citrus and vegetables are presented below in Table 4.4. Many fungicides are overlapping between both crops, where *Fosethyl-Al* is the AS most applied for both crops. It can also be noticed that the top five AS for both citrus and vegetables are dominating and they contribute to 93% and 86% respectively, of the total amount of applied fungicides.

Table 4.4: The top ten applied ***fungicides*** on citrus and vegetables respectively, illustrated in the total amount used [kg] and the share the active substance represents of the total fungicide group.

CITRUS FRUITS			VEGETABLES		
Active substance	**kg**	**%**	**Active substance**	**kg**	**%**
Fosethyl-al	214 812	57,94	Fosethyl-al	1 629 531	37,98
Mancozeb	80 412	21,69	Folpet	851 360	19,84
Sulfur	23 896	6,45	Sulfur	835 753	19,48
Copper oxychloride	23 836	6,43	Dimetomorpho	202 958	4,73
Copper oxide (I)	13 338	3,60	Cyprodinil	179 352	4,18
Metalaxyl	5 169	1,39	Mancozeb	125 482	2,92
Copper hydroxide	2 591	0,70	Fludioxonil	119 640	2,79
Folpet	1 813	0,49	Copper oxychloride	72 368	1,69
Calcium polysulfide	1 140	0,31	Propamocarbo	34 466	0,80
Dimetomorpho	777	0,21	Difenoconazole	25 614	0,60

The top ten applied herbicides on citrus and vegetables are presented below in Table 4.5. The only herbicides that the crops have in common are *Glyphosate, Diflufenican* and *Pendimethalin.* For citrus, it is clear that the two top herbicides, *Glyphosate* and *MCPA* are dominating the as they contribute to 93% of the total amount of applied herbicides. This shows how extremely small the shares of the other 22 applied AS of herbicides must be (See Figure 4.8). For vegetables though, it is a wider distribution where all the top ten AS together contribute with 93% of the applied herbicides.

Table 4.5: The top ten applied ***herbicides*** on citrus and vegetables respectively, illustrated in the total amount used [kg] and the share the active substance represents of the total herbicide group.

CITRUS FRUITS			VEGETABLES		
Active substance	**kg**	**%**	**Active substance**	**kg**	**%**
Glyphosate	153 856	77,97	Prosulfocarb	64 803	25,66
MCPA	28 957	14,67	Pendimethalin	46 156	18,28
Diflufenican	3 473	1,76	S-metolacloro	36 110	14,3
Pendimethalin	3 399	1,72	Propizamide	24 487	9,7
Fluroxypir	2 606	1,32	Aclonifen	21 095	8,35
Oxyfluorfen	2 523	1,28	Glyphosate	12 922	5,12
Dichlorprop-p	645	0,33	Metazachlor	11 274	4,46
2,4-D acid	554	0,28	Metribuzine	11 263	4,46
Propoxycarbazone-Na	260	0,13	Bromoxinil	4 118	1,63
Diquat	248	0,13	Diflufenican	3 780	1,5

In Table 4.6, the top ten applied insecticides on citrus and vegetables are presented. The insecticides *Paraffin, Sulfuryl fluoride, Acetamiprid* and *Bacillus thuringiensis kurstaki (BTK)* are the ones that are overlapping between the crops. The two types of *Paraffin* are the insecticides dominating for citrus fruits as they contribute with 89% of the total amount of applied insecticides. Again, this shows how small the shares of the other 42 AS of insecticides must be (See Figure 4.8). For vegetables, the distribution is much wider where the top ten AS stand for 83% of the total applied insecticides.

Table 4.6: The top ten applied ***insecticides*** on citrus and vegetables respectively, illustrated in the total amount used [kg] and the share the active substance represents of the total insecticide group.

CITRUS FRUITS			VEGETABLES		
Active substance	**kg**	**%**	**Active substance**	**kg**	**%**
Paraffin	789 699	74,58	Spinosad	80 885	33,51
Paraffin oil	156 440	14,77	Sulfuryl fluoride	43 262	17,92
Chlorpyrifos methyl	27 945	2,64	BTK	22 344	9,26
Sulfuryl fluoride	15 838	1,50	Parrafin	14 922	6,18
Pyriproxyfen	8 919	0,84	Beta-cyfluthrin	9 577	3,97
Acetamiprid	8 157	0,77	Chlorantraniliprole	8 713	3,61
Tau-fluvalinate	6 218	0,59	Maltodextrin	8 150	3,38
Etofenprox	5 483	0,52	Acetamiprid	5 176	2,14
Spirodiclofen	5 356	0,51	Deltamethrin	4 800	1,99
BTK	4 490	0,42	Pymetrozine	3 423	1,42

4.2.3 Missing characterisation factors in USEtox

In order to reach the final goal of performing a freshwater ecotoxicity assessment and deriving impact scores for the pesticides described in Section 3.3.3, characterisation factors (CF) were needed. The USEtox® version 2.12, was used to derive CFs for all AS applied on citrus and vegetables. It was however noticed that 10 herbicides, 54 fungicides and 44 insecticides were missing in USEtox and it was decided to derive new CFs for a selection of the missing pesticides.

As explained in the methodology, a few of the missing CFs in the thesis have been derived in a report by Nordborg et.al in 2014 [62], and they were added before the selection process. The derived CFs by Nordborg are presented below in Table 4.7.

Table 4.7: List of characterisation factors missing in USEtox, but derived by Nordborg et.al [62], whether the active substance (AS) is used on citrus (C) or vegetables (V), as well as which pesticide class the AS belongs to.

Active substance	**Used on**	**Pesticide class**	**CF** ($CTU_e/kg_{emitted}$)
Quizalofop-p-ethyl	V	H	27 257
Metrafenone	V	F	29 536
Pyraclostrobin	C, V	F	497 696
Boscalid	V	F	13 597
Epoxiconazole	V	F	112 489
Prothioconazole	V	F	70 791
Beta-cyfluthrin	C, V	I	490 012 232
Chlorantraniliprole	C, V	I	88 704
Thiamethoxam	V	I	3 441
Thiacloprid	V	I	6 256

4.2.3.1 Selection of pesticides for freshwater impact assessment

The selection of pesticides described in Section 4.2.3.1, was based on the three principles: I) Top ten applied AS within each class (F, H, I) in kg, II) Top ten applied AS within each class in hectares, and III) Pesticides that are used in Spain but prohibited in the European Union. Starting with the top ten applied AS within each pesticide class in both kg and hectares, the missing pesticides in USEtox for citrus and vegetables are presented in Table 4.8. Most of the top ten pesticides in hectares were already included in the top ten in kg and thus, only three pesticides were added in the terms of hectares.

Table 4.8: List of missing pesticides in USEtox, based on top active substances applied in kg or hectares, and whether the pesticide is used on citrus (C) or vegetables (V).

FUNGICIDES		
Sulfur	C, V	kg
Copper oxychloride	C, V	kg
Copper oxide (I)	C	kg
Copper hydroxide	C	kg
Calcium polysulfide	C	kg
HERBICIDES		
Dichlorprop-p	C	kg
Propoxycarbazone-sodium	C	kg
Penoxsulam	C	ha
Florasulam	C	ha
INSECTICIDES		
Paraffin	C, V	kg
Paraffin oil (CAS 8042-47-5)	C	kg
Sulfuryl fluoride	C, V	kg
Acetamiprid	C, V	kg
Spirodiclofen	C	kg
Bacillus thuringiensis kurstaki	C, V	kg
Flonicamid	C	ha
Spinosad	V	kg
Beta-cyfluthrin	V	kg
Chlorantraniliprol	V	kg
Maltodextrin	V	kg

Based on the European pesticide database there are a few pesticides that are used in Spain even though they are prohibited at European level. Active substances on that list, that are applied for either citrus or vegetables are presented below in Table 4.9.

Table 4.9: List of pesticides prohibited on European level.

Active Substance	Used for	Pesticide class	In USEtox
Benalaxyl	V	H	No
Famoxadone	C,V	H	No
Fenbuconazole	C,V	H	No
Flutriafol	V	H	No
Isopyrazam	V	H	No
Zeta-cypermethrin	V	I	No
Beta-cyfluthrin	C,V	I	Yes
Bromoxynil	V	H	Yes
Chlorpyrifos	C,V	I	Yes
Diethofencarb	V	H	Yes
Diflubenzuron	C	I	Yes
Imidacloprid	C,V	I	Yes
Indoxacarb	V	I	Yes
Mancozeb	C,V	H	Yes
Phosmet	C	I	Yes
Thiophanate-methyl	C,V	H	Yes

Out of the list on prohibited pesticides, there are six of them that are used on citrus and vegetables in Spain, but miss a CF in USEtox and these were added to the list to derive new CFs for.

4.2.3.2 Derivation of new characterisation factors

New CFs were derived for the selected pesticides presented in the previous section. The selection resulted in deriving new CFs for 10 fungicides, 4 herbicides and 12 insecticides. As described in the methodology in Section 3.3.2.1, several physicochemical factors were needed and derived in EPIsuite for each pesticide, and the parameters used can be found in Appendix D.2. Furthermore, ecotoxicity data i.e. EC50 values, was required for at least three trophical levels and the calculations for this data to derive avlogEC50 values, can be found in Appendix D.1.

The calculated CFs for the selected pesticides are presented below in Table 4.10. As can be noticed, for some pesticides it was not possible to derive new CFs. For *Paraffin*, the CAS-number was missing, *Bacillus thuringiensis kurstaki* is a bacteria and hence not a chemical, and the other pesticides could not be found in EPIsuite. Some pesticides are marked with a * in the list, indicating that a simplification was made. The three pesticides of copper have been given a CF of 56 300 since these three have been treated as the inorganic compound Cu(II) that has a value in USEtox. Regarding *Zeta-cypermethrin* that is also marked with a *, a CAS-number was found for this insecticide. However, EPIsuite interpreted it as *Cypermethrin* and *Zeta-cypermethrin* has received the same CF as Cypermethrin. Two pesticides in the list are marked with **, and those pesticides have been taken from the report by Nordborg et al. [62], see Table 4.7.

Table 4.10: List of the derived characterisation factors (CF) for the selected pesticides, presented as active substance its belonging CF with the unit $\mathrm{CTU}_e/\mathrm{kg}_{emitted}$.

FUNGICIDES	
Active substance	**CF**
Copper hydroxide *	56 300
Copper oxide (I) *	56 300
Copper oxychloride *	56 300
Sulfur	-
Calcium polysulfide	-
Benalaxyl	8 810
Famoxadone	3 410 000
Fenbuconazole	56 100
Flutriafol	11 500
Isopyrazam	-
HERBICIDES	
Active substance	**CF**
Dichlorprop-p	143
Propoxycarbazone-sodium	9 500
Penoxsulam	42 500
Florasulam	128 000
INSECTICIDES	
Active substance	**CF**
Paraffin	-
Paraffin oil (CAS 8042-47-5)	344
Sulfuryl fluoride	-
Acetamiprid/Acetaprid	572
Spirodiclofen	719 000
Bacillus thuringiensis kurstaki	-
Flonicamid	54
Spinosad	5 450
Beta-cyfluthrin **	490 012 232
Chlorantraniliprole **	88 704
Maltodextrin	-
Zeta-cypermethrin *	50 300 000

* Simplification was made

** CF derived by Nordborg et.al [62]

4.2.4 Freshwater ecotoxicity impact assessment

After deriving new CFs, the freshwater ecotoxicity impact assessment was done according to the methodology described in Section 3.3.3. In order to determine a national impact and the top ten pesticides with the highest impact scores (IS), Equation 3.4 was used to derive IS for all AS applied on citrus and vegetables. An example with a calculation of the IS is provided in Appendix E.

4.2.4.1 National and regional freshwater ecotoxicity impact

The impact scores (IS) for all applied active substances, were summed up within each pesticide class (F, H and I) and divided with both the amount of produced crop (IS/tonne crop) and agricultural land (IS/ha), and the results can be seen in Table 4.11-4.12. Although some characterisation factors are still missing, this provides an indication of the impact. Vegetables have a significantly higher total impact and the insecticides stand out for both crops.

Table 4.11: Sum of the impact scores within each pesticide class, divided with tonne produced crop [CTU_e/tonne crop].

Crop	**Fungicides**	**Herbicides**	**Insecticides**	**Total**
Citrus	14	3	77	94
Vegetables	975	41	4 642	5 658

Table 4.12: Sum of the impact scores within each pesticide class, divided with hectares of agricultural land [CTU_e/ha].

Crop	**Fungicides**	**Herbicides**	**Insecticides**	**Total**
Citrus	292	61	1 561	1 914
Vegetables	44 498	1 859	211 772	258 129

The share that each pesticide class represents of the total impact score per tonne crop, is visualised in Figure 4.11-4.12 (the shares are the same per hectare). In these figures, the shares of F, H and I in kg AS/kg crop are also included as a comparison between the mass applied and the corresponding freshwater impact. For citrus, the share of applied pesticides in kg is mostly allocated to insecticides (65%) and the same applies for the impact where the insecticides stand for 82% of the IS, while herbicides only represent 3% of the impact. When looking at the vegetables though, the majority of kg applied pesticides are fungicides (90%), while the IS is dominated by the insecticides (82%) and the herbicides are almost not even visible and stand for less than 1 % of the impact.

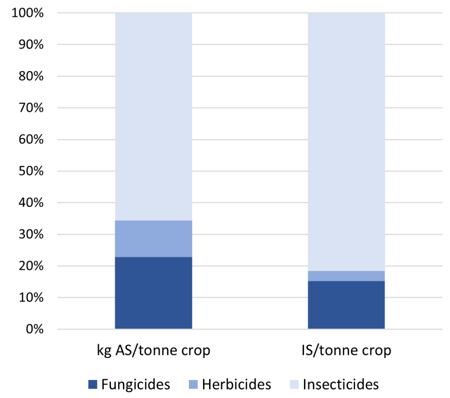


Figure 4.11: The share that each pesticide class (F, H or I) represents for citrus, presented for both the mass AS applied (kg AS/tonne) and the freshwater toxicity impact score (IS/tonne).

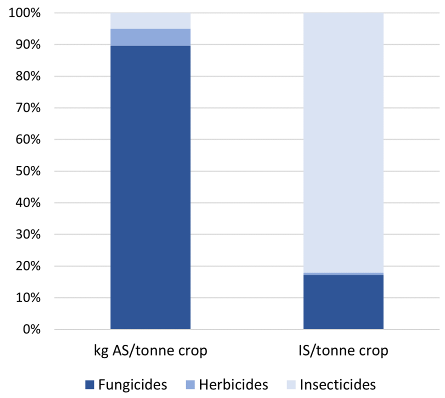


Figure 4.12: The share that each pesticide class (F, H or I) represents for vegetables, presented for both the mass AS applied (kg AS/tonne) and the freshwater toxicity impact score (IS/tonne).

An average impact for the largest producing regions could be obtained by multiplying the total IS/tonne crop with the amount of produced crop in each region of interest, and the results can be seen in Figure 4.13-4.14. Note, the large difference in the scale of IS between the figures. This result is however, based on the assumption that all regions apply equally large amounts of pesticides and use all active substances that are reported by MAPA. Thus, with this calculation the impact is only allocated based on how much each region produces, when in reality each region can use different large amounts of pesticides and apply a selection of the reported active substances. A more accurate regional impact could however not be obtained due to lack of data.

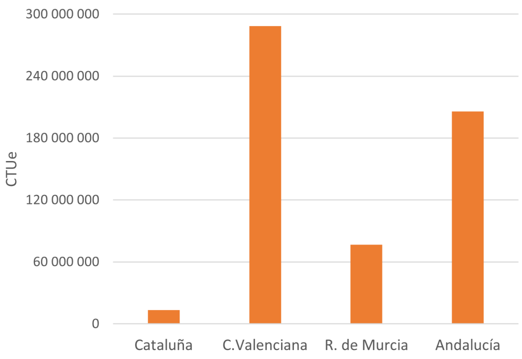


Figure 4.13: Impact scores (CTU_e) presented for the four largest producing regions of citrus fruits.

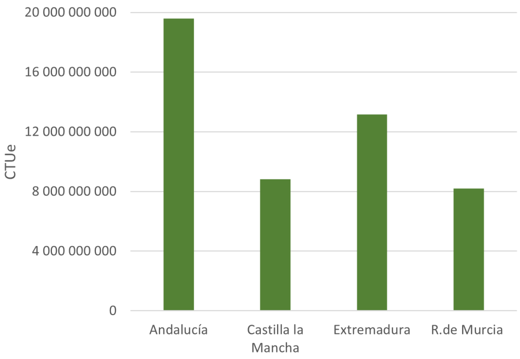


Figure 4.14: Impact scores (CTU_e) presented for the four largest producing regions of vegetables.

4.2.4.2 Top pesticides contributing to potential freshwater ecotoxicity

In Table 4.13, the top ten highest IS for citrus fruits and vegetables are illustrated. The coloured marks in the table illustrate pesticides that are not included in the top ten in kg applied. Thus, a large majority of the pesticides are not included in the corresponding list of the top ten in kg applied (see Table 4.2-4.3). Furthermore, the insecticides are contributing to a great majority of the impacts, with a representation of 80% for citrus and 50% for vegetables. Compared then to the mass applied, the insecticide class was standing for 40% for citrus and only 10% for vegetables. This illustrates the high ecotoxicity impact that insecticides are causing, even if they are applied in lower amounts.

Table 4.13: The top ten highest impact scores [CTU_e] for citrus and vegetables, which pesticide class the active substance belongs to and the mass applied on land.

CITRUS FRUITS

Active substance	**Class**	**Impact score**	**kg**
Chlorpyrifos methyl	I	203 722 112	27 945
Abamectin	I	74 906 550	4 381
Tau-fluvalinate	I	53 160 395	6 218
Mancozeb	F	42 296 665	80 412
Spirodiclofen ***	I	38 512 228	5 356
Lambda-cyhalothrin	I	27 247 654	530
Folpet	F	20 307 056	1 813
Beta-cyfluthrin**	I	19 061 476	4
Pyriproxyfen	I	16 946 347	8 919
Pyridaben	I	16 695 206	2 358

VEGETABLES

Active substance	**Class**	**Impact score**	**kg**
Beta-cyfluthrin **	I	46 929 696 489	9 577
Folpet	F	9 535 235 248	851 360
Cypermethrin	I	777 225 540	1 545
Pendimethalin	H	211 395 075	46 156
Chlorothalonil	F	207 250 632	18 180
Deltamethrin	I	164 641 715	4 800
Aclonifen	H	139 440 528	21 095
Chlorpyrifos	I	131 895 953	2 117
Fludioxonil	F	118 084 542	119 640
Lambda-cyhalothrin	I	105 095 010	2 045

** CF derived by Nordborg et.al [62]
*** CF derived in this thesis

The top ten highest IS within each pesticide class were also determined. Starting with the fungicides, the highest IS for citrus and vegetables can be seen in Table 4.14. Only three of the fungicides for both crops are coloured, indicating that a majority of the top ten IS are included in the top ten in kg applied (see Table 4.4). However, *Sulfur* and *Calcium polysulfide* are among the top ten in kg applied, but an IS could not be calculated due to missing characterisation factors. It is of interest to notice the difference between the mass applied. For instance, *Pyraclostrobin* is only applied with 131 kg compared to *Fosethyl-al* and *Mancozeb* that are the two dominating pesticides with 214 812 and 80 412 kg applied. But the high CF for *Pyraclostrobin* results in a high impact. Or, in the case of *Folpet* for vegetables, both the dose and CF are high which results in an extremely high IS.

Table 4.14: The top ten highest impact scores [CTU$_e$] for fungicides and their belonging characterisation factor [CTU$_e$/kg$_{emitted}$] and mass applied on land.

CITRUS			
Active substance	**kg**	**CF**	**IS**
Mancozeb	80 412	52 600	42 296 665
Folpet	1 813	1 120 000	20 307 056
Copper oxychloride *	23 836	56 300	13 419 555
Copper oxide *	13 338	56 300	7 509 108
Fosethyl-al	214 812	1 490	3 200 694
Copper hydroxide*	2 591	56 300	1 458 491
Pyraclostrobin **	131	497 696	651 733
Captan	433	84 800	367 074
Difenoconazole	134	129 000	172 538
Metalaxyl	5 169	956	49 414
VEGETABLES			
Active substance	**kg**	**CF**	**IS**
Folpet	851 360	1 120 000	9 535 235 248
Chlorothalonil	18 180	1 140 000	207 250 632
Fludioxonil	119 640	98 700	118 084 542
Mancozeb	125 482	52 600	66 003 290
Cyprodinil	179 352	28 000	50 218 501
Copper oxychloride*	72 368	56 300	40 742 908
Difenoconazole	25 614	129 000	33 042 628
Pyraclostrobin **	4 928	497 696	24 527 504
Fosethyl-al	1 629 531	1 490	24 280 018
Azoxystrobin	22 524	77 000	17 343 241

* Simplification was made (see Section 4.2.3.2)

** CF derived by Nordborg et.al [62]

The top highest IS for herbicides can be seen in Table 4.15. Most of the herbicides with the highest impacts are also included in the top ten in kg applied, where *Pendimethalin* clearly has the highest impact score for both citrus and vegetables. An interesting aspect is the fact that *Glyphosate* and *MCPA* are the dominating herbicides in kg applied on citrus (see Table 4.5), while the other active substances among the highest IS are being applied with significantly lower doses but still, result in a high impact due to the characterisation factor. For vegetables, it is a wider distribution of the mass applied, but it is clear that the two pesticides *Pendimethalin* and *Aclonifen* stand out when considering the final impact.

Table 4.15: The top ten highest impact scores [CTU_e] for herbicides and their belonging characterisation factor [$\text{CTU}_e/\text{kg}_{emitted}$] and mass applied on land.

CITRUS			
Active substance	**kg**	**CF**	**IS**
Pendimethalin	3 399	458 000	15 567 557
Oxyfluorfen	2 523	63 800	1 609 904
MCPA	28 957	1 880	544 389
Glyphosate	153 856	321	493 876
Diquat	248	77 000	190 860
Fluroxypir	2 606	2 910	75 840
Florasulam***	58	128 000	73 856
Diflufenican	3 473	1 700	59 040
Penoxsulam***	117	42 500	49 725
Fenoxaprop-p-ethyl	71	57 400	40 829
VEGETABLES			
Active substance	**kg**	**CF**	**IS**
Pendimethalin	46 156	458 000	211 395 075
Aclonifen	21 095	661 000	139 440 528
S-metolacloro	36 110	114 000	41 165 275
Prosulfocarb	64 803	31 000	20 088 815
Terbuthylazine	1 038	473 000	4 909 125
Metribuzine	11 263	9 470	1 066 572
Propyzamide	24 487	4 290	1 050 498
Phenmedipham	2 441	42 100	1 027 619
Metazachlor	11 274	7 450	839 941
Bromoxinil	4 118	16 500	679 422

*** CF derived in this thesis

When evaluating the AS that contributes to the highest impact scores for the insecticides, a clear majority of the pesticides are not included among the top ten insecticides in kg applied, see Table 4.16. However, an IS for *Paraffin, Bacillus Thuringiensis Kurstaki* and *Maltodextrin* that are among the top ten in kg applied, could not be calculated due to missing characterisation factors. When analysing the list of highest IS, many of the insecticides are highly toxic with extremely high characterisation factors in USEtox. Even a very low amount can cause a high impact, which is the case for *Beta-Cyfluthrin* and *Cypermethrin* with only 4 kg and 19 kg applied respectively on citrus. What is alarming then, is that *Beta-Cyfluthrin* is used on vegetables with a rather high amount and is included in the top ten in kg applied, which also leads to the highest IS of all pesticides (see Table 4.13).

Table 4.16: The top ten highest impact scores [CTU$_e$] for insecticides and their belonging characterisation factor [CTU$_e$/kg$_{emitted}$] and mass applied on land.

CITRUS			
Active substance	**kg**	**CF**	**IS**
Chlorpyrifos methyl	27 945	729 000	203 722 112
Abamectin	4 381	1 710 000	74 906 550
Tau-fluvalinate	6 218	855 000	53 160 395
Spirodiclofen***	5 356	719 000	38 512 228
Lambda cyhalothrin	530	5 140 000	27 247 654
Beta-cyfluthrin**	4	490 012 232	19 061 476
Pyriproxyfen	8 919	190 000	16 946 347
Pyridaben	2 358	708 000	16 695 206
Chlorpyrifos	217	6 230 000	13 509 755
Cypermethrin	19	50 300 000	9 335 680
VEGETABLES			
Active substance	**kg**	**CF**	**IS**
Beta-cyfluthrin**	9 577	490 012 232	46 929 696 489
Cypermethrin	1 545	50 300 000	777 225 540
Deltamethrin	4 800	3 430 000	164 641 715
Chlorpyrifos	2 117	6 230 000	131 895 953
Lambda cyhalothrin	2 045	5 140 000	105 095 010
Alpha cypermethrin	194	35 000 000	67 998 000
Zeta-cypermethrin*	47	50 300 000	23 666 150
Chlorpyrifos methyl	2 457	729 000	17 910 291
Tetrafluthrin	171	10 500 000	17 909 850
Abamectin	921	1 710 000	15 757 479

** CF derived by Nordborg et.al [62]
*** CF derived in this thesis

4.2.5 Alternative methodology to evaluate ecotoxicity

Table 4.17 presents results of another methodology of retrieving the *avlogEC50*-values for an AS. These values come from the AI-driven prediction model Trident described in Section 3.3.2.2.

The values predicted by the model are considered acute data and therefore divided by two to form chronic values, all according to the methodology described in Section 3.3.2.1 and Equation 3.2.

Table 4.17: EC50 values for 72h duration and three trophic levels, from Trident. [mg/L].

Substance	**Fish**	**Aquatic invertebrate**	**Algae**	***avlogEC50***
Glyphosate	22,8392	6,5933	5,1519	0,9633
Mancozeb	1,3897	0,0208	1,5231	-0,4521
Folpet	0,0804	0,1518	8,2907	-0,3316
Fosethyl-al	43,6932	133,7172	3,3631	1,4311
MCPA	57,4992	11,3527	7,3904	1,2278
Captan	0,1405	0,6327	0,5944	-0,4257
Alpha-Cypermethrin	0,0049	0,0001	0,0728	-2,5829
Lambda Cyhalotrin	0,0005	0,0002	0,5028	-2,4745
Imidacloprid	66,2570	0,4894	0,0307	-0,0007

Table 4.18 summarises the *avlogEC50* values calculated by using Trident and presented in the table above, as well as the inbuilt *avlogEC50*-value in the USEtox (version 2.12) template. Furthermore, the corresponding characterisation factors are presented to give an indication of how the ecotoxicological variations might affect the final CFs.

Table 4.18: Comparison of avlogEC50 values and characterisation factors (CF), inbuilt USEtox values or retrieved with Trident.

Substance	**avlogEC50**		**CF** (CTU$_e$/kg$_{emitted}$)	
	Trident	Usetox	Trident	Usetox
Glyphosate	0,96	1,47	1,03E+3	3,32E+2
Mancozeb	-0,45	-0,43	5,51E+4	5,26E+4
Folpet	-0,33	-1,63	5,66E+4	1,12E+6
Fosethyl-al	1,43	1,12	7,27E+2	1,49E+3
MCPA	1,23	2,00	5,33E+2	9,33E+1
Captan	-0,43	-0,5	7,19E+4	8,48E+4
Alpha-Cypermethrin	-2,58	-3,48	4,42E+6	3,50E+7
Lambda Cyhalotrin	-2,47	-4,47	1,40E+6	1,29E+8
Imidacloprid	-0,0007	0,93	2,69E+4	3,20E+3

From the table, it is clear that the ecotoxical data from the two methodologies vary and generate different characterisation factors. Although, there is no clear trend that USEtox or Trident always generates higher or lower results.

4.3 Water footprints

In this section, results correlated to water use will be presented. Initially some general data of irrigation techniques in Spain, later on the inventory analysis of water used for the crops of interest. Finally, a water scarcity footprint of the two crop groups will be presented.

4.3.1 Irrigation techniques in Spain

Figure 4.15 and 4.16 shows a general picture of the distribution of irrigation techniques in Spain [50]. These figures are based on the quantity of land irrigated with each technique. As can be seen in Figure 4.16, there is a geographical variation where drip irrigation is dominating in the southern part of Spain. In the mid/north parts there is a more diverse distribution, and in some regions gravity and sprinkler irrigation are used for the majority of the land. This is probably due to the different water scarcity situations in the regions which creates diverse demands for efficient irrigation.

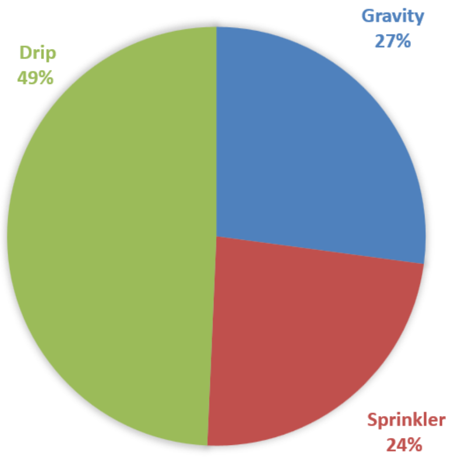


Figure 4.15: Share of land irrigated with each technique, Spain [50].

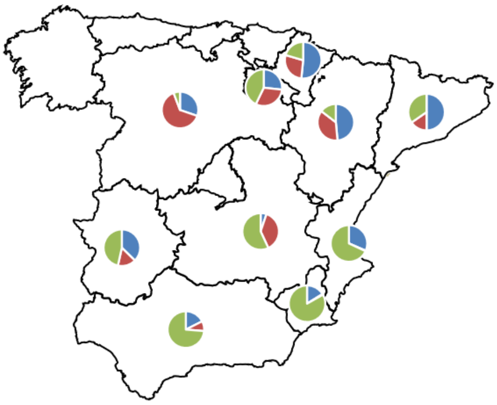
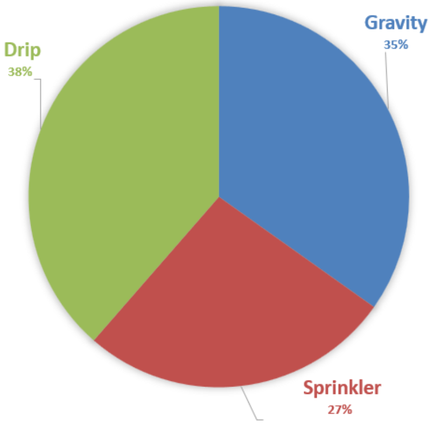


Figure 4.16: Share of land irrigated with each technique, per region [50].

Figure 4.17 and 4.18 visualises the total amount of water used by different techniques [52]. The left figure corresponds to Spain in general while the right map is divided into regions. Some regions are not considered due to lack of data. The shares reflect an average for the years 2018 and 2016-2013.



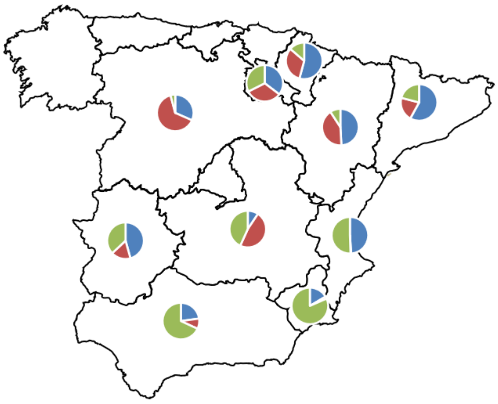


Figure 4.17: Share of water volumes used per technique in Spain [52].

Figure 4.18: Share of water volumes used per technique, per region [52].

What is interesting while observing these two different figures, one based on the quantity of irrigated land and the other based on water used by each technique, is that the shares differ. There are differences in how much water each technique uses per hectare in the different regions. This can be seen if comparing Figure 4.15 and 4.17 where the drip irrigation counts for around 49% in regard to ha, but only 38% in regard to water volume.

Figure 4.19 shows geographical differences in water availability according to the AWARE-factors for each region. There are clear differences between the regions and the availability is most critical along the coast of the Mediterranean sea.

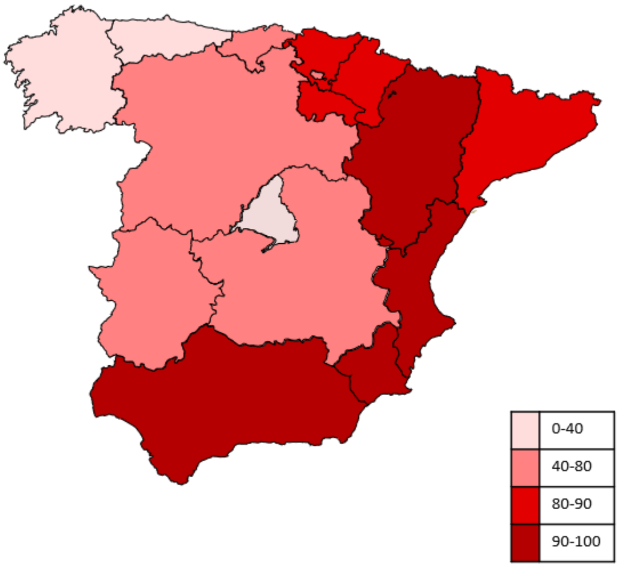


Figure 4.19: AWARE factors $[m^3_{eq}/m^3]$.

4.3.2 Water use

4.3.2.1 Citrus fruits

Table 4.19 summarises the calculations of water used irrigation (i.e. blue water) per tonne crop. These values are calculated according to the methodology presented in section 3.4.1. Full data sets of the data used for the calculations can be found in Appendix C, Table C.1, C.2, C.3 and Appendix A, Table A.1, A.2. Initially, calculations for the years 2013-2016 and 2018 were made. The year 2017 was excluded due to lack of data. Furthermore, an average of the five years was made and was used later on for water scarcity footprint calculations.

Table 4.19: Water use ($\frac{m^3}{tonne}$) in citrus cultivation, per year and region.

Region	Year	Water use
Cataluña	2018	196
	2016	129
	2015	145
	2014	170
	2013	187
	Average	165
C. Valenciana	2018	149
	2016	143
	2015	182
	2014	110
	2013	152
	Average	147
R. de Murcia	2018	116
	2016	134
	2015	167
	2014	138
	2013	156
	Average	142
Andalucía	2018	135
	2016	145
	2015	171
	2014	161
	2013	139
	Average	150

The results presented above in Table 4.19 are visualized below in Figure 4.20 for a better understanding of yearly variations and trends. It is possible to distinguish a trend for the regions *C. Valenciana*, *R. de Murcia* and *Andalucía* where an increase in water use can be seen in 2015 and a decrease the following years. Cataluña on the contrary follows another pattern with a minimal water use in 2016 and a drastic increase to the next measured year, 2018. All calculated values of water use per tonne citrus fruit range between 110-200 m^3 per tonne.

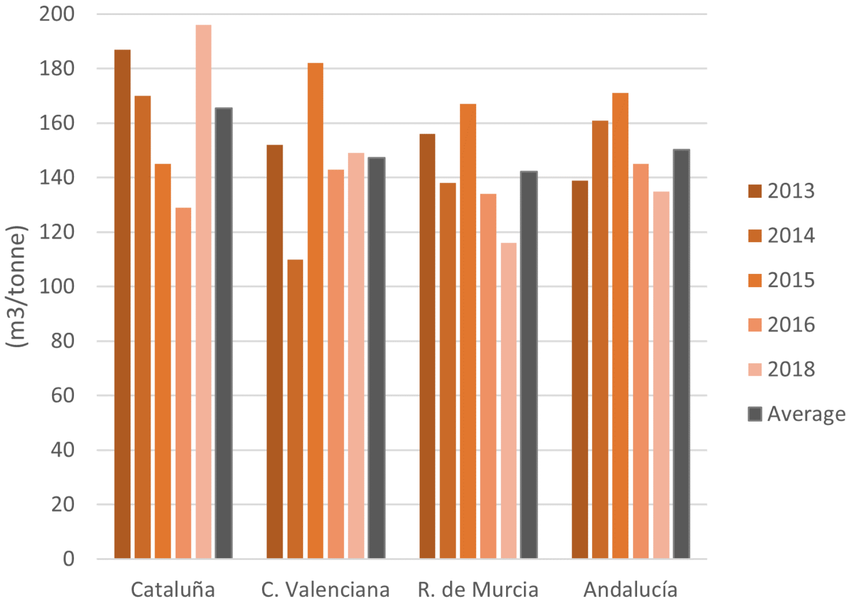


Figure 4.20: Water use per tonne citrus fruits in the four selected regions. Yearly calculations and five-years average.

4.3.2.2 Vegetables

Table 4.19 summarises the calculations of water use per tonne crop. These values are calculated according to the methodology presented in section 3.4.1. Full data sets of the data used for the calculations can be found in Appendix C, Table C.1, C.2, C.3 and Appendix A, Table A.3, A.3. Initially, calculations for the years 2013-2016 and 2018 were made. The year 2017 was excluded due to lack of data. Furthermore, an average of the five years was made and was used later on for water footprint calculations.

Table 4.20: Water use ($\frac{m^3}{tonne}$) in vegetable cultivation, per year and region.

Region	Year	Water use
Andalucía	2018	84
	2016	75
	2015	83
	2014	85
	2013	77
	Average	81
Castilla la Mancha	2018	82
	2016	116
	2015	91
	2014	84
	2013	92
	Average	93
Extremadura	2018	90
	2016	85
	2015	70
	2014	65
	2013	97
	Average	81
R. de Murcia	2018	114
	2016	163
	2015	197
	2014	130
	2013	126
	Average	146

The results presented above in Table 4.20 are visualized below in Figure 4.21 for a better understanding of yearly variations and trends. The region of Murcia attracts attention due to the high water use compared to the other regions. *Andalucía*, *Extremadura* and *Castilla la Mancha* are similar in water use per tonne crop and presents smaller variations over the years. *R. de Murcia* on the contrary shows a drastic increase in the water use between the years 2014-2015 and the value is thereafter decreasing to a similar level as in the years 2013-2014.

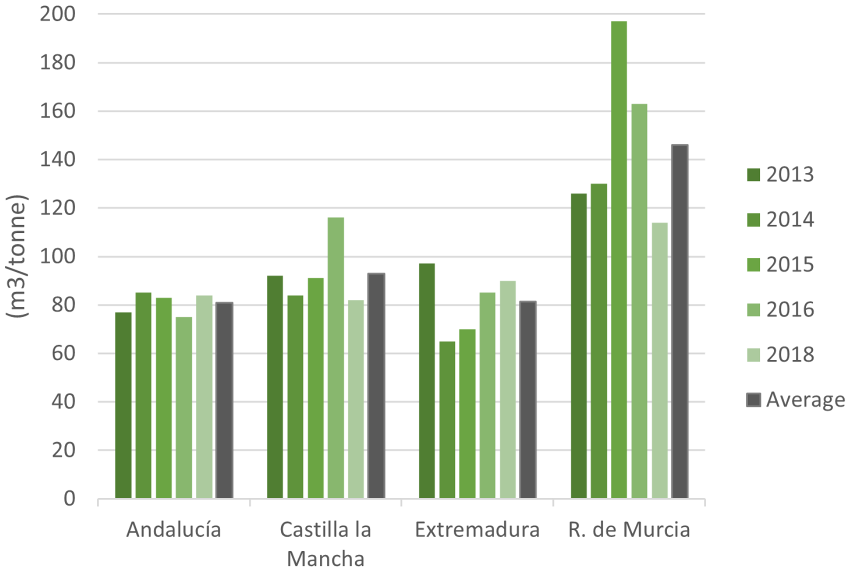


Figure 4.21: Water use per tonne vegetables in the four selected regions. Yearly calculations and five-years average.

4.3.3 Water Scarcity Footprints

4.3.3.1 Citrus fruits

The water footprint calculations were made by using the AWARE factors for each region and according to the methodology described in Section 3.4.2. This created a weighted impact value for each region and these are summarised in Table 4.21. The water scarcity footprint for one tonne of citrus fruit became around 14 000 $m^3_{eq}/tonne$ for all regions that were analysed. As can be seen in the table all regions have a relatively high AWARE-factor.

Table 4.21: Water scarcity footprint for citrus based on average water use of the years 2018 & 2016-2013 for each region.

Region	**Water use** $(m^3/tonne)$	**AWARE factor**	**Water scarcity footprint** $(m^3_{eq}/tonne)$
Cataluña	165	84,45	13 934,3
C. Valenciana	147	97,90	14 391,3
R. de Murcia	142	99,74	14 163,1
Andalucía	150	94,16	14 124,0

4.3.3.2 Vegetables

The water scarcity footprint calculations were made by using the AWARE factors for each region, found in Appendix C, Table C.4 and according to the methodology described in Section 3.4.2. This created a weighted impact value for each region and these are summarised in Table 4.22. As can be seen in the table the AWARE factors are ranging between 50-100 and are more diverse compared to the case of citrus. The water scarcity footprint for one tonne of vegetables became around 14 000 $m^3_{eq}/tonne$ for the region of Murcia which stands for the highest water footprint, the three other regions have a significantly lower footprint.

Table 4.22: Water scarcity footprint for vegetables based on average water use of the years 2018 & 2016-2013 in each region.

Region	**Water use** ($m^3/tonne$)	**AWARE factor**	**Water scarcity footprint** ($m^3_{eq}/tonne$)
Andalucía	81	94,16	7 627,0
Castilla la Mancha	93	64,85	6 031,1
Extremadura	81	49,15	3 981,2
R. de Murcia	146	99,74	14 562,0

Figure 4.22 below shows a comparison between the different regions of interest for citrus and vegetables as well as for the two crop types. This figure indicates that the water scarcity footprint in general is higher for citrus than for vegetables. Whereas, there also are large differences between regions, especially for the vegetables.

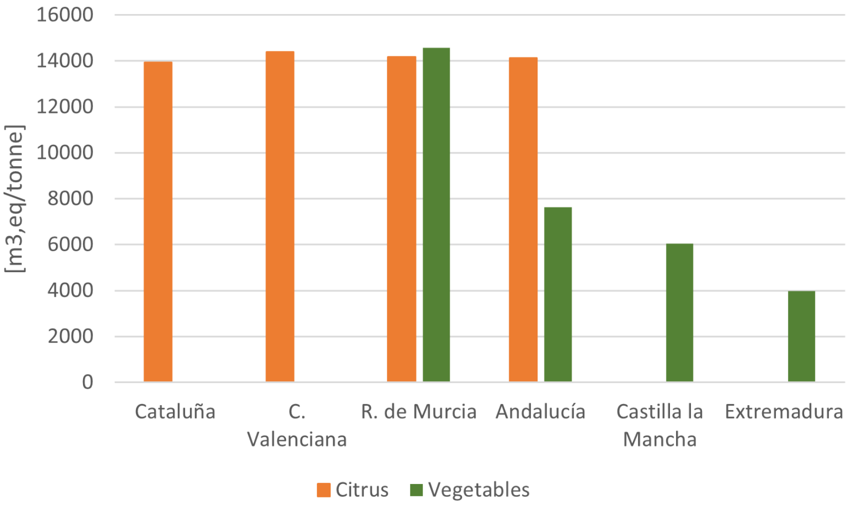


Figure 4.22: Comparative figure of water scarcity footprints ($m^3_{eq}/tonne$) for the two crop groups and selected regions.

4.4 The Swedish consumption pesticide- and water footprint

To calculate a Swedish consumption pesticide- and water footprint for citrus and vegetables imported from Spain, import statistics were used for the crops of interest. Below in Figure 4.23 the average, total import to Sweden between 2019-2021 is presented, along with the share originating from Spain. This gives an indication of how important Spain is for satisfying the Swedish needs of these crop groups. To generate the footprints, yearly import data to Sweden from Spain was needed, which can be found in Appendix B for 2013-2019.

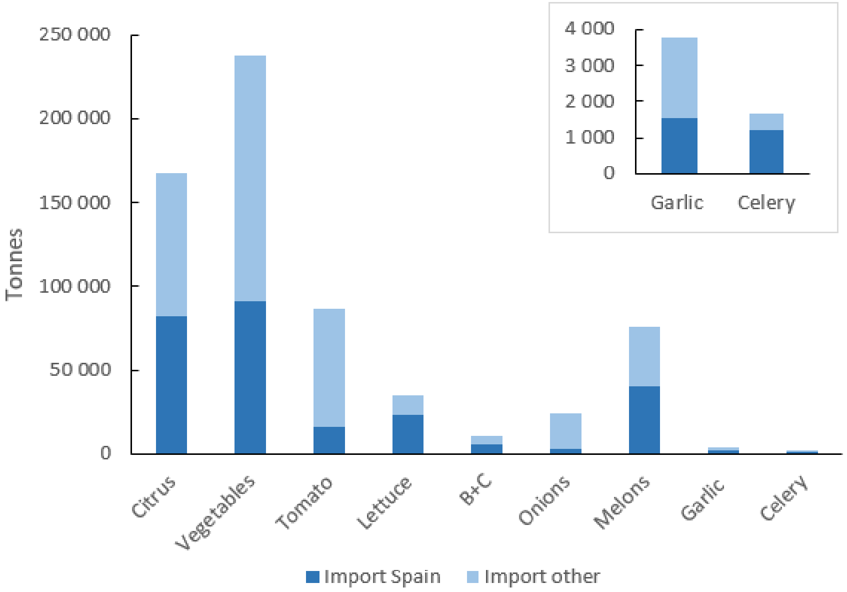


Figure 4.23: Average yearly import (2019-2021), to Sweden of the selected fruits and vegetables, presented as a total import (Jordbruksverket [4] and SCB [54]) and the share that Spain stands for (Eurostat [12]). The import of "vegetables", is the sum of all vegetable crops presented in the figure. Note, B+C stands for broccoli and cauliflower.

4.4.1 Pesticide footprint

The Swedish pesticide footprint was calculated, by multiplying the Spanish impact scores per tonne crop (see Table 4.11) with the import amounts to Sweden in 2019 (see Appendix B.3). The Swedish pesticide footprint is presented in Figure 4.24, which is illustrated for each pesticide class and as a total impact in the unit CTU$_{eq}$ (PAF*m^3*days). This calculation is based on the assumption that all reported active substances are used on the citrus fruits and vegetables that Sweden imports from Spain. In reality though, the regions in Spain that Sweden imports from most likely apply a selection of all the pesticides reported. Hence, these numbers are based on that all regions use all reported pesticides in similar amounts.

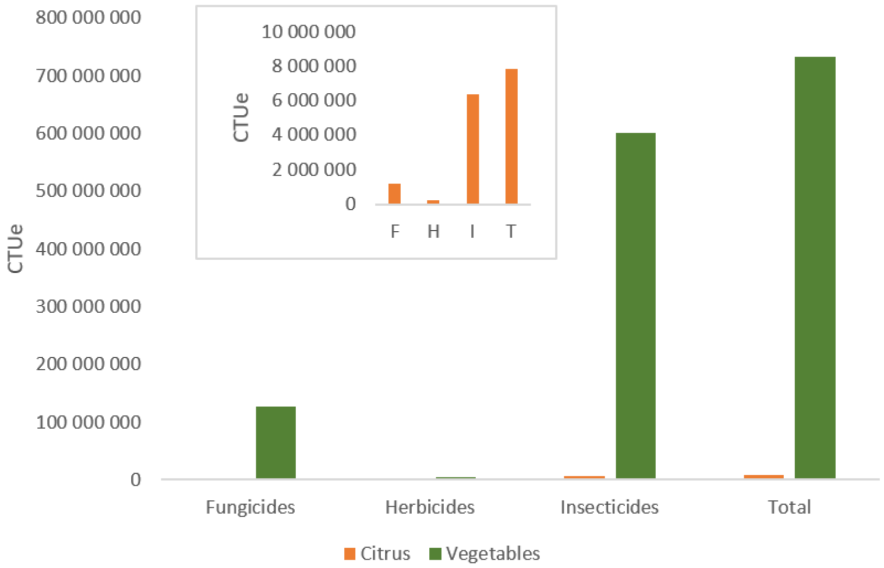


Figure 4.24: Pesticide footprint due to the Swedish import of citrus fruits and vegetables, presented as the impact score [CTU_e] that each pesticide class generate due to the Swedish import.

With the assumptions and uncertainty in the data, it can still be concluded that the Swedish import of vegetables causes a significantly higher impact than the import of citrus and the insecticides are the dominating class of the impact for both crops.

4.4.2 Water scarcity footprint

The results from the calculations of a Swedish footprint regarding water due to import from Spain are presented below in Table 4.23. The weighted WSF is based on an average of the years 2013-2016 and 2018, and adjusted, according to the methodology in Section 3.5.2, to reflect the production in each of the four regions. For Swedish imports, only national data is available. Thus, an assumption is made that the Swedish import of vegetables and citrus from Spain follows the regional production shares.

Table 4.23: Water scarcity footprint of Swedish import.

Crop	**Weighted WSF** [$m^3_{eq}/tonne$]	**Import** [$tonne$]	**Water Scarcity Impact** [m^3, eq]
Citrus	14 271	79 732	1 137 856 069
Vegetables	7 692	111567	858 192 521

This means that the average annual water scarcity footprint that Swedish import of citrus fruit and vegetables causes is 1,14 and 0,85 billion cubic meters of water equivalents respectively.

5

Discussion

5.1 Pesticide use and potential freshwater ecotoxicity impact

In this thesis, it was found that Spain has a significantly higher pesticide use of fungicides, herbicides and insecticides on vegetables, with around 4 784 tonnes applied, compared to citrus fruits with 1 627 tonnes. This resulted in a use of 0,46 kg AS/tonne vegetables and 0,26 kg AS/tonne citrus fruit.

An interesting aspect when evaluating the top ten active substances (AS) applied in mass, was that these ten chemicals were always contributing to the majority of the pesticides used. For instance, *Glyphosate* and *MCPA* represented 90% of the total herbicide use on citrus out of a total of 24 AS, meaning that the other chemicals are applied in much smaller amounts when only a few pesticides dominate. However, a very important point made in this thesis is that the use of pesticides as mass AS, is not a reasonable indicator when evaluating the environmental impact. If only considering pesticides applied in high amounts, the top ten in this case, low-dose pesticides that can be highly toxic will be excluded from the impact analysis. But as was shown in the case of vegetables in Figure 4.12, the insecticides used on vegetables represented only 4% of the total pesticides used, but as much as 82% of the total freshwater ecotoxicity impact quantified.

This highlights the necessity and importance of not excluding low-dose pesticides when performing an impact assessment. This was also shown in the results when evaluating the top ten highest impact scores (IS) of the insecticides, where a majority of the AS were not included in the corresponding top ten list in kg. For instance, *Beta-cyfluthrin* and *Cypermethrin* have a total use of only 4 kg and 19 kg respectively on citrus, but still made it to the top ten list of highest IS due to their extremely high characterisation factors (CFs). As can be seen in Table 5.1, these two insecticides have the highest CFs of all pesticides analysed and they belong to the group of the so called pyrethroids [18].

Table 5.1: The top 10, highest characterisation factors (CF) of all pesticides used in Spain, presented together with the class the pesticide belongs to, as well as the chemical classification.

Active substance	**Class**	**Chemical group**	**CF** ($CTU_e/kg_{emitted}$)
Betacyfluthrin	I	Pyrethroids	490 012 232
Cypermethrin	I	Pyrethroids	50 300 000
Zeta-cypermethrin	I	Pyrethroids	50 300 000
Alpha cypermethrin	I	Pyrethroids	35 000 000
Esfenvalerate	I	Pyrethroids	19 000 000
Diflubenzuron	I	Benzoylureas	12 000 000
Tetrafluthrin	I	Pyrethroids	10 500 000
Chlorpyrifos	I	Organophosphates	6 230 000
Lambda cyhalothrin	I	Pyrethroids	5 140 000
Deltamethrin	I	Pyrethroids	3 430 000

According to this list, the insecticides and specifically the pyrethroids are highly toxic and should be avoided which is currently not the case for Spain where seven pyrethroids are used and included in the top ten list of highest IS for vegetables. This also resulted in an extremely high total IS per tonne vegetable, compared to citrus fruits (Table 4.11). If *Beta-cyfluthrin* was removed though, it would have decreased the IS for insecticides from 4 642 CTUe/tonne vegetables to as little as 131 CTUe/tonne. If also removing the fungicide *Folpet* that has the second highest IS overall, the total IS for vegetables could decrease from 5 658 CTUe/tonne vegetable to only 231 CTUe/tonne, which is visualised in Figure 5.1-5.2. Hence, finding substitutes that are less harmful, or even removing *Beta-cyfluthrin* and *Folpet* would decrease the freshwater ecotoxicity impact significantly for vegetables.

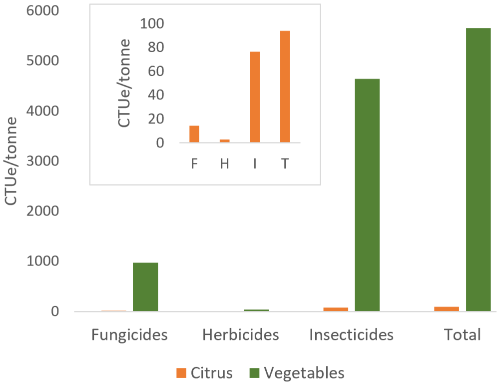


Figure 5.1: Impact scores per tonne crop (CTU_e/tonne) for each pesticide class, with all pesticides in the given data included.

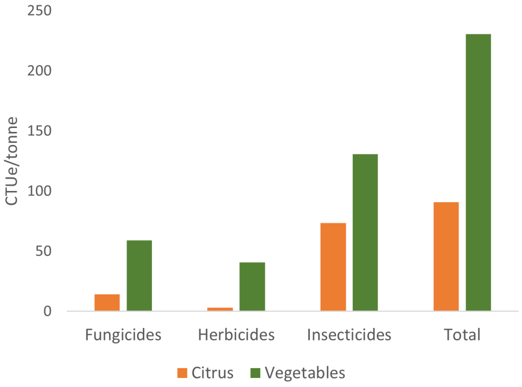


Figure 5.2: Impact scores per tonne crop (CTU_e/tonne) for each pesticide class, without *Beta-cyfluthrin* and *Folpet*.

These results have pointed out the high freshwater impacts the insecticides are causing, especially the pyrethroids. However, another group of insecticides called the neonicotinoids such as *Acetamiprid* and *Imidacloprid* [18], are used in Spain and cause severe negative effects on our important pollinator insects [31]. But from a freshwater ecotoxicity perspective, they instead had a low impact. This emphasizes the challenges of evaluating biodiversity losses due to pesticide emissions. Both in regard to the fact that a holistic impact assessment needs to assess all pesticides, not only those applied in the highest amount, but also that the magnitude of impact varies for different species and in different ecosystems.

5.2 Water use and potential environmental impact

The water footprints, both as use and as scarcity footprint, for citrus fruits show that there are no large differences between the four selected regions but that Cataluña, on average, has the highest water use. This is somehow a bit surprising since this region has both the lowest mean temperature and the highest annual precipitation of the four regions, and therefore possibly should have a lower water use for irrigation. While looking further into these numbers this result could be explained by the fact that Cataluña has a much lower yield (tonne/ha) than the three other regions which might lead to a higher water use ($m^3/tonne$).

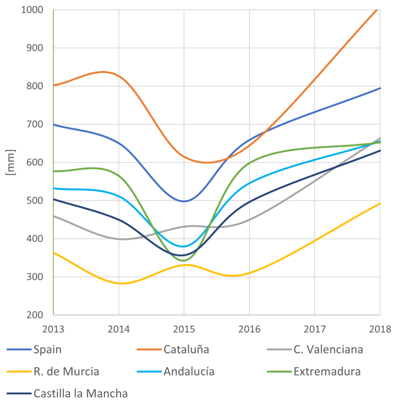


Figure 5.3: Annual mean precipitation in mm [66].

The results also showed increased water use in several regions during the year 2015. Weather data does not show a dramatic increase in the mean temperature this year, but on the other hand a decline in precipitation for the regions *Andalucía, Extremadura, Castilla la Mancha* and for Spain in general. It is therefore reasonable to come to the conclusion that less precipitation in 2015 increased the demand for irrigation which resulted in a higher water use.

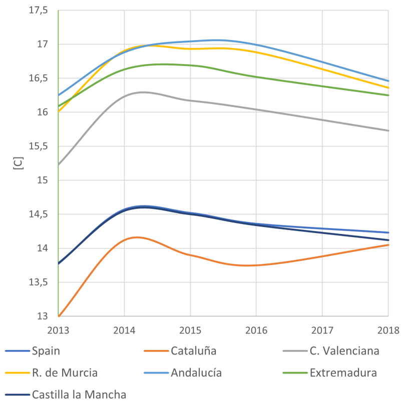


Figure 5.4: Annual mean temperature in °C [66].

If looking at the AWARE-factors it is obvious that there are large scarcity problems in the regions *Andalucía, R. de Murcia* and C. Valenciana. For citrus all regions have a similar water scarcity footprint, but in the case of vegetables *R. de Murcia* stands out compared to the other regions. This is due to both the high water use and the remarkably high AWARE-factor. The

Murcia region is especially interesting to highlight since this is the region (of the selected ones) that has the lowest annual precipitation, the highest mean temperature and a very large production in a small geographical area.

As described in the theory part there are several different methodologies of calculating a water footprint. The methodology developed by Hoekstra was used in 2010 to evaluate water use for numerous crops [67]. The study separates the water use into blue, green and grey water footprints of which the blue is comparable to the LCA WF of this thesis. The article presents results of the global blue water footprint, meaning the water use, and the numbers for oranges and vegetables are 110 and 43 ($m^3/tonne$) respectively [67]. This is lower, but in the same order of magnitude, compared to the results presented here and probably reasonable if considering that Spain is drier and warmer than the world average. Parra et al. (2020) also investigated the irrigation efficiency and water use in several orchards in the region of Valenciana. They recorded the water use at 102-151 ($m^3/tonne$), also this in the same magnitude as this thesis [68].

A comparison to Swedish production of apples, in regard to water use, is interesting in order to put the results for vegetables and especially citrus into perspective. An approximated water quantity used for irrigation according to Äppelriket, a large apple producer in Sweden, is 1500 m^3/ha, while the production is around 50 tonnes apples per hectare [69]. This generates a water use of 30 $m^3/tonnefruit$, to compare with the Spanish water use for citrus that is ranging between 150-170 $m^3/tonne$. This comparison is further extended if also considering the water scarcity and applying AWARE-factors to the water use. The AWARE-factor for Skåne, the region where Äppelriket is located, is 2,62 m^3_{eq}/m^3 and this generates a WSF of 78,6 m^3_{eq} per tonne apple [60]. The corresponding value for citrus is 14 271. This means that one tonne of Spanish citrus has almost a 200 times higher water scarcity footprint compared to one tonne of Swedish apples.

5.3 Challenges with the data and methodology

Starting with the pesticides, the main challenges have been to deal with uncertainties regarding the USEtox model, as well as the lack of disaggregated pesticide data at a regional level. Hence, this thesis could only perform a national impact assessment. In reality though, the pesticide use varies between different regions that would have been of interest to evaluate. Furthermore, this thesis made the assumption that 1% of the applied pesticides are released to freshwater, but the emissions can vary depending on regional differences in for instance soil type, application method and weather conditions. This was however, deemed to be too complicated to obtain, but if the PestLCI model could have been used, it would have provided a more accurate picture of the pesticide emissions.

The USEtox model has been a challenge when conducting the impact assessment. First off, there are still missing characterisation factors (CFs) and the final impacts are hence, not entirely accurate. Some pesticides among the top ten in kg such as *Paraffin* and *Sulfur* lack CFs that could have affected the final impact due to their high use. But compared to for instance the pyrethroids, they are expected to be much less toxic since *Paraffin* is a waxy solid that can be used for many everyday products [70], and *Sulfur* is a part of the natural environment and can be applied as fertilisers [71]. Thus, *Paraffin* and *Sulfur* are not necessarily produced solely for pesticide use, unlike for instance *Glyphosate* and the pyrethroids.

Furthermore, the EC50 factor is a large uncertainty when deriving new CFs. EC50 values were required for at least three trophic levels, but the avlogEC50 could vary significantly depending on the species included in the calculations. For instance, some species of algae were not as sensitive to a pesticide, indicating low toxicity, while other algae were very sensitive to the same pesticide and instead indicated high toxicity. In some cases, different databases also reported different EC50 values for the same species. The calculated CF could hence, vary depending on the included EC50 data and species, which became a large uncertainty. This was also shown when using the alternative methodology, with an AI-driven prediction model called *Trident* to derive EC50 values. The effect factor clearly varied between the AI model and USEtox, resulting in different CFs. Even though, it can not be said at this stage which approach is the most accurate, this thesis emphasises the need for a more standardised methodology for calculating the avlogEC50 parameter. Both when deriving new CFs but also for the already inbuilt effect values in the USEtox model, that have not been updated for a long time. Rosenbaum et.al also acknowledge the uncertainties with the USEtox model [37]. Currently, the model provides CFs that can differ by two to three orders of magnitude, and the effect factor and ecotoxicity data are some of the aspects that need further evaluation to improve the model [37].

When it comes to water, the largest uncertainty is the assumption of the irrigation techniques used for different crops. In this thesis, the shares of drip- sprinkler- and gravity-irrigation used on citrus and vegetables were required to calculate the water use. However, these shares were only reported on a national level and more specific data on regional differences could not be found, possibly affecting the results of the water use. Another aspect of this is that the water efficiency of a technique in a region is approximated as m^3/ha. It is likely that different crops are irrigated differently regarding quantity and frequency, which also could affect the actual water use and hence the water footprints.

5.4 Future outlooks

5.4.1 Climate change

Spain, as all of the world, is facing effects of global warming and climate change. Figure 5.5 shows changes in precipitation and yearly mean temperatures in Spain over the last 120 years [66]. As can be seen there are large variations in precipitation and no clear trend can be seen. The mean temperature on the contrary has a trend towards a warmer mean temperature, increased by almost 2 degrees from 12.5 to 14.5°C during this period.

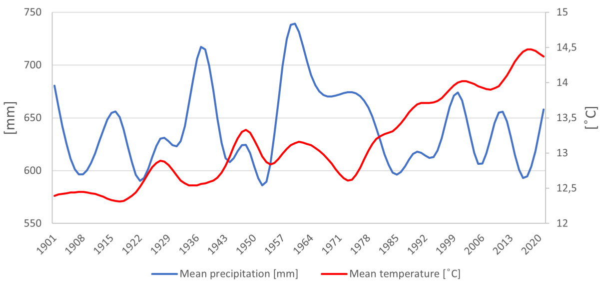


Figure 5.5: Historical changes in mean temperature and mean precipitation in Spain [66].

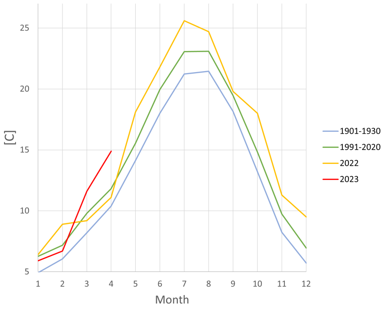


Figure 5.6: Monthly mean temperatures, 1901-1930, 1991-2020, 2022 and start of 2023 [66].

The year 2022 was exceptionally warm, affecting the yields as well as the water scarcity situation in Spain negatively. In Figure 5.6 the mean temperatures per month, for different time periods, can be found. If looking at the larger perspective there is an increase between the periods 1901-1930 and 1991-1920. But what is most interesting is the yellow line, the year of 2022 that clearly is above both periods. This led to large consequences for farmers in the last season and the agriculture minister estimated a decline with more than 40% in the olive harvest compared to the year before [72]. The first four months of 2023 started off with a similar situation as the year before. In April an early heatwave reached the corner of Europe, including Portugal and Spain, and temperatures almost reaching 40°C were measured in Spain [73]. This is about 20 degrees higher than normal for the season, creating concerns for the coming summer and how agricultural yields will be affected.

5.4.2 Pesticide resistance and climate change

The use of pesticides will continue to be important for maintaining intensive agricultural production to satisfy future demands for food. However, as has been pointed out, pesticide use can pose a large negative environmental impact even in low doses, as well as affecting human health. Obtaining a more sustainable use of pesticides will be key to sustaining high yields and at the same time reducing adverse risks on the environment.

Moreover, applying pesticides more sustainably will also be important for reducing the risk of pesticide resistance, which is becoming a growing issue and threaten global food security. A recent study projects that herbicide-resistant weeds are expected to increase [74]. Some European countries, including Spain, will be the most affected due to herbicide restrictions that will decrease the diversification of herbicides used, but also due to climate change [74]. The Pesticide Action Network (PAN) explains that agricultural pests will respond to climate change in several ways [75]. When it comes to weeds, increasing temperatures will most likely lead to increasing weed pressures since weeds are expected to be more resilient, and adapt to climate change better than cultivated crops [75]. Furthermore, a changing climate increases the risk of spreading weeds in other regions, thereby introducing unwanted invasive species. Scientists also expect that increasing temperatures will lead to decreasing crop resilience overall and weaken the natural defence of plants, making them more vulnerable to pest attacks. A warmer climate is also expected to stimulate population growth and the metabolism of insects and consequently, decreased crop yields [75].

This initiates a vicious cycle in which pesticide use will most likely increase to respond to climate change effects on insects and weeds. In turn though, this lead to a large risk of developing herbicide - and insecticide resistance, where a recent study has already noticed the development of resistance of *Lambda-cyhalothrin*, *Spinosad* and *Deltamethrin* [76]. These three insecticides are key to controlling the Mediterranean fruit fly, *Ceratitis capitata* which is one of the most destructive fruit pests that attacks citrus orchards in Spain [77]. Thus, increasing resistance problems and climate change raise great concerns regarding future pesticide use. Including integrated pest management principles and investigating alternative agricultural practices such as agroecological farming, crop diversification, and crop rotation systems, will be of great importance to combating the pesticide challenges that lie ahead.

5.4.3 Swedish perspective

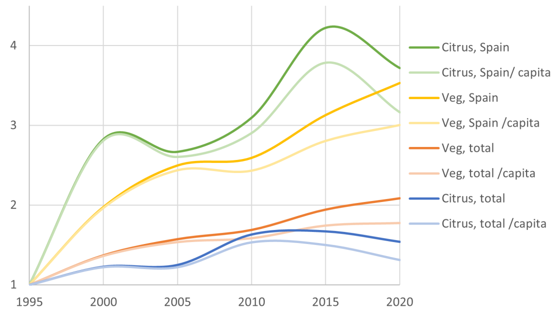


Figure 5.7: Changes in Swedish import, normalised to the year 1995. Total increase and per capita [54, 78].

An interesting aspect to bring up in regard to the impacts due to Swedish import is historical changes in our consumption. During the last 30 years, for the two crop groups citrus fruits and vegetables, it is obvious that the import in these categories has increased. By comparing import statistics from Statistikdatabasen, and normalise the values to the base year 1995, trends in import can be seen and are shown in Figure 5.7 [54, 78]. By looking at *Veg,total* and *Citrus, total* that corresponds to import changes from all countries to Sweden, an increase with a factor of 1.5 or 2 can be seen. If instead analysing *Citrus, Spain* and *Veg, Spain* that shows the import changes from Spain only, the factor is much higher with 3.5 for vegetables and almost 4 for citrus fruits since the year 1995. This could partly be explained by the population growth in Sweden during the same period, but if following the lines *Citrus, Spain/capita* and *Veg, Spain/capita* there are still increases with around a factor 3 compared to 1995.

A conclusion to these numbers could be that there have been changes in our consumption patterns during the last 30 years. Considering the total citrus and vegetables import per capita from all countries, the average person in Sweden consumes around 50-80% more citrus and vegetables respectively. But what is more concerning is the rapid increase of import from Spain and how this trend will evolve in the coming decades. It is likely that the Swedish pesticide and water footprints in Spain will worsen in the future.

The rapid increase of import from Spain since 1995 can be correlated with entry to the European Union (EU). Countries within the EU have access to an inner market where trade regulations are simplified and hence, affecting the import to Sweden. This could have caused the increased share from Spain, and decreased the import from other countries outside of the union.

From a water perspective it is likely that other countries along the Mediterranean coast are facing similar issues as Spain. A change in import origin would therefore not necessarily decrease the Swedish WSF. From a pesticide perspective the situation might be different. The European Union has among the strictest pesticide regulations globally [79]. Consequently, the Swedish pesticide footprint could be affected negatively by increasing the import from non-EU countries. It is also questionable to advocate a strict regulation and simultaneously import crops from another country, causing a large footprint outside of the union.

6
Conclusion

This thesis has investigated the freshwater ecotoxicity impacts of pesticides and the environmental impacts of water use, in the cultivation process of citrus fruits and vegetables in Spain.

The pesticide use is much larger on vegetables compared to citrus fruits. When evaluating the freshwater toxicity impacts caused by pesticide emissions, the use of pesticides as mass active substance is not an adequate indicator, due to the risk of excluding toxic low-dose pesticides. Overall, the insecticides cause the highest freshwater ecotoxicity impacts for both citrus fruits and vegetables, where many low-dose insecticides have an extremely high freshwater toxicity potential. When comparing the two crop groups, vegetables are causing a significantly higher impact than citrus, but if only the two pesticides *Beta-cyfluthrin (I)* and *Folpet (F)* were substituted the freshwater impact could decrease a lot. This thesis has also highlighted the difficulties when quantifying the toxicity impacts of pesticides due to uncertainties with the USEtox model. But also the fact that all pesticides require a characterisation factor to obtain an adequate impact assessment and that this thesis has only evaluated freshwater ecotoxicity.

Regarding water, citrus fruits have in general a higher water demand than vegetables. When applying the AWARE-factors and comparing regional differences, only small variations of the water scarcity footprint could be noticed for citrus, but for vegetables the region *R. de Murcia* stands out. The AWARE-factors used in this thesis indicate the high water scarcity problems that Spain is facing. Especially along the eastern coastline where citrus production is dominating, which is also leading to a higher water scarcity footprint for citrus compared to vegetables. The yearly water requirements can be affected by changes in precipitation and temperature where for instance, a general increase in water use for irrigation could be seen in 2015. This could possibly be due to a decline in precipitation that year, compared to the average precipitation levels. To put the Spanish production in perspective, a comparison was made between Swedish apples, where one tonne of citrus produced in Spain has approximately a 200 times higher water scarcity footprint compared to one tonne of Swedish apples.

This thesis has pointed out the high environmental pressures of both pesticides and water use. A worrying aspect then is climate change which might intensify the problems by increasing the risk of pesticide resistance and extreme droughts, ultimately affecting the yields negatively and increasing water scarcity risks in Spain. This, in combination with changed consumption patterns, leading to an increased demand for fruits and vegetables that will most likely continue to grow, raises concerns about how to satisfy the Swedish and global food demand in the future.

Bibliography

[1] David Gustafson et al. “In pursuit of more fruitful food systems”. In: *International Journal of Life Cycle Assessment* (Dec. 2022). ISSN: 16147502. DOI: `10.1007/s11367-022-02101-5`.

[2] Tiziana Crovella, Annarita Paiano, and Giovanni Lagioia. “A meso-level water use assessment in the Mediterranean agriculture. Multiple applications of water footprint for some traditional crops”. In: *Journal of Cleaner Production* 330 (Jan. 2022). ISSN: 09596526. DOI: `10.1016/j.jclepro.2021.129886`.

[3] Maria Nordborg, Christel Cederberg, and Göran Berndes. “Modeling potential freshwater ecotoxicity impacts due to pesticide use in biofuel feedstock production: The cases of maize, rapeseed, Salix, soybean, sugar cane, and wheat”. In: *Environmental Science and Technology* 48.19 (Oct. 2014), pp. 11379–11388. ISSN: 15205851. DOI: `10.1021/es502497p`.

[4] Lars-Anders Strandberg, Simon Lind, and Benny Karlsson. *Sveriges utrikeshandel med jordbruksvaror och livsmedel 2019–2021.* Tech. rep.

[5] Nancy Steinbach. *Miljöpåverkan från svensk konsumtion-nya indikatorer för uppföljning Slutrapport för forskningsprojektet PRINCE.* Tech. rep.

[6] Lubertus Bijlsma et al. “Ecological risk assessment of pesticides in the Mijares River (eastern Spain) impacted by citrus production using wide-scope screening and target quantitative analysis”. In: *Journal of Hazardous Materials* 412 (June 2021). ISSN: 18733336. DOI: `10.1016/j.jhazmat.2021.125277`.

[7] WWF. *17% of Europe’s population faces high risk of water scarcity by 2050.* Aug. 2022. URL: `https://wwf.panda.org/wwf_news/?6214416/17-of-Europes-population-faces-high-risk-of-water-scarcity-by-2050`.

[8] Susan E. Leetmaa, Carlos Arnade, and David Kelch. *The EU and United States Are Large Agricultural Producers.* Tech. rep. Economic Research Service, USDA. URL: `https://www.ers.usda.gov/webdocs/outlooks/40408/30645_wrs0404e_002.pdf`.

[9] La Mancloa. *Agricultura.* 2017. URL: `https://www.lamoncloa.gob.es/espana/historico/eh15/agricultura/Paginas/index.aspx`.

[10] Agneta Styrman. *Spanien - Jordbruk och fiske.* 2023. URL: `https://www.ui.se/landguiden/lander-och-omraden/europa/spanien/jordbruk-och-fiske/`.

[11] Abigail Orús. *Volume of agricultural production in Spain in 2021, by type of crop.* Oct. 2022. URL: `https://es.statista.com/estadisticas/1219140/agricultura-produccion-de-espana-por-cultivo/`.

[12] EUROSTAT. *EU trade since 1988 by HS2-4-6 and CN8.* URL: `https://ec.europa.eu/eurostat/databrowser/view/DS-045409/legacyMultiFreq/table?lang=en`.

[13] Lisa Tostado, Sr. Silke Bollmohr, and Caspar Shaller. *Pesticide Atlas. Fact and figures about toxic chemicals in agriculture 2022.* 2022. ISBN: 9789464007473. URL: `https://www.pan-europe.info/EU-Pesticide-Atlas-2022`.

[14] Ministerio de Agricultura Pesca y Alimentación, Secretaría General Técnica, and Centro de Publicaciones. *Encuesta de Comercializacíon de Productos Fitosanitarios.* Tech. rep. 2020. URL: `https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/estadisticas-medios-produccion/fitosanitarios.aspx`.

[15] Megha Sud. *Managing the Biodiversity Impacts of Fertiliser and Pesticide Use Overview and insights from trends and policies across selected OECD countries-Environment Working Paper N°155.* Tech. rep. URL: `www.oecd.org/environment/workingpapers.htm`.

[16] A. Kienzler et al. “Mode of Action (MOA) Assignment Classifications for Ecotoxicology: An Evaluation of Approaches”. In: *Environmental Science and Technology* 51.17 (Sept. 2017), pp. 10203–10211. ISSN: 15205851. DOI: `10.1021/acs.est.7b02337`.

[17] Fungicide Resistance Action Committee. *Fungicide Resistance Action Committee.* URL: `https://www.frac.info/fungicide-resistance-management/by-frac-mode-of-action-group`.

[18] The Insecticide Resistance Action Committee. *The IRAC Mode of Action Classification Online.* URL: `https://irac-online.org/mode-of-action/classification-online/`.

[19] Giuseppe E.Massimino Cocuzza et al. *A review on Trioza erytreae (African citrus psyllid), now in mainland Europe, and its potential risk as vector of huanglongbing (HLB) in citrus.* Feb. 2017. DOI: `10.1007/s10340-016-0804-1`.

[20] Giuseppe E.Massimino Cocuzza et al. *A review on Trioza erytreae (African citrus psyllid), now in mainland Europe, and its potential risk as vector of huanglongbing (HLB) in citrus.* Feb. 2017. DOI: `10.1007/s10340-016-0804-1`.

[21] Alan W Hodges and Thomas H Spreen. *Economic Impacts of Citrus Greening (HLB) in Florida.* Tech. rep. 2006. URL: `http://edis.ifas.ufl.edu/fe802`.

[22] The Insecticide Resistance Action Committee. “Mode of Action Classification Now including Nematicides”. In: (2023). URL: `https://irac-online.org/documents/moa-brochure/`.

[23] Nichola J. Hawkins et al. “The evolutionary origins of pesticide resistance”. In: *Biological Reviews* 94.1 (Feb. 2019), pp. 135–155. ISSN: 14647931. DOI: `10.1111/brv.12440`. URL: `https://onlinelibrary.wiley.com/doi/full/10.1111/brv.12440`.

[24] Shaon Kumar Das. “Mode of action of pesticides and the novel trends- A critical review”. In: *International Research Journal of Agriculture and Soil Science* 3.11 (Dec. 2013). DOI: `10.14303/irjas.2013.118`. URL: `http://www.interesjournals.org/IRJAS`.

[25] EU Pesticide Database. "Active substances, Spain 2023". In: (). URL: `https://ec.europa.eu/food/plant/pesticides/eu-pesticides-database/start/screen/active-substances`.

[26] Damian Carrington. *UK overrules scientific advice by lifting ban on bee-harming pesticides.* Mar. 2022. URL: `https://www.theguardian.com/environment/2022/mar/01/bee-harming-pesticide-thiamethoxam-uk-emergency-exemption`.

[27] Department for Environment Food and Rural affairs. *Emergency pesticide authorisation to protect sugar beet crops.* Jan. 2022. URL: `https://www.gov.uk/government/news/emergency-pesticide-authorisation-approved-to-protect-sugar-beet-if-specific-conditions-are-met`.

[28] Britannica. *Herbicide.* URL: `https://www.britannica.com/science/herbicide`.

[29] Herbicide Resistance Action Comittee. *Global Herbicide Classification Lookup.* URL: `https://hracglobal.com/tools/classification-lookup`.

[30] Holly Holt. *Neonics.* URL: `https://ento.psu.edu/research/centers/pollinators/resources-and-outreach/disappearing-pollinators/neonics`.

[31] Makoto Ihara and Kazuhiko Matsuda. *Neonicotinoids: molecular mechanisms of action, insights into resistance and impact on pollinators.* Dec. 2018. DOI: `10.1016/j.cois.2018.09.009`.

[32] Atul M. Ramchandra, Binila Chacko, and Peter J. Victor. "Pyrethroid poisoning". In: *Indian Journal of Critical Care Medicine* 23 (2019), S267–S271. ISSN: 1998359X. DOI: `10.5005/jp-journals-10071-23304`.

[33] Jordbruksverket. *Insekticidresistens - ökade problem med bekämpning av insekter.* Tech. rep. 2009. URL: `http://www2.jordbruksverket.se/webdav/files/SJV/trycksaker/Pdf_ovrigt/ovr178.pdf`.

[34] Rosalie Van Zelm et al. "Pesticide ecotoxicological effect factors and their uncertainties for freshwater ecosystems". In: *International Journal of Life Cycle Assessment* 14.1 (Jan. 2009), pp. 43–51. ISSN: 09483349. DOI: `10.1007/s11367-008-0037-5`.

[35] Peter Fantke and Olivier Jolliet. "Life cycle human health impacts of 875 pesticides". In: *International Journal of Life Cycle Assessment* 21.5 (May 2016), pp. 722–733. ISSN: 16147502. DOI: `10.1007/s11367-015-0910-y`.

[36] Morten Birkved and Michael Z. Hauschild. "PestLCI-A model for estimating field emissions of pesticides in agricultural LCA". In: *Ecological Modelling* 198.3-4 (Oct. 2006), pp. 433–451. ISSN: 03043800. DOI: `10.1016/j.ecolmodel.2006.05.035`.

[37] Ralph K. Rosenbaum et al. "USEtox - The UNEP-SETAC toxicity model: Recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment". In: *International Journal of Life Cycle Assessment* 13.7 (Nov. 2008), pp. 532–546. ISSN: 09483349. DOI: `10.1007/s11367-008-0038-4`.

[38] Editor Peter Fantke et al. *USEtox ® User Manual USEtox ® User Manual USEtox ® 2.0 User Manual (Version 2).* Tech. rep. URL: `http://usetox.org`.

[39] Daniela Lovarelli, Jacopo Bacenetti, and Marco Fiala. *Water Footprint of crop productions: A review.* Apr. 2016. DOI: `10.1016/j.scitotenv.2016.01.022`.

[40] Arjen Y. Hoekstra et al. *The Water Footprint assessment manual.* Tech. rep. 2011. URL: `www.earthscan.co.uk`.

[41] Stephan Pfister et al. *Understanding the LCA and ISO water footprint: A response to Hoekstra (2016) "A critique on the water-scarcity weighted water footprint in LCA".* Jan. 2017. DOI: `10.1016/j.ecolind.2016.07.051`.

[42] Arjen Y. Hoekstra. "A critique on the water-scarcity weighted water footprint in LCA". In: *Ecological Indicators* 66 (July 2016), pp. 564–573. ISSN: 1470160X. DOI: `10.1016/j.ecolind.2016.02.026`.

[43] Anne Marie Boulay et al. "The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE)". In: *International Journal of Life Cycle Assessment* 23.2 (Feb. 2018), pp. 368–378. ISSN: 16147502. DOI: `10.1007/s11367-017-1333-8`.

[44] Ministerio de Agricultura Pesca y Alimentación. *Encuesta sobre superficies y rendimientos de cultivos - Análisis de los regardios en España.* Tech. rep. 2021. URL: `https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/esyrce/informes-sectoriales/`.

[45] Pesca y Alimentacíon Ministerio de Agricultura. *El regadío en España.* URL: `https://www.mapa.gob.es/es/desarrollo-rural/temas/gestion-sostenible-regadios/regadio-espanya/`.

[46] Pesca y Alimentacíon Ministerio de Agricultura. *Encuesta sobre superficies y rendimientos de cultivos.* Tech. rep. URL: `https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/esyrce/resultados-de-anos-anteriores/default.aspx`.

[47] Instituto Nacional de Estadística. *Encuesta sobre el uso del agua en el sector agrario (EUASA).* Tech. rep. 2020.

[48] Peter Malm and Peter Berglund. *Bevattning och växtnäringsutnyttjande. Jordbruksinformation 5.* Tech. rep. Jordbruksverket, 2007. URL: `https://www2.jordbruksverket.se/webdav/files/SJV/trycksaker/Pdf_jo/jo07_5.pdf`.

[49] Z Plaut and A Meiri. *Management of Water Use in Agriculture. Crop Irrigation.* Tech. rep. 1994. DOI: `10.1007/978-3-642-78562-7`.

[50] Minsistero de Agricultura Pesca y Alimentacío. "Encuesta sobre Superficies y Rendimientos Cultivos (ESYRCE): resultados de años anteriores. Years 2013-2019". In: (). URL: `https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/esyrce/resultados-de-anos-anteriores/default.aspx`.

[51] Judit Monotoriol Garriga. *The use of water in agriculture: making progress in modernising irrigation and efficient water management.* Apr. 2022. URL: `https://www.caixabankresearch.com/en/sector-analysis/agrifood/use-water-agriculture-making-progress-modernising-irrigation-and-efficient`.

[52] Instituto Nacional de Estadística. "Encuesta sobre el uso del agua en el sector agrario. Serie 2000-2018. Distribución de agua a las explotaciones agrícolas por comunidad autónoma, tipos de cultivos/técnicas de riego y periodo." In:

(). URL: `https://www.ine.es/jaxi/Datos.htm?path=/t26/p067/p03/serie/l0/&file=02003.px`.

[53] Ministerio de Agricultura Pesca y Alimentacíon. *Anuario de Estadística.* URL: `https://www.mapa.gob.es/es/estadistica/temas/publicaciones/anuario-de-estadistica/`.

[54] Statistiska Centralbyrån Statistikdatabasen. *Varuexport till samtliga länder efter varugrupp KN 2, 4, 6, 8-nivå och handelspartner, sekretessrensad, ej bortfallsjusterat. År 1995 - 2022.* URL: `https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__HA__HA0201__HA0201B/ExpTotalKNAr/`.

[55] Ministerio de Agricultura Pesca y Alimentacío. *Encuesta de Utilización de Productos Fitosanitarios.* 2019. URL: `https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/estadisticas-medios-produccion/fitosanitarios.aspx`.

[56] Food and Agriculture Organization of the United Nations. *Database.* URL: `https://www.fao.org/faostat/en/#data`.

[57] Ministerio de Agricultura Pesca y Alimentación. *Análisis de los regadíos en España.* Tech. rep. URL: `https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/regadios2021_tcm30-621075.pdf`.

[58] Instituto Nacional de Estadística. *Survey on the use of water in the agricultural sector (SUWAS) Year 2016.* Tech. rep. URL: `https://www.ine.es/en/prensa/euasa_2016_en.pdf`.

[59] Anne Marie Boulay and Leo Lenoir. “Sub-national regionalisation of the AWARE indicator for water scarcity footprint calculations”. In: *Ecological Indicators* 111 (Apr. 2020). ISSN: 1470160X. DOI: `10.1016/j.ecolind.2019.106017`.

[60] WULCA. “Supplementary Information - AWARE sub-national factors”. In: (). URL: `https://wulca-waterlca.org/aware/sub-national-aware/`.

[61] Zampori L and Pant R. “Suggestions for updating the Product Environmental Footprint (PEF) method”. In: *Publications Office of the European Union* (2019), p. 45. URL: `https://publications.jrc.ec.europa.eu/repository/handle/JRC115959`.

[62] Maria Norborg, Christel Cederberg, and Göran Benders. *Modelling potential freshwater ecotoxicity impacts due to pesticide use in biofuel feedstock production.* URL: `https://publications.lib.chalmers.se/records/fulltext/228755/local_228755.pdf`.

[63] Mark Huijbregts et al. *Title: USEtox TM Chemical-specific database: organics.* Tech. rep. 2010.

[64] Mikael Gustavsson et al. “Transformers enable accurate prediction of acute and chronic chemical toxicity in aquatic organisms”. In: *bioRxiv Preprint* (Apr. 2023). DOI: `10.1101/2023.04.17.537138`. URL: `https://doi.org/10.1101/2023.04.17.537138`.

[65] WULCA. *How to apply AWARE.* URL: `https://wulca-waterlca.org/aware/how-to/`.

[66] Climate Knowledge Portal and World Bank. *Climatology, Spain. Observed Annual Mean-Temperatures.* URL: `https://climateknowledgeportal.worldbank.org/country/spain/climate-data-historical`.

[67] M M Mekonnen and A Y Hoekstra. “The Green, Blue and Grey Water Footprint of Crops and Derived Crop Products. Volume 1: Main Report”. In: *Value of Water Research Report Series* 47 (Dec. 2010). DOI: `https://doi.org/10.5194/hess-15-1577-2011`.

[68] Lorena Parra et al. “Evaluating irrigation efficiency with performance indicators: A case study of citrus in the east of spain”. In: *Agronomy* 10.9 (Sept. 2020). ISSN: 20734395. DOI: `10.3390/agronomy10091359`.

[69] Henrik Stridh. Äppelriket. *Personal communication.* 2023.

[70] Britannica. *paraffin wax.* May 2018. URL: `https://www.britannica.com/science/paraffin-wax`.

[71] EPA Environmental protection Agency. *Sulfur.* Tech. rep. 1991. URL: `https://www3.epa.gov/pesticides/chem_search/reg_actions/reregistration/fs_PC-077501_1-May-91.pdf`.

[72] Raquel Redondo and Joseph Wilson. *Drought tests resilence of Spain’s olive groves and farmers.* Nov. 2022. URL: `https://apnews.com/article/europe-business-droughts-spain-weather-6254cc9ced0d275cea6b4eda1f410fc3`.

[73] Ian Livingston. *Europe sees hottest April weather on record as Spain and Portugal swelter.* Apr. 2023. URL: `https://www.washingtonpost.com/weather/2023/04/27/spain-portugal-record-april-heat/`.

[74] José María Montull and Joel Torra. *Herbicide Resistance Is Increasing in Spain: Concomitant Management and Prevention.* Feb. 2023. DOI: `10.3390/plants12030469`.

[75] Pesticide action network. PAN. “Climate change and pesticides”. In: *2022* ().

[76] Javier Castells-Sierra et al. “First detection of resistance to deltamethrin in Spanish populations of the Mediterranean fruit fly, Ceratitis capitata”. In: *Journal of Pest Science* (2022). ISSN: 16124766. DOI: `10.1007/s10340-022-01578-1`.

[77] Ignacio Plá et al. *Sterile insect technique programme against mediterranean fruit fly in the valencian community (Spain).* May 2021. DOI: `10.3390/insects12050415`.

[78] Statistiska Centralbyrån and Statistikdatabasen. *Folkmängden efter ålder och kön . År 1860 - 2022.* URL: `https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__BE__BE0101__BE0101A/BefolkningR1860N/`.

[79] Paula Kuchheuser and Marc Birringer. “Pesticide residues in food in the European Union: Analysis of notifications in the European Rapid Alert System for Food and Feed from 2002 to 2020”. In: *Food Control* 133 (Mar. 2022). ISSN: 09567135. DOI: `10.1016/j.foodcont.2021.108575`.

A

Cultivation and production

A.1 Yearly production of citrus fruits

Table A.1: Yearly citrus production in Spain and per region for the years 2013-2019. [Tonnes]

Region	2013	2014	2015	2016	2017	2018	2019
Spain	6630041	7048335	5970493	7087204	6330626	7528310	6258696
Galicia	9859	9357	9363	9357	9042	8960	8405
P. de Asturias	104	104	108	111	111	195	234
Cantabria	173	173	144	58	68	68	62
País Vasco	21	21	22	14	16	14	15
Navarra	0	0	0	0	0	0	0
La Rioja	0	0	0	0	0	0	0
Aragón	0	0	0	0	0	0	0
Cataluña	166 615	191602	164089	206713	115610	133891	142947
Islas Baleares	12380	13405	12476	13202	13433	12387	11748
Castilla y León	70	83	83	83	75	0	0
C. de Madrid	0	0	0	0	0	0	0
Castilla La Mancha	0	0	0	0	0	0	0
C. Valenciana	3604230	3926043	3198189	3943213	3168382	4051534	3067517
R. de Murcia	753153	943548	701628	839846	846552	980513	816955
Andalucía	2062934	1942153	1864230	2054644	2158153	2323429	2189665
Extremadura	931	1108	506	1097	886	978	1 119
Islas Canarias	19571	19632	19 643	18 866	18 208	16 341	19 029

A.2 Yearly cultivation of citrus fruits

Table A.2: Yearly citrus production in Spain and per region for the years 2013-2019. [Ha]

Region	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Spain	303028	299477	299518	297535	297017	304619	307561
Galicia	195	195	195	192	188	189	191
P. de Asturias	0	0	0	0	0	0	0
Cantabria	0	0	0	0	0	0	0
País Vasco	12	10	10	10	12	12	12
Navarra	0	0	0	0	0	0	0
La Rioja	0	0	0	0	0	0	0
Aragón	0	0	0	0	0	0	0
Cataluña	11333	11259	11157	10955	10958	10872	10930
Islas Baleares	1161	1048	1050	962	950	959	984
Castilla y Léon	0	0	0	0	0	0	34
C. de Madrid	0	0	0	0	0	0	0
Castilla la Mancha	0	0	0	0	0	0	0
C. Valenciana	168087	165359	162093	161009	158859	162934	160912
R de Murcia	40278	40505	41078	41719	42559	43947	45758
Extremadura	21	21	20	36	19	19	77
Andalucía	80835	79970	82772	81534	82328	85440	87461
Islas Canarias	1107	1113	1143	1120	1146	1239	1202

A.3 Yearly production of vegetables

Table A.3: Yearly production of vegetables in Spain and per region for the years 2013-2019. [Tonnes]

Region	2013	2014	2015	2016	2017	2018	2019
Spain	8423273	9675509	9603457	10233064	10265791	9826380	10402356
Galicia	158980	150250	155539	146172	152776	148612	143418
P. de Asturias	7975	6888	6816	6916	7090	7769	6833
Cantabria	983	841	841	1575	1116	1718	1936
País Vasco	20012	21130	22109	21629	20596	18159	19370
Navarra	217810	257117	303760	335149	278251	292644	288396
La Rioja	29610	29428	31595	35301	36903	35538	32242
Aragón	109502	148174	127462	190404	197850	190082	162994
Cataluña	146543	145842	140723	147324	135768	129145	132509
Islas Baleares	47543	42154	37311	43147	36211	33033	34700
Castilla y León	134398	133366	105429	113095	115232	106404	118564
C. de Madrid	28324	36521	35559	41356	41356	42932	63237
Castilla La Mancha	1534899	1480897	1349079	1424503	1413192	1505560	1559450
C. Valenciana	346744	379125	425959	441326	453551	444563	460556
R. de Murcia	1344918	1391227	1260955	1414510	1437736	1443976	1449385
Andalucía	2924401	3338848	3407030	3902538	3627417	3243413	3463940
Extremadura	1210196	1976086	2052624	1842786	2192242	2048696	2325794
Islas Canarias	160435	137525	140666	125333	118540	134136	137033

A.4 Yearly cultivation of vegetables

Table A.4: Yearly cultivation of vegetables in Spain an per region for the years 2013-2019. [Ha]

Region	2013	2014	2015	2016	2017	2018	2019
Spain	199104	211337	211 254	223 960	228 373	224 223	228 027
Galicia	3 399	3 325	3 343	3 409	3 315	3 133	3 051
P. de Asturias	412	403	400	402	403	354	334
Cantabria	55	45	45	45	32	33	42
País Vasco	864	863	872	921	895	888	866
Navarra	7 982	9 006	9 751	10 426	9 847	10 400	9 820
La Rioja	999	969	971	1 009	1 007	996	977
Aragón	2 048	3 383	3 148	3 188	4 591	4 743	4 272
Cataluña	4 804	4 618	4 499	4 680	4 354	4 280	4 460
Islas Baleares	1 509	2 361	1 247	1 403	1 297	1 256	1 316
Castilla y León	4 387	4 354	3 974	4 470	4 490	3 992	3 987
C. de Madrid	1 246	1 415	1 427	1 721	1 721	1 838	2 361
Castilla La Mancha	39 241	40 095	37 905	42 363	44 120	43 719	44 463
C. Valenciana	10 640	11 976	12 061	12 763	12 448	12 277	12 439
R. de Murcia	40 207	40 662	39 181	40 691	41 597	41 933	42 825
Extremadura	19 275	25 461	27 037	27 958	30 838	29 709	29 552
Andalusía	59 497	59 769	62 659	65 758	64 807	60 870	64 151
Islas Canarias	2 532	2 670	2 725	2 550	2 611	3 218	3 200

B

Import statistics

B.1 Statistiska Centralbyrån

Table B.1: KN-codes used for search in SCB database

Crop	KN-code
Citrus	0805
Broccoli and cauliflower	070410
Onion	070310
Celery	070940
Garlic	0703200000
Lettuce	0705
Tomatoes	0702
Melon (group)*	0807
Watermelon	0807110000
Melon	080719
Papaya	0807200000

* The melon group includes melon, watermelon and papaya. Papaya therefore needed to be removed from the group.

Table B.2: Import statistics to Sweden from Spain in tonnes per year. From SCB statistikdatabasen.

Crop	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Citrus fruits	71 836	80 062	91 267	81 759	79 931	69 501	83 128	80 369	82 214
Tomatoes	19 658	19 952	20 628	21 304	19 615	19 681	17 085	15 795	15 306
Lettuce	28 032	26 134	26 369	24 264	23 266	23 411	23 682	22 154	23 243
Broccoli and Cauliflower	19 658	19 952	20 628	21 304	19 615	19 681	17 085	15 795	15 306
Onions	2 163	2 366	2 802	2 353	2 532	3 205	3 625	2 718	2 583
Melon and Watermelon	28 892	33 270	32 974	36 299	37 549	36 753	38 936	41 909	40 050
Garlic	1 243	1 244	1 292	1 357	1 445	1 451	1 505	1 710	1 431
Celery	700	700	730	804	858	966	1 126	1 283	1 175

B.2 Eurostat

Table B.3: Import statistics to Sweden from Spain in tonnes per year, retreived from Eurostat

Crop	2013	2014	2015	2016	2017	2018	2019	2020	2021
Citrus fruits	71 836	80 062	91 267	81 759	79 931	69 501	83 128	80 369	82 214
Tomatoes	19 658	19 952	20 628	21 304	19 615	19 681	17 085	15 795	15 306
Lettuce	28 032	26 134	26 369	24 264	23 266	23 411	23 682	22 154	23 243
Broccoli and Cauliflower	4 063	4 554	4 995	5 385	5 911	5 457	6 037	5 562	5 328
Onions	2 163	2 366	2 802	2 353	2 532	3 205	3 625	2 718	2 583
Melons and Watermelon	28 893	33 270	32 974	36 299	37 549	36 753	38 935	41 909	40 050
Garlic	1 243	1 244	1 292	1 357	1 445	1 451	1 505	1 710	1 431
Celery	700	700	730	804	858	966	1 126	1 283	1 175

B.3 Jordbruksverket

Table B.4: Total import to Sweden in tonnes per year. Reported by Jordbruksverket, and the value for celery is reported by SCB

Crop	2019	2020	2021
Citrus fruits	163 477	167 660	172 581
Tomatoes	85 529	88 103	86 891
Lettuce	36 003	33 113	35 812
Broccoli and Cauliflower	11 963	10 649	10 084
Onions	27 338	24 873	20 574
Melons and Watermelons	69 341	86 079	71 562
Garlic	3 528	3 948	3 844
Celery	1 710	1 586	1 652

C

Irrigation and water use

C.1 Water use for irrigation in each region. Total and per technique.

Table C.1: Irrigation data per technique. In Spain and per region. Unit: [1000 m^3]

Irrigation technique	**Year**	**Spain**	**Cataluña**	**Castilla la Mancha**	**Valenciana**
Total	2018	15494642	1005576	1523746	1337413
	2016	14948500	993388	1655033	1234802
	2015	14944684	942682	1445977	1218034
	2014	15129132	990328	1384978	1343012
	2013	14534563	1110239	1594521	1038620
Gravity	2018	5107395	563876	113378	684513
	2016	4967791	559278	125782	636118
	2015	5204360	565621	143161	581730
	2014	5454884	529826	189742	663300
	2013	5400337	706235	142447	454866
Sprinkler	2018	4120616	221825	685480	6986
	2016	4089971	228479	739800	4744
	2015	4001094	208333	699806	2296
	2014	3996423	204007	693874	14312
	2013	3751399	198314	785879	4535
Drip	2018	6266631	219875	724888	645914
	2016	5890738	205631	789451	593940
	2015	5739230	168728	603010	634008
	2014	5677825	256495	501362	665400
	2013	5382827	205690	666195	579219

Irrigation technique	Year	R. de Murcia	Extremadura	Andalucia	
Total	2018	500569	1777957	4175562	
	2016	531117	1577803	4086586	
	2015	544267	1464760	4216350	
	2014	609319	1441677	4204812	
	2013	531099	1620829	3763249	
Gravity	2018	66575	718513	901513	
	2016	80200	696904	929598	
	2015	84907	630370	1037233	
	2014	95538	697772	1004950	
	2013	120292	859320	787209	
Sprinkler	2018	4004	302251	350075	
	2016	13277	261311	404696	
	2015	13062	222090	354173	
	2014	13996	271035	395252	
	2013	8799	303740	354657	
Drip	2018	430990	757193	2923974	
	2016	437640	619588	2752292	
	2015	446298	612300	2824954	
	2014	499785	472870	2804610	
	2013	402008	457769	2621383	

C.2 Irrigated areas in each region. Total and per technique.

Table C.2: Irrigation data per technique. In Spain and per region. Unit: [Hectare]

Irrigation technique	Year	Spain	Cataluña	Castilla la Mancha	Valenciana
Total	2021	3804786	270441	582702	289499
	2020	3759398	267354	572211	290689
	2019	3758003	265008	567798	292531
	2018	3703741	260601	553888	290720
	2017	3663990	256698	540193	289074
	2016	3589743	255478	518233	286690
	2015	3570875	253997	509830	286099
	2014	3540066	250273	504414	284669
	2013	3478475	247778	493243	279492
Gravity	2021	864136	127868	27092	77976
	2020	888094	125730	27775	79338
	2019	902163	126646	27195	81477
	2018	908075	124637	23313	84061

	2017	926748	126105	25308	86325
	2016	943203	127243	23536	87585
	2015	978428	129729	29902	90853
	2014	986628	126176	28170	91585
	2013	1004941	126087	23478	95045
Sprinkler	2021	897208	43206	174039	908
	2020	884766	42001	175979	729
	2019	893828	40643	183445	724
	2018	877686	40595	183836	937
	2017	889055	39351	185175	1736
	2016	861344	40880	185524	1577
	2015	865106	39051	181431	1364
	2014	762189	38037	192230	1845
	2013	827384	36649	196161	1364
Drip	2021	2043476	99367	381571	210615
	2020	1986539	99623	368457	210621
	2019	1962011	97719	357157	210330
	2018	1917980	95369	346739	205722
	2017	1848187	91242	329710	201012
	2016	1785195	87355	209173	197528
	2015	1727341	85216	298397	193882
	2014	1691084	86061	284014	191236
	2013	1645491	85002	273603	183068

Irrigation technique	**Year**	**R. de Murcia**	**Extremadura**	**Andalucia**	
Total	2021	176985	290412	1067310	
	2020	173163	284539	1062720	
	2019	180413	282735	1053422	
	2018	183517	280857	1048617	
	2017	183106	273635	1043181	
	2016	181451	267214	1029997	
	2015	176507	259575	1016343	
	2014	178052	258848	1000873	
	2013	173421	256789	991780	
Gravity	2021	24602	74614	138738	
	2020	24141	80040	154529	
	2019	26086	84074	160663	
	2018	25784	89858	169875	
	2017	28716	93146	173747	
	2016	30513	98014	174108	
	2015	29166	99966	183938	
	2014	29503	98574	182242	
	2013	28907	103709	182048	
Sprinkler	2021	892	39833	85329	
	2020	778	42288	83528	
	2019	773	40465	79730	

	2018	641	40898	81782	
	2017	822	40140	94870	
	2016	1199	42806	93027	
	2015	1024	43316	91231	
	2014	2152	47634	89596	
	2013	1363	38043	89983	
Drip	2021	151491	175964	843244	
	2020	148245	162211	824662	
	2019	153554	158196	813029	
	2018	157093	150101	796960	
	2017	153568	140348	774564	
	2016	149738	126393	762863	
	2015	146317	116292	741167	
	2014	146396	112639	729023	
	2013	143149	105038	719749	

C.3 Approximated water use per hectare and irrigation technique.

Table C.3: Approximated water use per hectare. Per region and technique. Unit:$[\frac{1000m^3}{ha}]$

Irrigation technique	Year	Spain	Catalonia	Castilla la Mancha	Valencia
Total	2018	4,18	3,86	2,75	4,60
	2016	4,16	3,89	3,19	4,31
	2015	4,19	3,71	2,84	4,26
	2014	4,27	3,96	2,75	4,72
	2013	4,18	4,48	3,23	3,72
Gravity	2018	5,62	4,52	4,86	8,14
	2016	5,27	4,40	5,34	7,26
	2015	5,32	4,36	4,79	6,40
	2014	5,53	4,20	6,74	7,24
	2013	5,37	5,60	6,07	4,79
Sprinkler	2018	4,69	5,46	3,73	7,46
	2016	4,75	5,59	3,99	3,01
	2015	4,62	5,33	3,86	1,68
	2014	5,24	5,36	3,61	7,76
	2013	4,53	5,41	4,01	3,32
Drip	2018	3,27	2,31	2,09	3,14
	2016	3,30	2,35	3,77	3,01
	2015	3,32	1,98	2,02	3,27
	2014	3,36	2,98	1,77	3,48
	2013	3,27	2,42	2,43	3,16

Irrigation technique	Year	R. de Murcia	Extremadura	Andalucia	
Total	2018	2,73	6,33	3,98	
	2016	2,93	5,90	3,97	
	2015	3,08	5,64	4,15	
	2014	3,42	5,57	4,20	
	2013	3,06	6,31	3,79	
Gravity	2018	2,58	8,00	5,31	
	2016	2,63	7,11	5,34	
	2015	2,91	6,31	5,64	
	2014	3,24	7,08	5,51	
	2013	4,16	8,29	4,32	
Sprinkler	2018	6,25	7,39	4,28	
	2016	11,07	6,10	4,35	
	2015	12,76	5,13	3,88	
	2014	6,50	5,69	4,41	
	2013	6,46	7,98	3,94	
Drip	2018	2,74	5,04	3,67	
	2016	2,92	4,90	3,61	
	2015	3,05	5,27	3,81	
	2014	3,41	4,20	3,85	
	2013	2,81	4,36	3,64	

C.4 AWARE factors

Table C.4: AWARE (agri region) factors for all regions.

Region	AWARE factor
Andalucía	94,16
C. Valenciana	97,90
Extremadura	49,15
Galicia	17,92
La Rioja	89,98
País Vasco	85,92
P. de Asturias	7,36
R. de Murcia	99,74
Aragón	90,04
Cantabria	43,47
Castilla la Mancha	64,85
Castilla y León	69,34
Cataluña	84,45
C. de Madrid	11,43
Navarra	89,79

D

Derivation of new characterisation factors

D.1 Ecotoxicity data

Table D.1: Ecotoxicological data for avlogEC50 calculations

Trophic level	Species	Days	EC50		Reference	LOG
			Acute	**Chronic**		
Spinosad						
Fish	*Oncorhynchus mykiss*	4	27	13,5	PPDB	1,13
Aq. invertebrates	*Daphnia Magna*	2	1	0,5	BPDB	-0,30
Aquatic plant	*Lemna Minor*	7	10,6	5,3	BPDB	0,72
Algae	*Anabaena flos-aque*	3		6,1	BPDB	0,079
Algae	N*avicula pelliculosa*	N/A		0,079	ECHA	-1,10
Acetamiprid						
Fish	*Oncorhynchus mykiss*	4	100	50	PPDB	1,70
Aq. invertebrates	*Daphnia Magna*	2	49,8	24,9	PPDB	1,40
Aquatic plant	*Lemna Gibba*	7	1	0,5	PPDB	-0,30
Algae	*Scenedemus subspicatus*	3		98,3	PPDB	1,99
Algae	*Navicula Pelliculosa*	5		1,1	ECOTOX	0,04
Algae	*Anabaena flosaque*	5		1,3	ECOTOX	0,11
Flonicamid						
Fish	*Oncorhynchus mykiss*	4	100	50	PPDB	1,70
Aq. invertebrates	*Daphnia Magna*	2	100	50	PPDB	1,70
Aquatic plant	*Lemna Gibba*	7	119	59,5	PPDB	1,77
Algae	*Pseudokirchneriella subcapitata*	3		100	PPDB	2
Spirodiclofen						
Fish	*Oncorhynchus mykiss*	4	0,035	0,0175	PPDB	-1,76
Aq. invertebrates	*Daphnia Magna*	2	0,051	0,0255	PPDB	-1,59
Algae	*Pseudokirchneriella subcapitata*	3		0,06	PPDB	-1,22
Sulfuryl flouride						
Fish	*Danio Rerio*	4	0,89	0,445	PPDB	-0,35
Aq. invertebrates	*Daphnia Magna*	2	0,62	0,31	PPDB	-0,51
Algae	*Pseudokirchneriella subcapitata*	3		0,58	PPDB	-0,24
Paraffin oil						
Fish	*Onchorhynchus Mykiss*	4	35,05*	17,52	PPDB/EFSA	1,24
Aq. invertebrates	*Daphnia Magna*	2	0,36*	0,18	PPDB/EFSA	-0,74
Algae	*Desmodesmus subspicatus*	3		70,45	PPDB	1,85
ζ-cypermetrhin						

Fish	*Onchorhynchus Mykiss*	4	0,00069	0,000345	PPDB/EFSA	-3,46
Aq. invertebrates	*Daphnia Magna*	2	0,00014	0,00007	PPDB/EFSA	-4,15
Algae	*Pseudokirchneriella Subcapitata*	3		1	PPDB	0
Dichlorprop-P						
Fish	*Onchorhynchus Mykiss*	4	109	54,5	PPDB	1,74
Aq. invertebrates	*Daphnia Magna*	2	100	50	PPDB/EFSA	1,70
Aquatic plant	*Lemna Gibba*	7	4,1	2,05	PPDB	0,31
Algae	*Pseudokirchneriella Subcapitata*	3		67	PPDB	1,83
Algae	*Anabaena Flos-aque*	3		26,5	EFSA	1,42
Propoxycarbaxone -sodium						
Fish	*Onchorhynchus Mykiss*	4	77,2	38,6	PPDB	1,59
Aq. invertebrates	*Daphnia Magna*	2	107	53,5	PPDB	1,73
Aquatic plant	*Lemna Gibba*	7	0,0064	0,0032	PPDB	-2,49
Algae	*Pseudokirchneriella Subcapitata*	3		1,57	PPDB	0,20
Algae	*Navicula Pelliculosa*	4		111	ECOTOX	2,05
Algae	*Anabaena Flos-aque*	4		11,3	ECOTOX	1,05
Penoxsulam						
Fish	*Onchorhynchus Mykiss*	4	100	50	PPDB	1,70
Aq. invertebrates	*Daphnia Magna*	2	100	50	PPDB	1,70
Aquatic plant	*Lemna Gibba*	14		0,00329	EFSA	-2,48
Algae	*Anabaena Flos-aque*	3		0,233	PPDB	-0,63
Algae	*Pseudokirchneriella Subcapitata*	4		0,0864	EFSA	-1,06
Algae	*Navicula Pelliculosa*	5		49,6	ECOTOX	1,70
Florasulam						
Fish	*Onchorhynchus Mykiss*	4	100	50	PPDB	1,70
Aq. invertebrates	*Daphnia Magna*	2	292	146	PPDB	2,16
Aquatic plant	*Lemna spp.*	7	0,001	0,0005	PPBD	-3,30
Algae	*Anabaena Flos-aque*	5		0,363	ECOTOX/EFSA	-0,44
Algae	*Pseudokirchneriella Subcapitata*	3		0,00894	EFSA	-2,05
Algae	*Navicula Pelliculosa*	5	1,157*	0,058	ECOTOX/EFSA	-0,24
Benalaxyl						
Fish	*Onchorhynchus Mykiss*	4	3,75	1,875	PPDB	0,27
Aq. invertebrates	*Daphnia Magna*	2	0,59	0,295	PPDB	-0,53
Algae	*Selanastrum Capricornutum*	4		4,97*	ECOTOX/PPDB	-0,44
Algae	*Anabaena flos-aque*	4		17,74	ECOTOX	1,25
Algae	*Microcystis flosaque*	4		6,617	ECOTOX	0,82
Famoxadone						
Fish	*Onchorhynchus Mykiss*	4	0,011	0,0055	PPDB/EFSA	-2,26
Aq. invertebrates	*Daphnia Magna*	2	0,033	0,0165	PPDB/EFSA	-1,78
Aquatic plant	*Lemma Gibba*	7	0,0081	0,00405	PPDB	-2,39
Algae	*Pseudokirchneriella Subcapitata*	3		0,00308	EFSA/PPDB	-2,51
Algae	*Anabaena flos-aque*	5		0,083	ECOTOX	-1,08
Algae	*Navicula Pelliculosa*	5		0,0135	ECOTOX	-1,87
Fenbuconazole						
Fish	*Onchorhynchus Mykiss*	4	1,5	0,75	PPDB/EFSA	-0,12
Fish	*Leopomis Macrochirus*	4	0,68	0,34	ECOTOX	-0,47
Aq. invertebrates	*Daphnia Magna*	2	2,3	1,15	PPDB/EFSA	0,06

Algae	*Pseudokirchneriella Subcapitata*	3		0,33	PPDB	-0,48
Flutriafol						
Fish	*Leopomis Macrochirus*	4	33	16,5	PPDB/EFSA	1,22
Aq. invertebrates	*Daphnia Magna*	2	67	33,5	PPDB/EFSA	1,53
Aquatic plant	*Lemna Gibba*	7	0,65	0,325	PPDB	-0,49
Algae	*Raphidocelis Subcapitata*	3		12	PPDB	1,08
Algae	*Scenedesmus Subspicatus*	3		1,9	EFSA	0,28

* Cases where more than one value for a species have been collected. A geometrical mean has been calculated for the two values, presented as the acute EC50 value. Both references presented.

Abbreviations: *PPDB - Pesticide Properties DataBase. EFSA- European Food Safety Authority. ECOTOX- The ECOTOXicology Knowledgebase.*

D.2 Physical and chemical parameters for USETox

Table D.2: Parameters used for derivation of new characterisation factors in USETox® (version 2.12)

Active substance	**CAS-nr**	**MW**	K_{ow}	K_{oc}
Benalaxyl	71626-11-4	324,41	2,51E+3	3,47E+3
Famoxadone	131807-57-3	374,4	4,47E+4	2,79E+3
Fenbuconazole	114369-43-6	374,4	1,70E+3	1,5E+3
Flutriafol	76674-21-0	301,3	1,95E+2	7,59E+1
Dichlorprop-p	15165-67-0	235,07	2,69E+3	1,18E+0
Propoxycarbazone-Na	181274-15-7	420,37	2,09E+1	2,13E+1
Penoxsulam	219714-96-2	483,37	8,91E+2	8,88E+3
Florasulam	145701-23-1	359,28	1,35E+2	1,61E+2
Paraffin oil	8042-47-5	114,23	1,51E+5	3,13E+4
Sulfuryl flouride	2699-79-8	102,06	2,57E+0	2,06E+1
Acetamiprid/acetaprid		222,68	3,55E+2	5,05E+2
Spirodiclofen	148477-71-8	411,33	1,62E+6	4,23E+4
Flonicamid	158062-67-0	229,16	3,16E+0	3,31E+1
Spinosad	168316-95-8	734,04	4,07E+5	2,10E+5
Active substance	$K_{H,25}$	$P_{VAP,25}$	Sol_{25}	$kdeg_A$
Benalaxyl	1,18E-2	1,00E-5	3,70E+1	2,05E-5
Famoxadone	4,61E-3	4,80E-9	5,20E-2	4,25E-5
Fenbuconazole	8,42E-3	3,75E-8	2,00E-1	7,33E-6
Flutriafol	1,65E-8	7,11E-9	1,30E+2	7,24E+6
Dichlorprop-p	6,27E+2	4,52E-3	5,90E+2	8,55E-6
Propoxycarbazone-Na	4,70E-13	6,55E-18	1,71E+2	1,08E-5
Penoxsulam	3,67E+2	2,76E-9	2,75E+0	4,52E-5

Florasulam	1,71E-2	5,77E-7	8,24E+1	4,70E-6
Paraffin oil	3,25E+5	1,97E+3	6,60E-1	6,21E-6
Sulfuryl flouride	6,58E+12	1,25E+6	5,16E+4	7,50E-14
Acetamiprid/acetaprid	5,44E+3	1,97E+3	6,60E-1	6,21E-6
Spirodiclofen	5,57E-7	1,05E-7	1,29E-2	3,61E-5
Flonicamid	4,26E+2	2,99E-4	6,22E+3	5,84E-7
Spinosad	8,71E-11	3,49E-11	3,4E-3	2,40E-4

Active substance	$kdeg_W$	$kdeg_{SD}$	$kdeg_{SL}$	$avlogEC50$
Benalaxyl	2,10E-7	2,33E-8	1,05E-7	0,33
Famoxadone	1,30E-7	1,44E+8	6,50E-8	-1,98
Fenbuconazole	1,30E-7	1,44E-8	6,50E-8	-0,25
Flutriafol	4,50E-8	5,00E-9	2,25E-8	0,72
Dichlorprop-p	2,10E-7	2,33E-8	1,05E-7	1,4
Propoxycarbazone-Na	2,10E-7	2,33E-8	1,05E-7	0,51
Penoxsulam	4,50E-8	5,00E-9	2,25E-8	0,15
Florasulam	4,50E-8	5,00E.9	2,25E-8	-0,36
Paraffin oil	9,30E-7	1,03E-7	4,65E-7	0,78
Sulfuryl flouride	5,30E-7	5,89E-8	2,65E-7	-0.36
Acetamiprid/acetaprid	2,10E-7	2,33E-8	1,05E-7	0,82
Spirodiclofen	4,50E-8	5,00E-9	2,25E-8	-1,52
Flonicamid	1,30E-7	1,44E-8	6,5E-8	1,79
Spinosad	4,50E-8	5,00E-9	2,25E-8	0,25

E

Freshwater ecotoxicity impact assessment

E.1 Calculating impact scores

In order to perform the freshwater ecotoxicity impact assessment, impact scores needed to be calculated for all pesticides. In Table E.1, an example is provided on the calculation of impact scores for the top ten applied fungicides on citrus fruits. The calculation followed the methodology described in Section 3.3.3 and Equation 3.4:

$$IS_{freshwater} = CF_{i,j} * m_{i,j} * 0,01 \quad [CTU_{eq} = PAF * m^3 * day] \tag{E.1}$$

Table E.1: An example on the derivation of IS for the top ten applied fungicides on citrus fruits.

Active substance	**kg applied on land**	**kg emitted to freshwater**	**CTUe/ kg emitted**	**IS**
Fosethyl-al	214 812	2 148,12	1 490	3 200 694
Mancozeb	80 412	804,12	52 600	42 296 665
Sulfur	23 896	238,96	-	-
Copper oxychloride	23 836	238,36	56 300	13 419 555
Copper oxide (I)	13 338	133,38	56 300	7 509 108
Metalaxyl	5 169	51,69	956	49 414
Copper hydroxide	2 591	25,91	56 300	1 458 491
Folpet	1 813	18,13	1 120 000	20 307 056
Calcium polysulfide	1 140	11,40	-	-
Dimetomorpho	777	7,77	2 740	21 279

DEPARTMENT OF SPACE, EARTH AND ENVIRONMENT
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se