CHALMERS
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Pesticide footprint of Brazilian soybeans

A temporal study of pesticide use and impacts in the Brazilian soybean cultivation

Master's thesis in Industrial Ecology

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Department of Space, Earth and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

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Cover: Spraying of pesticides in a Brazilian soybean field. Photo credit: Christel Cederberg

Typeset in LaTeX
Gothenburg, Sweden 2020

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Abstract

Pesticide use is rarely included in environmental and/or human impacts assessments of food products. This study aims to evaluate the use and impacts of pesticides in the Brazilian soybean cultivation during the ten year period 2009-2018. Brazil is one of the largest soybean producers and pesticide users while the reporting on pesticide use is inadequate and comprehensive monitoring of pesticide residuals is lacking. In 2014, the Food and Agriculture Organization of the United Nations (FAOSTAT) reported a number of 377 176 tonnes sold pesticide active ingredient (A.I) while the Brazilian Institute of Environment and Renewable Natural resources (IBAMA) reported 539 944 tonnes. Furthermore, if three or less companies sell a pesticide with a specific active ingredient, it is not published by IBAMA due to commercial competition. Information about a large number of individual A.I:s were not published during the studied period which means that a complete impact assessment could not be done.

Different indicators were used to evaluate the impacts of the most commonly used herbicides, insecticides and fungicides on soybeans. The total average use per hectare soybean is 6.5 kg A.I/ha of which 69 % is herbicides, 16 % is insecticides and 15 % is fungicides. The pesticide emissions were estimated using the Joint Research Center's (JRC Europe) Product Environmental Footprint (PEF) manual with emissions of 9 % to air and 1 % to surface water of the applied pesticide. The potential freshwater ecotoxicity impacts were then calculated using USEtox v.2.12's characterization factors (CF). Results showed that insecticides have the highest potential freshwater ecotoxicity impact, followed by fungicides and herbicides. This is due to the high aquatic toxicity and thus high CF:s of the pyrethroids that have had a strong increase in use. A qualitative assessment showed that the A.I:s (in all pesticide groups) with relatively highest increase in use are the ones with the most toxic notations. This study proposes that pesticide resistance towards active ingredients used in large volumes is important for explaining the increases of these A.I:s.

Keywords: Pesticides, Brazilian soybean, freshwater ecotoxicity, USEtox, herbicides, insecticides, fungicides, pesticide resistance.

Acknowledgements

I would like to start by thanking my supervisor and examiner Christel Cederberg for the continuous support throughout this entire project. Thank you for all the knowledge you have shared with me, the many meetings and making this an interesting and fun subject to work with, I could not have wished for a better supervisor. A huge thanks to my opponent Filip Danielsson for all of the feedback and very helpful comments and discussions whenever I needed it. Thank you Isac, my wonderful family and my amazing friends for all the laughter, support and for always believing in me. I could not have done this without you.

Hedvig Pollak, Gothenburg, June 2020

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1
Introduction

The global challenge of sustaining and feeding the growing population is an increasing problem due to a variety of reasons. The agricultural sector contributes to environmental pressures such as carbon dioxide release from land use change and loss of biodiversity due to deforestation to mention a few, but also conflicts about what type of crops that are going to be cultivated on the land depending on the economic value of the yield [1]. As the demand for crops used for anthropocentric needs increase, the economic incitement for cultivating these types of commodities becomes higher. Some of these goods, like coffee, feed for animals and crops cultivated for biofuel compete with cultivation of crops that can feed the population [2][3].

The agricultural sector continues to expand and the global trade of agricultural products is only increasing [4]. Thus, assessing the environmental impacts of agricultural activities becomes more prominent. One product that has exploded in popularity during the last century is the soybean, which is one of the most traded agricultural commodities [5]. Soybean is a very important source of high quality protein feed in the global livestock production, most important for mono gastric animals as well as being used for biofuels. The absolute largest part of the soybean (80 %) is used for soy-meal [6], favored by the high protein contents in combination with suitable amino acids makes it a good commodity for animal feed, and it is supplied as a protein flour or oil to the animals. The high energy content of the soybean also makes it suitable as a biofuel, where the bean is pressed to extract the oil [7].

One of the largest producers of soybean is Brazil, where thousands of hectares are dedicated to enormous soybean plantations with an extensive mono-culture, resulting in immense pressure for surrounding ecosystems and land use change [5]. The traded volume of soybeans from Brazil in 2017 was 115 million tonnes [8], and in 2019, Brazil produced 122 million tonnes of soybean, making it the second largest soybean producer in the world after the United States. Furthermore, the soybean is the leading commodity for the production of biodiesel in Brazil, making it an economically valuable crop for a variety of industries [9].

Some environmental impacts connected to the soybean production have been analyzed throughout the the years, e.g the deforestation resulting in carbon emissions and biodiversity loss, while other impacts severely lack assessments. Impacts caused by pesticide use on the soybean crops, such as human toxicity and freshwater ecotoxicity, are two examples that are not often considered in Life Cycle Assessment (LCA) studies which is the most common tool for product impact assessments [10].

The impacts pesticides have on the surrounding environment and the personnel working with the application on the crops are not, to a great extent, known [10]. While some studies have been done on the effects of pesticides for bystanders, this is for individuals living near the fields, and not the individuals that work with the application [11]. This is concerning, not only because Brazil is the second largest user of pesticides in the world after the United States [4], but also since there is a huge data gap on how much pesticides that are actually used, hence, the impacts remain unknown. While FAOSTAT reports state that Brazil used 377 176 tonnes of active ingredients in 2017 [4], official data from the Brazilian government report that the use is 539 944 tonnes in the same year [12]. The reason for this is unclear - which is a further incentive to study the use of these chemicals and the impact they have on the environment and humans. Furthermore, one of the controversial facts about pesticide use is that pesticides banned in the EU are used in Asia, South America and the US, but they are produced and distributed by European companies such as Syngenta and BASF [13][14].

To be able to study the environmental impacts of pesticide use in soybean cultivation, multiple factors have to be considered. This includes, but is not limited to, the application technique and amount applied, the active substance, the design of the soybean field (e.g. does it have buffer zones and/or surrounding water environment) soil quality and clay content. The latter greatly affects the mobility of the pesticides in the soil and can be studied to understand the possibility of leeching of pesticides to the surface water [15]. The complexity of pesticide footprints is much due to the many different types of chemical compounds and the fact that they are applied differently depending on where in the world it is used.

1.1 Aim

The aim of this thesis is to investigate and calculate pesticide footprints of the Brazilian soybean by:

- Collect and map data - of individual active substances in pesticides - from Brazilian agencies.
- Compare and analyse temporal changes on pesticide use in soybean cultivation in Brazil. Over a time period 2009-2018.
- Estimate and calculate the indicators for measuring pesticides trends and their impacts:
  - Total amount of active ingredient in soybean cultivation.
  - Use of active ingredient per harvested hectare and ton produced soybean.
  - Analyse trends in the pesticide use over 10 years.
  - Qualitative assessment of pesticides.
  - Freshwater ecotoxicity based on LCA methods.

1.2 Research questions

To further specify what this thesis is going to cover, some research questions are presented. These are meant to formulate the problem with pesticide footprint and will be discussed throughout the project.

- How does FAOSTAT and Brazilian agencies differ in their pesticide reporting?
- How much pesticides does Brazil use? Totally and in soybean cultivation.
- Are there temporal differences on pesticide use in Brazil over a 10 year period and how could those trends be explained?
- What type of challenges and changes does pesticide resistance cause in the soybean cultivation?
- What type of indicators can be used to evaluate the use and impacts of frequently used pesticides in soybean cultivation?

1.3 Delimitations

- The active ingredients that will be considered are the ones that are classified as herbicides, fungicides and insecticides and not classes like bacteria and rodenticides.
- The emissions of pesticides when a certain amount is applied are not calculated due to many uncertainties with the LCI tool PestLCI for tropical climate. The emissions of pesticides are instead assumed to be 9 % to air and 1 % to freshwater in accordance with the European Directive for Product Environmental Footprint (PEF) [16].
- The ecotoxicity will only be calculated from the five largest herbicides, insecticides and fungicides as well as the relatively most increasing insecticides and fungicides due to uncertainties with the USEtox model and unavailability of pesticide individual active ingredient. This unavailability is due to commercial competition [12].

2
Background

In this section, pesticides and the main classes herbicides, insecticides and fungicides will be presented. An introduction to Brazil's agriculture, the soybean cultivation and the pesticide use it contributes to will provide the necessary background information.

2.1 Pesticides

Pesticides are used to prevent and kill diseases and animals that are considered pests. They are chemical compounds that help prevent diseases for e.g. crops and humans that could potentially decrease or wipe out the crop yield or infect people with e.g. malaria. Pesticide is a collection name for various chemical compound groups that form different categories such as herbicides, insecticides and fungicides [17]. The part of the pesticide that prevents a targeted pest from damaging the object is called active ingredient (A.I). An active ingredient is the part of a substance that induces biological or chemical effect [18]. While pesticides do not only contain active ingredient but also additives such as e.g. surfactants that help the substance integrate with the crop, this is the most crucial part of the product. This section will explain different classes of pesticides to give an understanding of the pesticide usage in the Brazilian soybean cultivation.

Mode of action (MoA) is the part of a pesticide that is poison for e.g. weeds, insects or fungi. Or, more specifically, the series of events resulting in injury for the pest, meaning that this is how the active ingredient works against the pest. The mode of action is a chemical reaction were molecules in the pesticide and the applied object - either weed, insect or fungi - interact and causes death to the targeted pest [19]. The mode of action is different depending on what kind of pest it is desired to treat, insecticides have a wide range of MoA since there are multiple ways to kill insects [20]. For herbicides, it is often called target site when describing the location where the molecules react and the herbicide inhibits a process in the weed [19], thus inhibiting it from growing and spreading in areas where it is not desired.

There are multiple ways of treating crops with pesticides, but the two most common ones are that the pesticides are sprayed on the crops, a so called foliar treatment, or seed treatment where the seeds are sprayed before planting. The protection against the pest are systemic if the seeds are sprayed since the crop will ha have an internal protection, while foliar sprayed pesticides often affect the pest upon contact [21][22].

Pesticides have contributed immensely to the latest growth in agricultural efficiency. In fact - together with chemical fertilizers - they have contributed with a doubling of production of food in the last century. The development between 1950-2000 show an increase of pesticide production from 0.2 million tons to over 5 million tons worldwide [4][23]. This does not come without a price, multiple records show that contamination of surrounding environments like soil, water and terrestrial ecosystems [23] have occurred. Poisoning of humans via food contaminated with pesticides has also been detected during the last decades [23], but also for people living near fields where pesticides are applied [24]. However, the exposure route of pesticides to humans is primarily ingestion of products that have been treated with pesticides [25].

Since the main aim with pesticide application is to be toxic towards weeds and certain animals, they have a high bio-activity. While the activity is meant to work effectively towards the target pest or insect, the high bio-activity may also effect a number of other organisms [26]. This means that not only target pests or insects have to be evaluated from a toxicological viewpoint, but also the people in contact with or living nearby the fields as well as the surrounding and ecosystems.

2.1.1 Herbicides

Herbicides are a classification of pesticides that aims to control weed pests in agricultural crops. Unwanted plants and agricultural weed are inhibited to grow when herbicides are used, which means that a mechanical control, that often requires resources and time, can be reduced or stopped completely [27]. The large scale production of multiple herbicides increased heavily during the research in World War Two, this included the first selective herbicide 2,4-D that today is used widely in e.g. Brazil [19] [12]. Herbicides can help with plant protection at a relatively cheap cost compared to machinery cultivation, which has made this type of pesticide economically successful [19].

There are two categories of herbicides, selective and non-selective where:

- Selective herbicides only target a specific weed or weed category, i.e. toxic to some species, less toxic to other.
- Non-selective affects all weeds, i.e. broadleaf and grass weeds [28].

Herbicides are also classified on how and when they are applied, t.e. if they are applied before the planting of the crop (preplanting), before the weed emerge (pre-emergence) and after the weed has emerged from the soil (postemergence) [28]. These are important factors to be able to have a successful pest management in the crop cultivation.

While selective pesticides may sound like the preferred option to control the actual weed pest, the non-selective herbicide has stimulated a development for GMO crops that are tolerant against the active ingredient Glyphosate. Thus, the crop is unharmed by the non-selective A.I, while everything else that is sprayed dies. This means that the spraying of Glyphosate can increase immensely without damaging the soybean crop and yield. This has happened in many of the soybean cultivation fields in South and North America, with the goal to be able to reduce the total usage of pesticides with different modes of action [27]. Unfortunately this has not happened and Glyphosate - the most used pesticide worldwide - is applied to crops in large volumes around the globe [23]. Since the crop remains undamaged to this herbicide, there is no economic incitement not to spray the fields with large amounts of this product to stop the growth of everything but the soybean. This in turn has caused a problem with weeds that are resistant towards Glyphosate [29]. Thus, more types of herbicides are needed to control the weeds resistant to Glyphosate, see Section 2.2.4.

2.1.2 Insecticides

Insecticides are pesticides that aim to proactively and actively prevent insects from attacking the crop or seed. They can be categorized in many ways depending on the chemical structure, penetration mode and the effect they have on the insects. The latter classification includes if they affect the insects by digestion, inhalation or penetration of their body [30]. Insecticides can either work systemic or contact wise on the insect. This means that the insect is either affected when it comes to contact with the crop, or through metabolism when it has consumed part of the crop [21].

Insecticides have, as mentioned before, many modes of action (MoA). These modes of actions can be classified as how they prohibit the insects from destroying the crops, thus, how the insects are controlled and/or killed. In Table 2.1 an overview of different groups and active ingredients can be viewed, they are also the most commonly used insecticide active ingredients in Brazil during the last decade [12][31]. The site of action is the targeted site for the mode of action, where it is stated how the insecticide chemical affects the insect. All of the site of action listed in this table have a mode of action that affects the insect's nerve-muscle system, but in different ways. The groups are sub-groups to the mode of action, meaning that they may have similar MoA but different chemical structure and interaction with the insects, one example being carbamates and organophosphates that are in the same MoA group but have different chemical formula and can thus affect the insecticide differently. Hence, the *selectivity* (see Section 2.1.1) can be different even if the MoA is the same, e.g. the chemical can be target-site based or metabolic, which will interact differently within the affected insect [31].

Table 2.1: Insecticide site of action - for the largest MoA class; nerve-muscle - chemical grouping and examples of active ingredients that have the site of action stated [31].

Site of Action	Group	Examples of active ingredient
Acetylcholinesterase (AChE) inhibitors	A. Carbamates	Methomyl, Thiodicarb

	B. Organophosphates	Accephate, Chlorpyrifos, Malathion
Chloride channel blockers	A. Organochlorines	Endosulfan
	B. Fiproles	Fipronil
Sodium channel modulators	Pyrethroids	Bifenthrin, Cypermethrin, Lambda-cyhalothrin
Nicotinic acetylcholine receptor (nAChR) competitive modulators	Neonicotinoids	Acetamiprid, Imidacloprid

The primary target of the insecticides on the market today is the nerve-muscle system, resulting in a 85 % dominance on the total sales of insecticides in 2013. The MoA effect on the nerve system is increasingly amplified with a large scale effect on the insects - even if the dose is small the effect is high - which is why this type of MoA is so attractive for pest control. The largest market share in this MoA is currently the group called neonicotinoids, accounting for 27 % of the nerve-muscle sold insecticides. This is, compared to organophosphates, carbamates and pyrethroids, the same amount as all of them combined [20], which is a further explanation that even if the MoA is the same, the actual effect on the insects are different.

A growing problem within agriculture is insecticide resistance. In the same way that the over use of the non-selective herbicide Glyphosate has caused weeds to be resistant, the use of the same MoA insecticide has caused resistance in insecticides [31]. This resistance has increased to a level far higher than herbicide and fungicide resistance and continues to do so [20]. This includes the various chemical groups, meaning that even if the molecule structure differ, the resistance may occur towards the MoA and not the different site of activity in the insecticide (e.g metabolic or a specific site in their system). Some of the insects have genetic mutations that can resist the MoA and these reproduce to create offsprings that have the same genetics. Thus, a growing population of MoA resistant insects can damage the crops. This can be controlled with a so called insecticide resistance management, where insecticides with different MoAs should be combined to prevent insects from developing a resistance [31]. This may be problematic, since there is a limited number of different MoA and the research within this area is lacking. The high costs and time it takes to develop a new insecticide with new MoA makes it extra important to be careful with the insecticide spraying so the product development is not in vain. Thus, an integrated insecticide management becomes very prominent in order not to develop multi-resistant insects that cannot be controlled. Some examples of MoA outside the nerve-muscle one are growth-development, respiration and non-specific ones where growth-development accounts for 9 % of the total MoA sales [20]. Considering that the nerve-muscle MoA dominates 85 % of the market, it should be no surprise that the insecticide resistance has become a severe problem, even if the site of action varies within the MoA.

2.1.3 Fungicides

To be able to control the spread and attack of fungi on crops, fungicides can be applied. Since fungi can cause both economic damage and cause health issues for humans and animals, fungicide use is common within the agricultural sector. Fungicides have been in use since the late 1800s and have been developed intensely since the 1960 when the chemical industry increased multiple productions. One example of the early use of fungicides was in 1807 when the firm Prevost showed that copper sulfate could control fungus and to some extent kill the fungal structures in the fungal disease *Tilletia caries*, discovered in wheat. From this, it took about half a century until it became known that sulfur could also be applied to grapes and vines to control some fungal diseases [32].

Fungicides' different MoA vary, just like the herbicide and insecticide MoA vary, with different ways of affecting and killing the fungus. In Table 2.2, an overview of some MoA and chemical groups that are the most common fungicide active ingredients in Brazil can be studied [12][33].

Table 2.2: Fungicide mode of action, grouping and examples of active ingredients that have the mode of action stated [33].

Mode of action	Group	Examples of active ingredient
Multi-site contact activity	A. Dithio-carbamates	Mancozeb, Thiram
	B. Chloronitriles	Chlorothalonil
	C. Inorganic	Copper and its different salts
Cytoskeleton and motor protein	A. Thiophanates	Thiophanate-methyl
	B. Benzimidazoles	Carbendazim
Respiration	Methoxy-acrylates	Azoxystrobin
Sterol biosynthesis in membranes	Triazoles	Cyproconazole, Tebuconazole

Fungicide resistance is a growing problem due to the same reasons as herbicide and insecticide resistance; overuse of the same type of active ingredient and/or the same type of MoA. However, it is not only the MoA resistance that has caused a loss of effective fungicides, but also environmental and health effects that have caused concern and bans of certain active ingredients. The same way one can try to prevent resistance towards herbicides and insecticides can be applied to fungicides - integrated management of the fungicides where different MoA are used. One difference between insecticide and fungicide resistance management is that there is a certain class of MoAs in fungicides; the so called multi-site activity MoA. Here, the target site is in different parts of the fungi pathogen [34], see Table 2.2 for the different types of chemical groups that have this MoA [33]. Thus, there is a lower chance of resistance building up in the different fungal diseases when these substances are used [34].

2.2 Brazilian agriculture

To understand why Brazil is on the map concerning excessive pesticide use, the historical and current agricultural situation in the country have to be explained. Brazil is one of the largest agricultural economies with extensive export to all parts of the world, with products such as coffee, soybean, sugarcane, cotton and many other commodities [35]. This requires enormous investments in technology, infrastructure and pesticides, the latter to keep damaging pests away from the valuable crops. Brazil has undergone an immense development of agriculture the last century that will be presented below.

2.2.1 Historical development

In the beginning of the 1900s, much like today, Brazil's agricultural business was mainly designed to meet the need of foreign demands. This included coffee, cocoa, soybean and cotton and up until the 1960s, these products accounted for 55 % of the exports from Brazil. Despite the intense agriculture that produced so many commodities, Brazil continued to receive food aid well until the 1960s and imported large amount of food into the 1980s. In 1970, the commercial and traditional agriculture developed through scientific research which resulted in higher yields and large expansions throughout the country. Since then, Brazil has industrialized and high technology machines and processes have made the country competitive and continuously growing economically, which has resulted in urbanisation and higher income growth for a big part of the population. This urbanization enhanced the possibility to extend the farming land even more since more land was available to cultivate crops on. One of the noticeable results from this was a drop from 64 % to 16 % of Brazil's rural population from 1950 to 1990, meaning that more of the population moved to cities from land that was transformed to agricultural fields. Furthermore, this transformation increased Brazil's GDP and stimulated a further agricultural expansion [35].

The pressure for agricultural goods to ensure food for export and the growing population - in Brazil and worldwide - stimulated an industrial transformation and a shift towards modern agricultural processes. Not only did the yield and production have to increase, but more land needed to be transformed into crop fields. The industrial transformation stimulated more innovation and development in the tropical climate areas, and the traditional agriculture was developed to a scientific one. This innovation created possibilities of large scale expansions and even higher yields, with a 240 % increase in production and a yield increase of 2.5 of Brazilian grains between 1976-2011 [35]. One of the areas that this expansion affected was the Cerrado biome, a biome where 5 % of the biodiversity in the world exists due to savannah-like conditions that cannot be found anywhere else in the world [29][35]. The expansion of soybean cultivation in Cerrado has continued well into the 2000s due to technologies that made farming in the poor quality soil of the savannah possible and Cerrado is now one of the top producing beef and grain areas in the world, where soybeans and cotton are the drivers behind the biggest expansion [35].

One of the most important characteristics of Brazilian agricultural development is the transition from small family farms to large monocultural fields that cover thousands of hectares as well as the focus on high productivity gains in beef and milk production [35]. The monoculture is a threat to biodiversity since the farms only cultivate one or few crops where only certain animals and plants can benefit and the farming is very intensive. Furthermore if an uncontrollable disease or unfortunate weather condition were to occur, there is nothing to protect the huge farming areas that are exposed without the benefits of a mixed landscape with pastures, forests, buffer zones and mixed crops and vegetation [29], thus resulting in a risk for possible economic disaster.

2.2.2 Current agricultural situation

In 2016, 28 % of Brazil's total land area was dedicated to agriculture. Astonishing 235 254 of the country's 835 814 thousand hectares [4] is used for this and this accounts for 23.5 % of the country's total GDP while employing around 10 % of the working population [9]. Most of this area is in the central and south-central part of the country, where the development of agriculture has not been as hindered by policy agreements as in the Amazon region [35] and it is dedicated to pastures and soybean cultivation as well as sugarcane for ethanol production. Today, Brazilian sugarcane contributes with 17.5 % of the country's renewable energy, and to more than 15 % of the agricultural production value in the country which supports the continuation of this crop's cultivation [36]. Thus, the agribusiness in Brazil is a very important part of the economy and the trend is a continuous increase in production. According to the U.S department of agriculture, Brazil's export of coffee, soybeans and sugar was respectively 27 %, 43 % and 45 % of the total world export in 2017 [36], truly making it the agricultural industry of the world.

Since the new Bolsonaro government has taken office in Brazil, environmentalists worldwide have expressed a concern about the policy changes and the expansion of agriculture and other business that would put pressure on the ecosystems in Brazil even further than the current agribusiness has. Bolsonaro went to the election with vows to withdraw the country from the Paris agreement and to integrate the Ministry of Environment into the Ministry of Agriculture. "Brazil has too many protected areas" that "stand in the way of development" are quotes that Bolsonaro has made throughout his election tour. Mining and agriculture are two of the main focuses that threaten the Amazons - by some called the Earth's lungs - and are examples on what the new government plans to do with the now protected areas [37].

According to the climate change and agricultural scientist Eduardo Assad, the production of Brazilian agriculture could be doubled if degraded or abandoned land would be used again [37]. Hence, an increase of agricultural commodities and economic growth could be reached without further expansion of farming land in important ecosystems. This is one of the reasons that many environmentalists have been protesting the new campaigns about expanding agribusiness.

2.2.3 Soybean cultivation in Brazil

The soybean cultivation has exploded in Brazil in the last decades, where the main driver is the increased demand for soy-meal intended for livestock feed [6]. The bean was introduced to Brazil in 1882 and farmers started to cultivate it in the early parts of the 20th century, mainly in the southern parts of the country due to favorable weather conditions. Thus, it took about 50 years before the real explosion in popularity and wide expansions of the soybean fields. During the 90s and 00s, the total soybean production increased three-fold and the trend is moving up due to major investments in advanced farming technology, where Mato Grosso and Paraná are the two largest soybean producing regions with 17.2 Mtons and 11.8 Mtons produced respectively in 2008 [29].

In Brazil, the soybean is planted between October and beginning of January, which is spring and summer in Brazil, while it is harvested between end of January and beginning of May. Around 66 % of the Brazilian soybean producers use so called double cropping their soybean cultivation with maize. This means that they get two harvests per year, one of soybean and one of maize. The maize grows during the winter season and is by the farmers called "the minor harvest" [29]. This increases the economic value for the farmer but also results in very intensely managed farms and landscapes.

2.2.3.1 Harvested hectare and yield

The development of soybean plantations and yield in Brazil over the last decade can be viewed in Figure 2.1 and Figure 2.2 [4].

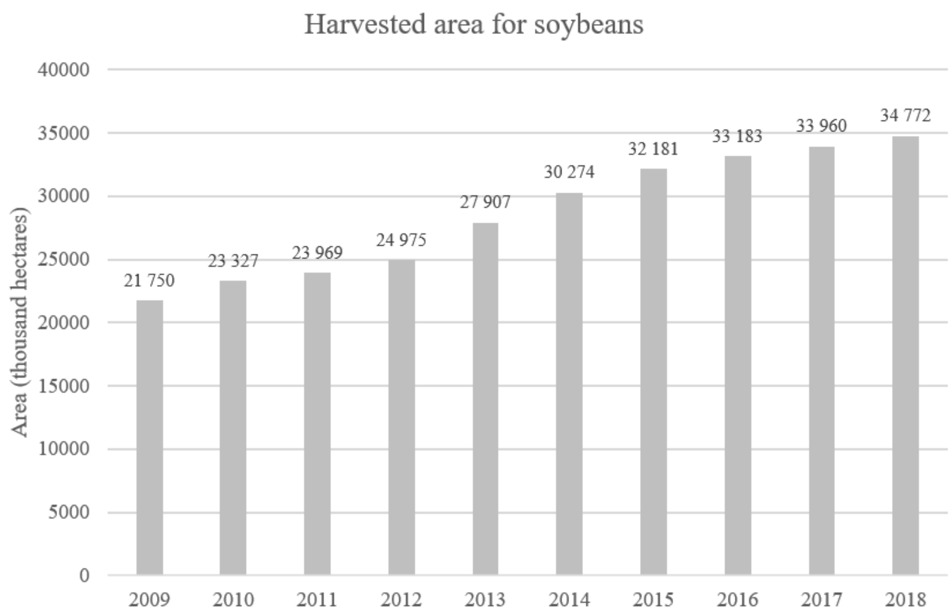

Figure 2.1: Total amount of harvested hectares soybean in thousand hectares [4].

The increase from 21 750 to 34 771 thousand hectares used for soybean cultivation is an increase of 60 % in ten years. This clearly shows that the demand has grown and Brazil is investing in meeting this demand.

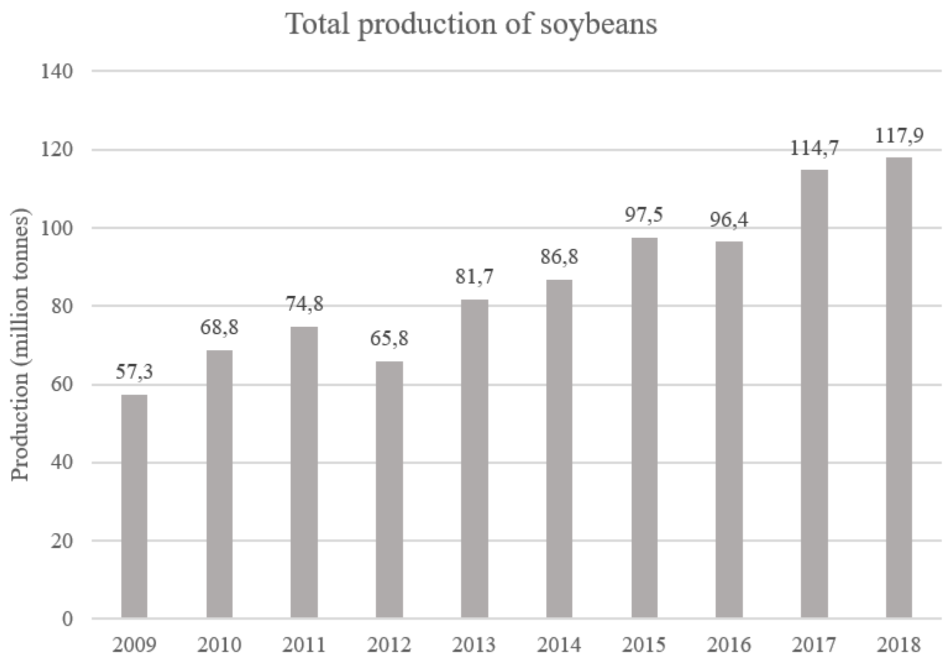

Figure 2.2: Total amount of produced soybeans in million tonnes [4].

The production increase of soybean over the last decade is 154 %. This is much due to the general agriculture development in Brazil discussed in Section 2.2.1, where Brazil has invested in advanced technologies to develop the agriculture in the country and thus increasing the GDP of the country and meeting global demand for agricultural commodities. As can be seen in Figure 2.2, in 2018, the total yield was almost 118 million tonnes of soybean, where the largest part is exported [6].

2.2.3.2 Genetically engineered soybean

The genetically engineered soybean (GE soybean) has increased immensely the last decades. The GE soy was primarily engineered to be resistant towards the pesticide active ingredient Glyphosate so the application of other harmful pesticides could decrease and the soybean fields would just be sprayed with this herbicide. Glyphosate is a non-selective herbicide [28], which means that it would kill all other weeds except the GE soybean. The most common GE soybean is the "RoundUp Ready" soybean that is resistant to Glyphosate and is used to a great extent in both the US and Brazil today. The main aim with the GE soybean was to decrease the amount of pesticides used in the cultivation but this has not been the case since the trend of pesticide use in Brazil has shown an increase of use instead [12][29]. Today, the GE soybean is the most common soybean variety around the world with approximately 80 % of the total soybean production. The demand for soy is constantly increasing and the country that import most of the soy from Brazil is China. The GE soybean growth is stimulated by this increased demand and future perspective does not show a different trend than an increasing one [29].

The last development of this can be viewed in Figure 2.3, where over 90 % of the soybean cultivated hectares has been used for GE soy since 2012, with the latest number being 92 % in 2018 [38].

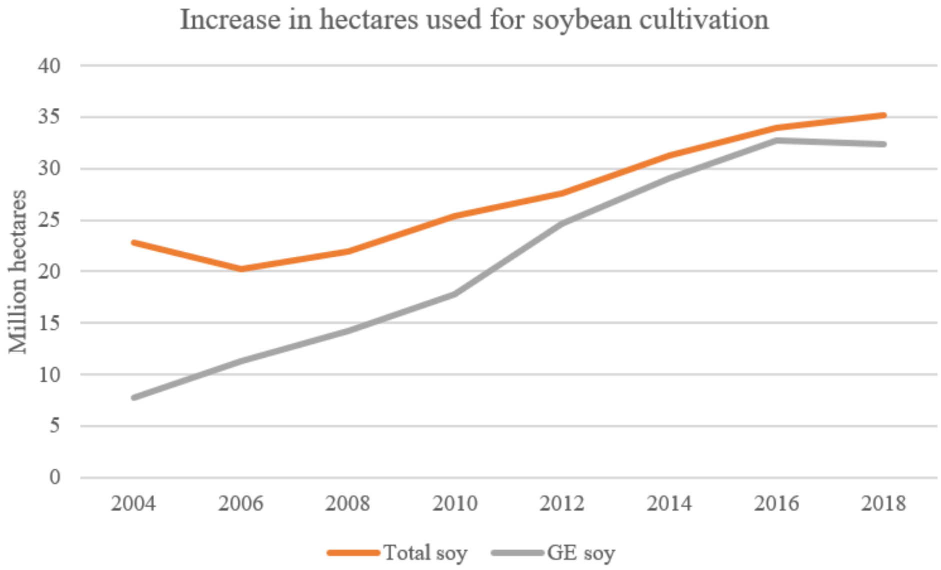

Figure 2.3: Increase of hectares dedicated to GMO soybean in Brazil [38].

In 2016 and 2017, the number was 97 % GE soybean, so a slight decrease has happened the last year, but the GE soy is undoubtedly the most cultivated soybean variety. This is not only the case for Brazil but the GE soybean dominates the world market. One consequence of this is, as mentioned above, the increased spraying of Glyphosate. Further consequences of this are still somewhat unknown and recent studies show that there is a knowledge gap in the actual risks of Glyphosate residues in food since the amount sprayed on the farms are higher than the field studies where the residues have been studied [39].

2.2.4 Pesticides in Brazilian soybean production

In Brazil, pesticide use started in the 1960s. Much of the herbicide use increased when machine operations - in this case tillage - decreased due to the discovery that it damaged the soil. So called no-tillage farming systems were introduced and with that, more pesticides were needed to control weeds that would otherwise have been removed by tillage. The available herbicides in the 1970s, when the no-tillage systems were introduced, were Paraquat and 2,4-D, substances that are banned today in the EU. The most commonly used herbicide since the 1980s, when it was registered for the first time, is Glyphosate, but this herbicide was still too expensive to use for many farmers long into the 1990s, thus resulting in the continuous use of many other toxic substances [29].

Weed management is an important part of soybean production, and when the use of herbicides increased, the complexity of handling the different substances increased too. Weeds that were resistant to some of the herbicides developed and caused problems with the yields. This is when the genetically engineered (GE) soybean was introduced and quickly became popular.

The need for pesticides that targeted foliar and fungal diseases developed during the 1970s, when Brazil suffered from multiple crop damaging diseases. Fungicides and inhibitors were then introduced and since then the amount of registered fungicides has only increased. The biggest challenge concerning fungal diseases is the Asian soybean rust. It was first discovered in Brazil in 2001, and the rust still cause damages throughout the country if not treated correctly. The pathogenic fungi is favored by the warm and humid climate in the central west region of Brazil, and yield losses can be very high (up to 100 %) during summer seasons when the weather is the most favorable. Today, there are about 45 fungicides registered for battling this rust, either alone or in combination with each other [40], where triazoles (cyproconazole and tebuconazole) have shown a better performance than other groups [41].

Apart from controlling weed with herbicides and fungi with fungicides, insecticides are used to prevent insects from affecting the soybean yield. Some of the insects discovered in soybean plantations in Brazil are soybean looper, green stinkbug and velvetbean caterpillar. Some of the insects are attacking the roots, while other attack the leaves. Thus, there are two different classifications of insecticides, foliar and seed protecting ones, and several different active ingredients of these two classifications are applied to control the insects. Insecticides follow the trend of pesticides with an increasing amount being applied to the soybean fields. In the years 2004-2010 the amount grew from 97 000 to 148 000 tonnes, an increase of around 65 % [29].

Pesticides are sprayed at all stages in the soybean cultivation. In Figure 2.4, an overview of the pesticide management and commonly sprayed pesticides in Brazil can be seen [29]. The non genetically engineered soybean is sprayed with multiple different herbicides during the vegetative and reproductive stage, while the genetically engineered soybean is only sprayed with Glyphosate during this stage. One important notion is that Paraquat and Diuron is sprayed both in pre-planting and in the harvest stage for both cases. This is much due to the increasing problem with Glyphosate tolerant weeds. These two herbicides are sprayed to kill off every weed before the sowing of the soybean, but also to help the soybean to mature in the last stage before harvest. The pre-harvest spraying is needed because the fields ripen uneven, some soybeans are mature enough for harvest earlier than other. Paraquat is sprayed together with Diuron to make the soybeans that are not ready for harvest ripen as well as killing off glyphosate tolerant weeds before the second sowing of maize ("the minor harvest") [29][42]. Another remark is that since Glyphosate is sprayed during the vegetative stage in the soybean cultivation in Brazil, the risk of glyphosate residues in the ready product soybean greatly increases, with residues way over the accepted amount in EU [39]. This type of pre-harvest spraying with Glyphosate is forbidden in Sweden due to risks of chemical residues.

INPUT	STAGE / TIME	PRE-PLANTING (DESICCATION)	VEGETATIVE STAGE			REPRODUCTIVE STAGE	HARVEST/POST PLANTING (DESICCATION)		
		SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
MAJOR HERBICIDES (A.I) USED	GM	2,4 D, 2,4 D + Glyphosate, Paraquat, Diuron + Paraquat	Glyphosate				Paraquat, Diuron + Paraquat, Diquat		
	NON-GM		Metribuzin, cletodin, trifluralin		Bentazone, fomesafen, Imazetapyr, lactofen, fenoxaprope-p-ethyl, clorimuron, clorimuron-ethyl				
MAJOR INSECTICIDES (A.I) USED	GM / NON-GM			Endulsulfan*, methamidophos**, thiamethoxam+ciproconalzol, lambdacialotrina+thiamethoxam, imidacloprid + betacyfluthrine, triflumuron, flube					
MAJOR FUNGICIDES (A.I) USED	GM / NON-GM					Pyraclostrobin + epoxiconazol, azoxystrobin + cyproconazol, pyraclostrobin, picoxystrobi, trifloxystrobin + cyproconazol			

* Sales of endosulfan will be prohibited from 2013. **Sales of methamidophosis were forbidden in 2012

Figure 2.4: Overview of when different classes of pesticides are sprayed in the soybean cultivation [29].

2.3 Indicators for measuring pesticides and their impacts

Various indicators can be used to assess the use and impacts from pesticides, these can be both quantitative and qualitative and are presented below.

2.3.1 Use of pesticides

One of the most straightforward way of presenting pesticides is to calculate and obtain numbers on the applied amount of pesticides on the fields. This gives an idea of how much and how many chemicals that are used in the cultivation of the crop. This indicates pressure on the environment since the majority of pesticides are synthetic and the more that is applied (types and amounts), the larger risk of affecting surrounding environment. Thus, two ways for measuring pesticide use are the indicators kilograms of pesticide per hectare and per produced ton crop - in this case soybean [10]. This indicator is based on sales statistics of pesticide active ingredients and interpreted as used amount on the fields.

2.3.2 Qualitative indicators

Another method that can help to evaluate the impacts from the pesticide use is to make a qualitative assessment of the different pesticide active ingredients. The active ingredients are organic and inorganic chemicals and are evaluated by different authorities and organizations like many other chemicals. Examples are chemical pictograms and hazard statements from the European Chemicals Agency and the Environmental Protection Agency in the US [21][43]. These indicates how toxic and/or dangerous the chemicals are for humans, animals and environment regardless of quantity. Therefore, this contributes with a qualitative assessment of pesticides.

2.3.3 Life Cycle Assessment in agriculture

To be able to environmentally assess products and processes, Life Cycle Assessment (LCA) is the most commonly used and recommended tool [16]. It is a well established tool that can assess food and other agricultural commodities to be able to give customers and retailers information on the environmental footprint the different products have. However, LCA on agricultural systems often only include narrow ways of environmentally assessing products, like emissions of CO_2-equivalents and climate impact due to land-use change. Few tools exist to assess e.g. biodiversity and chemical footprints [44], while the ones that do are not applicable to every part of the world since climate, species variation and weather differ around the globe. Hence, a crop cultivated in a temperate climate in Europe may have a very different chemical footprint compared to one cultivated in tropical climate in e.g. Brazil [45]. Today, there are LCA models that can be used for evaluating chemical footprints, two of them - PestLCI and USEtox - are presented below and will give some insight to how the impacts of pesticides can be studied [46]. While a broader perspective on the impacts agricultural products have is needed, the consumer interest for sustainable food supply chains is large and there are initiatives to further develop the possibility of doing justified and fair environmental footprint evaluations of products.

2.3.3.1 PestLCI

The model PestLCI 2.0 was developed and published in 2011 with the aim to evaluate emissions of pesticide residues to air, surface water and groundwater [26]. It is a model developed to be able to accurately create a Life Cycle Inventory specified to pesticides emissions from field application. This model can be used to help determine the different emissions from applied pesticides. Studies show that the distribution of the pesticide emissions are very much dependant on soil characteristics and local climate [26], since humidity, precipitation and wind will greatly affect the amount of pesticide leached or emitted to air. The field is considered a part of the technosphere in this model, meaning that the soil and the air above it is not a part of the ecosphere but a part of an anthropocentric system. This concern 1 meter depth in the soil and the 100 meter column of air above the field. When the chemical emissions to air, surface water and groundwater have been accounted for, the impact of the pesticide emissions are calculated using characterization models like USEtox [26].

As previously mentioned, pesticides consist of more than an active substance, there are also chemical compounds like surfactants, wetting agents and solvents that can be equally or more toxic to humans and nature. PestLCI is, however, only validated for the active substances, but if further validation was done for different chemical compounds, it could be used for the entire pesticide compound [26]. The PestLCI model is based on European conditions, while this thesis focuses on Brazil that has a different climate and weather. This problem may be solved by customizing the model for the Brazilian conditions, by changing soil, rain and sun radiation parameters in different regions in Brazil, such as Sao Paolo and Mato Grosso.

2.3.3.2 USEtox

To characterize the potential freshwater ecotoxicity impact from pesticides, the LCA impact assessment model USEtox is used. USEtox is a scientific model that has been developed to evaluate the impacts of different chemical compounds as an initiative from United Nations Environment Program (UNEP)–Society for Environmental Toxicology and Chemistry (SETAC). In USEtox, 991 organic substances for human toxicity exists, as well as 1299 organic substances for freshwater ecotoxicity, making it the best model for impact assessment of various chemical compounds [47]. It is also the largest substance covered LCA tool available and will therefore be used to evaluate the impacts on freshwater ecotoxicity from the pesticide active ingredients applied to the soybean fields in Brazil.

While USEtox is a useful tool for evaluating freshwater ecotoxicity of various chemicals, the index is still narrow. The impacts from pesticide exposure for workers and populations living nearby sprayed fields are to a large extent unknown and there are currently no LCA tools for evaluating this. USEtox is one of the available LCA impact assessment models for evaluating pesticides, but it is still not complete. In the Product Environmental Footprint manual by JRC Europe it is ranked in a lower class in terms of robustness than assessment models for other impacts, e.g. climate change. [16].

USEtox is developed for temperate climates, making it a useful tool for European pesticide footprints, but not available for more global impact assessments. Currently, there are no LCI emission models or LCIA toxicity characterization models for tropical climates [45]. Modeling done by Gentil et al suggests that degradation and volatilization in tropical regions may have a faster kinetic rate than temperate ones, which would result in higher drift off from sprayed pesticides and other impact driven factors. While a rough estimation of toxicity can be done for pesticides used in tropical climates, the uncertainties remain large and the model is currently not suitable for doing studies in tropical regions [45].

2.3.4 DPSIR

DPSIR is a framework used for environmental assessments and can be utilized to discuss different effects on the environment and how indicators for measuring these can be developed. The abbreviation stands for: driving forces, pressures, states, impact and responses [48]. These different words form links between each other that can be used to describe impacts that humans have on nature in environmental science. It is widely used and adopted by the European Environment Agency (EEA) and commonly used to discuss environmental problems [48]. The framework can be viewed in Figure 2.5 and will be used to discuss the effects of pesticide use and which part of the chain different indicators belong to.

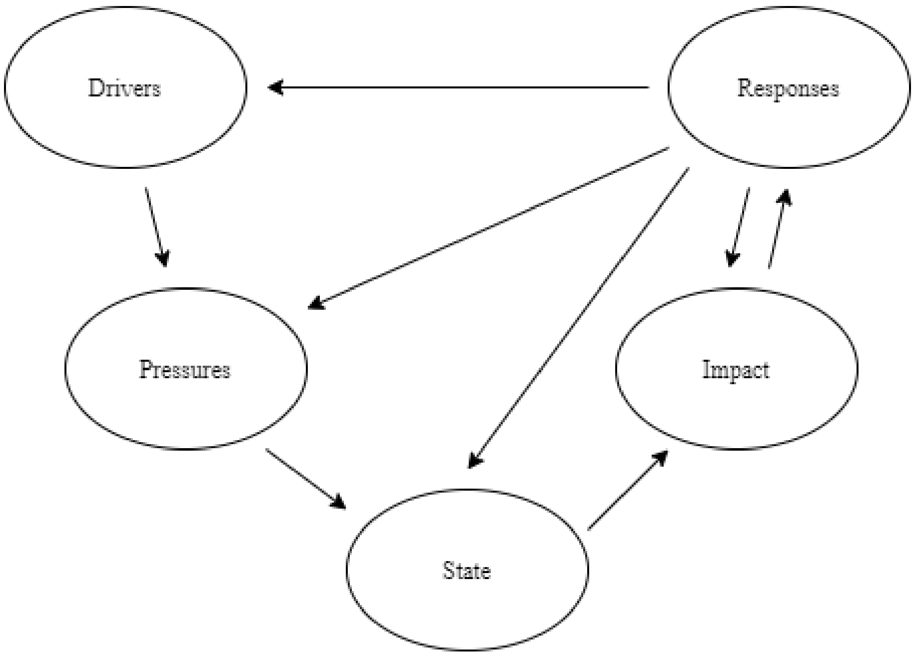

Figure 2.5: A figure of the DPSIR framework [48].

All of the words in the abbreviation have a significant meaning, explained below together with where in the chain of events the indicators in thesis can be assigned to [48]:

- Drivers - The economic or anthropocentric incitement, the need for a product or process. Individual needs may be divided into primary and secondary driving forces, where examples of primary ones are food and water, and secondary ones are e.g. culture. More economic and industrial ones are the need for profit and not having underemployment in the country. The use of pesticides in the soybean cultivation is a driver for protecting the soybean crop from pests and thus drives a following pressure on the fields.
- Pressures - The meeting of the need, the driving forces. When meeting these needs, pressures on the environment are created. These pressure can be divided

into:
  - Over-use of environmental resources, exploitation.
  - Land use change, e.g. deforestation.
  - Emissions of e.g. chemicals, waste; Direct and indirect. The emissions of pesticides from the use is a pressure on the surrounding environment. Unfortunately, the emissions from pesticides using PestLCI is not possible due to the model not being developed for tropical climates which is why the emissions are instead assumed to be 9 % to air and 1 % to water in accordance with the PEF-manual [16]. The pressure on the fields and the environment is hence uncertain and should be further developed.
- States - This is the state of nature/environment, how the environment is affected by the pressures, like the quality of water, air or soil. The biological, physical and chemical state of the environment.
- Impacts - The impacts are the changes in the state of the environment due to the pressures that result in a change. Often degradation of the function of the environment, e.g. a change of pH in a lake that results in a decrease of ecosystem services. The results from USEtox that indicates the potentially affected fraction of freshwater ecotoxicity is an indicator that provides information on the impacts from pesticide use. The qualitative assessment is also an indicator of different impacts, which provides a good compliment to the quantitative ones that are estimated.
- Responses - This is the response by society or policy makers. The response from different actors regarding pesticide use is very various. While NGOs have expressed concern, the current government in Brazil encourages the use, this is further discussed in Chapter 5.

Emissions of pesticides are hence part of the pressure part of DPSIR, where the states and impacts are not known to a great extent [10]. This thesis will discuss the impacts from large pesticides groups used for soybean cultivation and evaluate the time trends of these impacts, how has the pesticide trend developed during the last decade and how large are the ecotoxicity impacts?

3
Method

To be able to evaluate the environmental footprint of pesticides, a large amount of data needs to be processed and analyzed. The data gathered from Brazilian agencies is reported in various ways, e.g. active substance and total amount of sold active ingredients, so the data mapping was one of the core objectives in the thesis.

3.1 Approach to obtain pesticide footprint

The first approach was to map data of different pesticides and categorize them in herbicides, insecticides and fungicides while evaluating how much of them are used. The data is given at national level. The mapping of data is crucial for the understanding of how pesticides are used in the soybean cultivation and one of the most time consuming part of the thesis. It is also important to understand how the pesticide data is reported, since restrictions on the reporting in Brazil might hinder full access to the data.

3.1.1 Data mapping

Data on pesticide use in Brazil was found published on the website of the environmental ministry of Brazil. The ministry - IBAMA - collects and publishes data from all companies that sell pesticides to the farms using pesticides, both large and small, throughout the country [12]. The data was presented and sorted in different ways including:

- Which active ingredient and how much.
- Usage per region, amount of active ingredients and total amount.
- Most common active ingredient.
- Amount of pesticide sorted on toxic classification.

Since this data includes the total sale of pesticides, including crops, livestock and domestic use, the share that ends up being used in soybean cultivation had to be sorted and calculated. This will be explained in Section 3.2.

In addition to the pesticide data, the Food and Agriculture Organization of the United Nations Statistics (FAOSTAT), provides numbers on amount of hectares dedicated to soybean production and the produced tonne soybeans throughout the studied years in Brazil. This data can be downloaded from their webpage and be used to calculate indicators such as active ingredient per hectare and yield [4].

3.1.2 Method for pesticide classification

Data on sold pesticide active ingredients from 2009-2018 could be found on the governmental webpage IBAMA [12]. The data is sorted on active ingredient and classified as herbicide, insecticide or fungicide and the amount used in total throughout Brazil. The pesticide active ingredients are qualitatively classified using Pesticide Property Database, developed at the University of Hertfordshire [21]. The database provides information on each active substance and what type of pesticide they are classified as, but also detailed information on toxicological effects and what crops they are usually used on.

Further classification of herbicides, insecticides and fungicides was needed to find out what kind of characteristics the active ingredients have. Herbicides are classified as selective or non-selective, while fungicides and insecticides are classified as being either foliar or seed applied as treatment on the crops. Foliar application is a spray application on the leafs of the weeds, for both pre-emergence and post-emergence pests, i.e. it can be sprayed proactive before the crops have started growing or when the pest has established. Seed treatment is when the seeds of the crops are treated with a coating of the pesticide to proactively hinder pests from damaging the crops [21]. These classifications was needed to evaluate how much of the commercial products that are used for soybeans, since the sold products are sorted into products that are either non-selective, selective, foliar or seed applied. See example in Section 3.2.

3.2 Calculation of pesticides in soybean

To calculate the amount of pesticides used for soybean cultivation, information about the commercially sold pesticides in Brazil was gathered from the National Union of the Industry of Products for Plant Defense (SINDIVEG) [49]. SINDIVEG provides information on how large share of pesticide sales that is allocated to the different crops and what type of classification they have, e.g. selective or non-selective for herbicides. For example; in 2014, 347 780 tonnes of non-selective herbicide active ingredients were sold and of those, 234 674 tonnes were dedicated to the soybean crop, see Equation 3.1.

$$Share\ to\ soy = \frac{234\,674}{347\,780} = 0,67 \tag{3.1}$$

Data from SINDIVEG on the share of commercial products dedicated to different crops was not available for the year 2009 and 2015-2018. Therefore, the assumption that the same share of pesticides are dedicated to soybean in 2009 as in 2010 and that 2015-2018 have the same share as 2014 had to be done. The calculated share to soybeans by SINDIVEG can be viewed in Table 3.1.

Table 3.1: Share allocated to soy according to SINDIVEG for the different pesticide classes [49].

			Herbicide - non-selective		
	2010	2011	2012	2013	2014
Share	0,56	0,61	0,63	0,65	0,67
			Herbicide - selective		
	2010	2011	2012	2013	2014
Share	0,18	0,15	0,16	0,15	0,16
			Fungicides - Foliar application		
	2010	2011	2012	2013	2014
Share	0,44	0,47	0,49	0,50	0,49
			Fungicides - Seed treatment		
	2010	2011	2012	2013	2014
Share	0,62	0,57	0,61	0,54	0,63
			Insecticides - Foliar application		
	2010	2011	2012	2013	2014
Share	0,45	0,45	0,53	0,60	0,61
			Insecticides - seed treatment		
	2010	2011	2012	2013	2014
Share	0,46	0,57	0,70	0,74	0,69

By using these shares, the amount of pesticide A.I:s allocated to the soybeans could be calculated. An important assumption done to be able to calculate this is that the amount of active ingredient allocated to soy assumes that all active ingredients can be used for soybean cultivation. I.e all A.I:s are registered for use in soybeans. This is however not the case, for example; Atrazine is a herbicide active ingredient that is registered in maize, but it is still included in the total amount of herbicides used in Brazil. Furthermore, a very small part of the sold fungicides and insecticides are registered as seed treating ones. For example, in 2014, only 2,6 % of the insecticides and 4,5 % of the fungicides were registered for this according to SINDIVEG. Thus, it was assumed that all of the fungicide and insecticide active ingredients are sprayed on the fields, i.e. as foliar treatment. This assumption was further motivated by the classification (see Appendix 1), where very few of the A.I are classified as only seed treatment.

The data collected and mapped from IBAMA with the sold amount of pesticide active ingredient - classified as non-selective, selective, foliar and seed - was multiplied with the share that is sold to the soybean crop according to SINDIVEG. Another example from 2014 and non-selective herbicides; the total amount of reported non-selective herbicides in 2014 - 204 664 tonnes active ingredient - was multiplied with the share that goes to soy - 0,67 - to obtain the amount of non-selective herbicides used for soybean cultivation, see Equation 3.2.

$$Amount\ in\ soy = 204\,664 * 0,67 = 137\,125\ tonnes. \tag{3.2}$$

Furthermore, this was done for non-selective, selective herbicides, foliar and seed applied fungicides and insecticides to obtain numbers on the pesticide use in soybeans for all three pesticide groups.

3.2.1 Active substance per hectare and produced tonne soybean

The total amount of active ingredients allocated to soybeans for each pesticide class was then allocated per hectare soybean and per tonne produced soybean. The amount of herbicides, insecticides and fungicides from 2009 to 2018 was divided with the hectares and yields the same year and show a time trend of the use. The statistics of hectares and tonne produced soybean are from FAOSTAT [50]. An example of these calculations can be seen in Equations 3.3 and 3.4, where numbers of non-selective plus selective herbicides in 2014 are used.

$$A.I\ per\ hectare = \frac{(137\,125 + 12\,989) * 1000}{30\,273\,763} = 4.96\frac{kg}{ha} \tag{3.3}$$

$$A.I\ per\ yield = \frac{(137\,125 + 12\,989) * 1000}{86\,761\,577} = 1.73\frac{kg}{tonne\ yield} \tag{3.4}$$

3.3 Study of relative use-trend

To get an overview of use-trends for some of the most commonly used pesticides in soybean plantations, active ingredients in each class were studied over the ten year period 2009-2018 and plotted to show relative trends of the use. To be able to fully understand the trends of insecticides and fungicides, not only the active ingredients sold in the largest volumes was studied but also the strong increase in so called low-dosage pesticides. Low-dosage pesticides are pesticides that only require a low amount of A.I to combat the pests. For example; the insecticide A.I Lambda-Cyhalothrin has a recommended dose of 12 g A.I/ha [51] compared to other insecticides (such as Malathion) that require a dose of 1000 g A.I/ha [52]. These low-dosage pesticides have increased relatively much and are known to be used in soybean cultivation, i.e. they have increased over time but they are not the largest amount of tonnes used. Therefore, a literature study on trends in the cultivation systems was done to be able to acknowledge the general pesticide trend in Brazil and why some pesticides have increased more than others, especially in the soybean production [31][33][40][41]. The low dosage A.I may play an important part in the toxicity impacts even if the actual dose is lower than other pesticides. Examples of low-dosage pesticides are the fungicide Azoxystrobin, which is used for battling the rust, and the insecticide Bifenthrin

Regarding the common pests in Brazil, this is mostly the fungi pathogen Asian soybean rust, which is why a study of the most effective and commonly used fungicides for combating this pathogen was done. This gave an insight on why some fungicides have increased more than other since the Asian rust is a large problem in Brazil [40].

The pesticide resistance problem was studied to get a better insight on why some herbicides, insecticides and fungicides have increased more since resistance may have caused a shift from some active ingredients to other ones.

3.4 Qualitative assessment

To evaluate how toxic the commonly used and most increasing pesticides are, the Pesticide Property Database (PPD) and the list of Highly Hazardous Pesticides (HHP) by the Pesticide Action Network (PAN) was used to classify the pesticides in human health toxicity and ecotoxicity [21][53]. This gave a qualitative assessment of the studied pesticides and is an important complement to the quantitative indicators. The Pesticide Property database classifies the pesticides in accordance with the European Union directives, even if the pesticides are not approved in the EU, while the PAN list of HHP has collected classifications from different sources e.g. European Directives and the US Environmental Protection Agency (EPA). The HHP list was used complimentary to PPD, since classifications of which insecticides that are toxic to bees are stated in this list.

3.5 Freshwater ecotoxicity impact assessment

Since not all of the individual active substances are published, the most commonly used active ingredients were chosen for the life cycle impact assessment, where the potential freshwater ecotoxicity is modeled. Considering that the data on individual A.I:s was investigated at a national level and not a regional, the PestLCI uncertainty for tropical climates poses a problem. The problem with using national data of applied pesticides is that they are used throughout Brazil, where various climates - temperate and tropical - affect the pesticide emissions. This is due to volatility and run-off characteristics of the pesticides, where tropical climates have shown an effect of increasing these particular attributes of the emissions [45]. Due to these uncertainties with PestLCI, estimations of pesticide emissions were made based on the Joint Research Centre Europe's (JRC Europe) Product Environmental Footprint manual, where it is stated that 9 % of the applied pesticides are emitted to air and 1 % is emitted to water [16]. By using this information, the amount of emitted pesticide can be calculated since the total applied amount is known.

To calculate the pesticide emissions, the kilograms of pesticide is multiplied with the share to soy, as explained in Section 3.2, and then divided by the hectares used for soybean cultivation to obtain how many kilograms pesticides that are applied per hectare to the soybeans P_a. This number is then multiplied with 0.09 and 0.01, resulting in numbers on *how much of the pesticide that is emitted to the surrounding environment per applied kilogram per hectare.* The emitted pesticides, $P_e\ air$ and $P_e\ water$ are calculated using Equations 3.5 and 3.6.

$$P_e\ air = \frac{P_a\ (kg)}{Area(ha)} * 0,09 \tag{3.5}$$

$$P_e\ water = \frac{P_a\ (kg)}{Area(ha)} * 0,01 \tag{3.6}$$

When pesticide emissions were established, the USEtox characterization factors were used to calculate the potential freshwater impacts [47] [54]. By using this estimate of how much of the applied pesticides that are emitted, USEtox could be utilized to calculate a so called Potential Affected Fraction (PAF) for freshwater ecotoxicity. This is an indicator on how many of the organisms in a freshwater environment that could be affected by the emitted pesticide. The PAF is measured in a unit called Comparative Toxic Unit (CTU) and in this thesis, the CTU of freshwater ecotoxicity was calculated in CTUe per hectare and year, see further Nordborg et al [46]. This will give a quantitative indicator of the potential freshwater ecotoxicity impact from the commonly used pesticides in soybean cultivation.

3.5.1 USEtox characterization factors

To calculate the Potentially Affected Fraction from the emitted pesticides, midpoint characterization factors were used. The USEtox model has characterization factors (CF) for all of the studied active ingredients and will give an indication of the PAF [46]. By multiplying the characterization factors with the emitted amount of pesticide, the potential freshwater ecotoxicity can be quantified [55]. The CF:s are different depending on air or water emissions due to chemical properties of the pesticide active ingredient. The characterization factors for all studied herbicide, insecticide and fungicide active ingredients can be seen in Table A.31, A.32 and A.33 in Appendix.

USEtox integrates two scales, continental and global to obtain CF. The CF:s are dependent on various chemical factors of the substance, one example being pKa values that represent the acidity of the substance. CF:s are measured in Comparative Toxic Unit per kilogram emitted substance and 1 CTUe= PAF m^3*day. The landscape data for the characterization factors is a default continent and not a specific site, with an uncertainty range of 1-2 order of magnitude, which again proves that the freshwater ecotoxicity impacts in this thesis are a rough estimation since the USEtox model is designed for temperate climates and many of the soybean plantations in Brazil are located in tropical climates [29][45][46].

3.5.2 Calculations of impacts

In these type of LCA calculations, the so called impact scores are calculated as in Equation 3.7. Where $P_e\,air$ and $P_e\,water$ is the kilograms of pesticide emitted to air and water respectively (using the 9 % and 1 % estimated emissions from the JRC Europe PEF method), CF_{air} and CF_{water} are the USEtox characterization factors for air and water respectively.

$$Impact\left(\frac{CTUe}{ha/yr}\right) = P_e\,air * CF_{air} + P_e\,water * CF_{water} \tag{3.7}$$

This was done for all of the most commonly and largest used herbicides, insecticides and fungicides as well as the low-dosage active ingredients that showed a steep increase in the use trend.

4
Results

In this section, the results of the thesis will be presented. This includes results on data research and reporting, quantitative results from the data mapping of the pesticide use; active ingredient per hectare and produced tonne soybean and a freshwater ecotoxicity estimation of the commonly used pesticides with a large increase over time. Furthermore, a temporal trend on the commonly used pesticides is presented together with a qualitative assessment of these. The qualitative assessment presents a dimension of human and other environmental toxicities and is a an important complement to the LCIA freshwater ecotoxicity estimation. The results are first presented as total numbers of pesticides, then amount of pesticides in soybean to then be narrowed down to present the indicators of the classes herbicides, insecticides and fungicides on their own. Lastly, a summary and comparison of these three classes are presented to give an overview of the indicators of the footprints of the different classes.

4.1 Pesticide data reporting and use in soybeans

The initial result was found when the data research and mapping was done. One of the first discoveries was that FAOSTAT reports significantly less pesticide use in Brazil than what the country itself actually does. FAOSTAT reports a number of 377 176 tonnes while IBAMA reports 539 944 tonnes, a difference of 162 768 tonnes.

One of the first key results was that the ministry of environment, IBAMA, does not publish all of the sold pesticide active ingredients. If three or less companies sell a pesticide with a specific active ingredient, it is not published on the governmental sites due to commercial competition. In Figure 4.1, the number of published, non published and total number of registered pesticides can be viewed. While the majority of individual active ingredient presented in the sold products are not published, as much as 90 % of the total sale of pesticides is attributed to the published individual active ingredients. Obviously, the non-published active ingredients are sold in very small volumes. In Figure 4.2, the amount of active ingredients over the years can be seen. To see all of the reported and published pesticides and their applied amount each year, see Appendix 1.

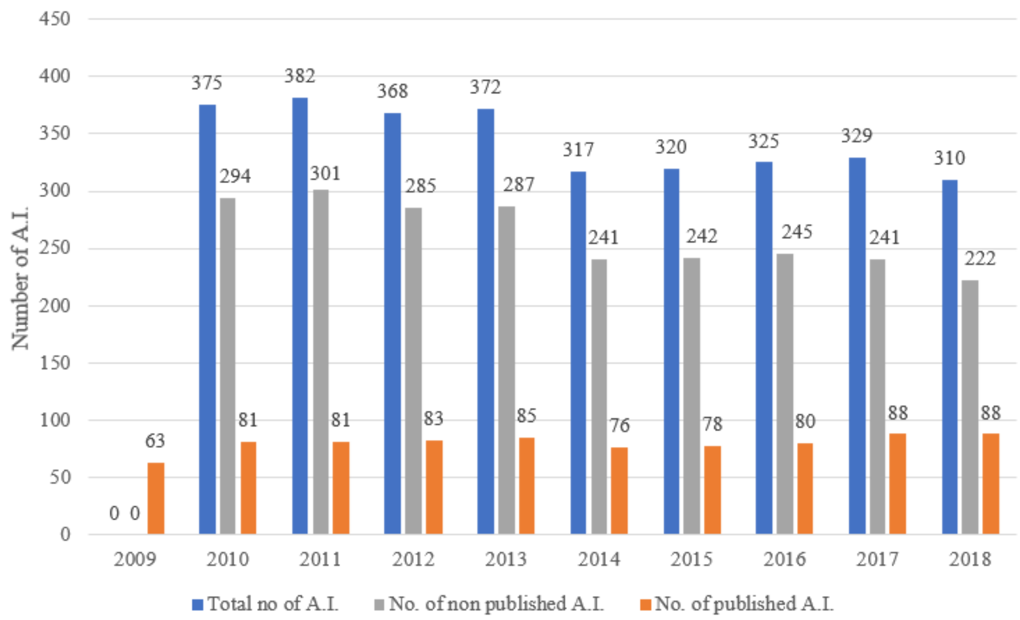

Figure 4.1: Plot of the total number of registered active ingredients (A.I:s), A.I:s that are not published and the number of published A.I:s from IBAMA.

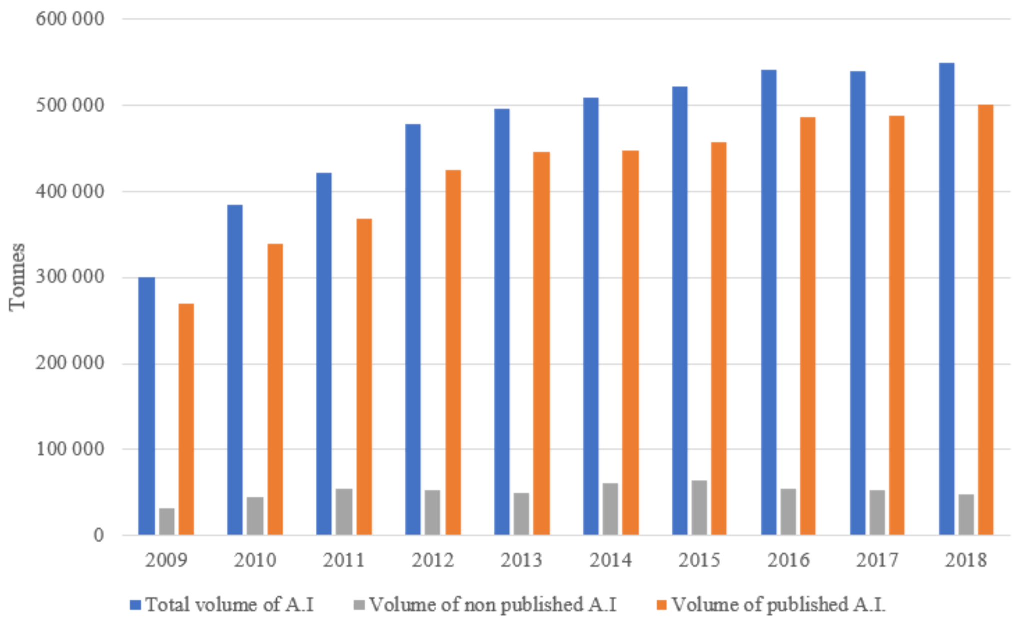

Figure 4.2: Total volume of sold pesticides as active ingredient (A.I), volume of sold A.I with published individual A.I:s and volume of sold A.I with non-published A.I:s.

4.1.1 Pesticide use in soybean production

When the amount of pesticides used each year in Brazil was established, the amount dedicated to soybeans was calculated, see Section 3.2. The results of herbicides, insecticides and fungicides dedicated to soybean production can be seen in Figure 4.3. The class of non-selective herbicides (glyphosate being the largest ones) is without a doubt the largest class used in the soybean cultivation, which is in line with the big share of the cultivated hectares being GE glyphosate resistant soybean. An increase of all classes can be seen.

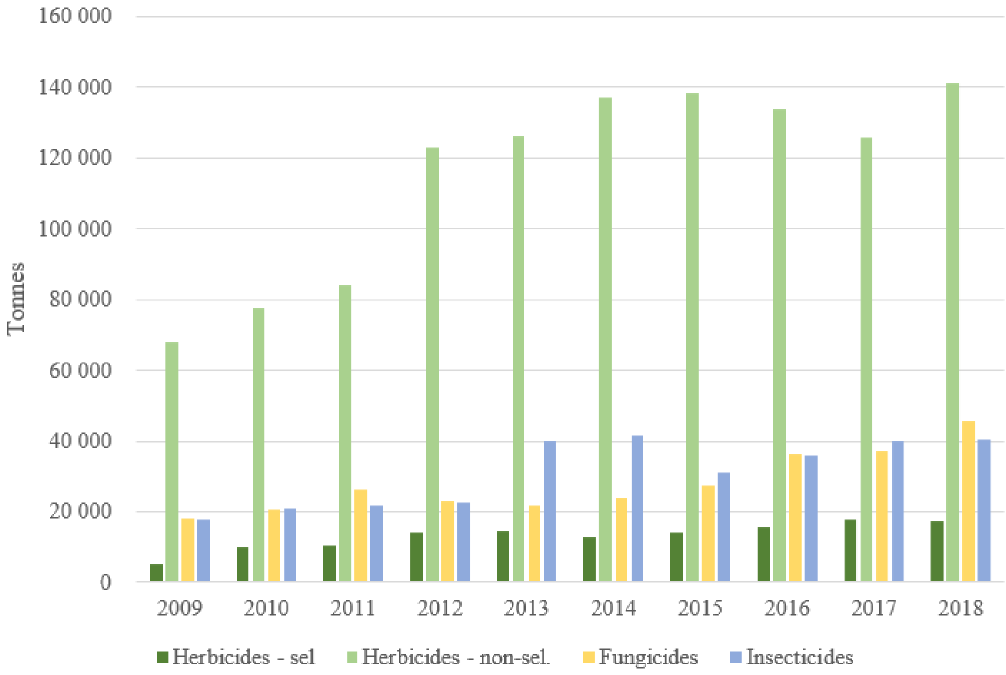

Figure 4.3: Total volumes of active ingredients estimated to be used in soybeans from 2009 to 2018. (Herbicides are divided into selective and non-selective substances, see further text under Section 3.1.2).

4.2 Herbicides

Herbicides are the largest class of applied pesticides in the Brazilian soybean cultivation. Here, the different indicators for pesticide footprints from herbicides will be presented.

4.2.1 Use per hectare and tonne soybean

The first indicator is the use in kilograms of A.I per hectare cultivated soybean and per tonne produced soybean and the results can be viewed in Figure 4.4 and Figure 4.5.

Figure 4.4: Use of herbicides, active ingredient (A.I) kg/ha, in soybeans during the period 2009 - 2018.

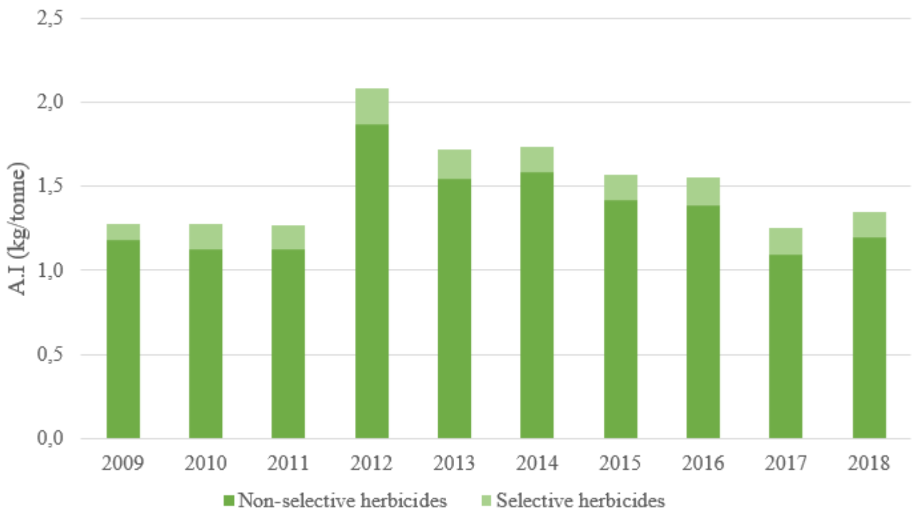

Figure 4.5: Use of herbicides, active ingredient (A.I) kg/tonne soybean, during the period 2009 - 2018.

An increase in A.I per hectare can be seen, even if the hectares dedicated to soybean has increased as well. When looking at the kilograms of A.I per produced soybean, the increase is not as remarkable. This can be explained by Brazil's intense technological development of agriculture that has resulted in a high soybean yield. The pesticide use increase between 2009 and 2018 is around 1 kg/ha, which is still a large increase of overall applied herbicides on the fields.

4.2.2 Relative trends and qualitative assessments

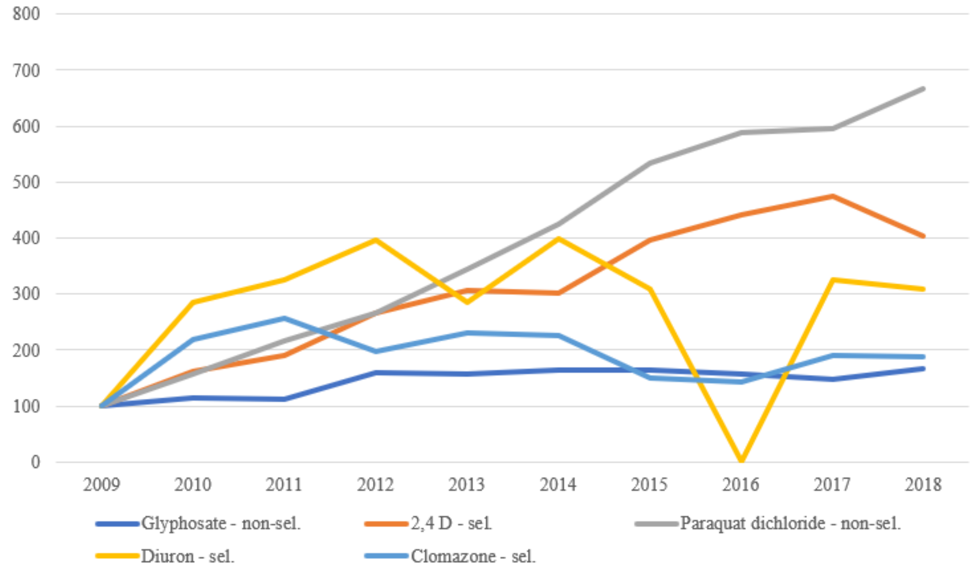

Figure 4.6: Relative trends in use of the five largest herbicides in soybean cultivation. Use in 2009 is 100.

The relative trends in Figure 4.6 show that the curves representing Paraquat dichloride, 2,4-D and Diuron are very steep, with a factor increase of 6.7, 4 and 3 respectively over the 10 year period. The Diuron gap in 2016 is most likely to a data reporting gap due to commercial competition or other reasons and not because no Diuron was used that year. In Table 4.1, the qualitative assessment of risks with these herbicides can be viewed.

Table 4.1: Qualitative risk assessment of the five largest herbicides in soybean cultivation. Classified using Pesticide Property Database (PPD) and list of Highly Hazardous Pesticides (HHP) by Pesticide Action Network (PAN) [21][53].

Herbicide	Human risk classification	Environmental risk classification
2,4-D	Harmful if swallowed. Risk of serious damage to eyes. May cause sensitisation by skin contact. Irritating to respiratory system.	Harmful to aquatic organisms. May cause long-term adverse effects in the aquatic environment.
Clomazone	Harmful by inhalation. Harmful if swallowed.	Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.

Diuron	Danger of serious damage to health by prolonged exposure. Harmful if swallowed. Limited evidence of a carcinogenic effect.	Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.
Glyphosate	Risk of serious damage to eyes.	Toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment
Paraquat dichlorid	Very toxic by inhalation. Toxic in contact with skin. Toxic if swallowed. Irritating to respiratory system. Irritating to skin. Irritating to eyes. Danger of serious damage to health by prolonged exposure.	Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.

Paraquat dichloride, 2,4-D and Diuron has the most toxic classifications and are also the ones that have increased the most during the studied time period.

4.2.3 Freshwater ecotoxicity impacts

The potential freshwater ecotoxicity impact as estimated by USEtox of the most commonly used herbicides can be seen in Figure 4.7. The freshwater impacts are highest from Paraquat chloride and Diuron emissions and the trend is an increasing toxicity over the years.

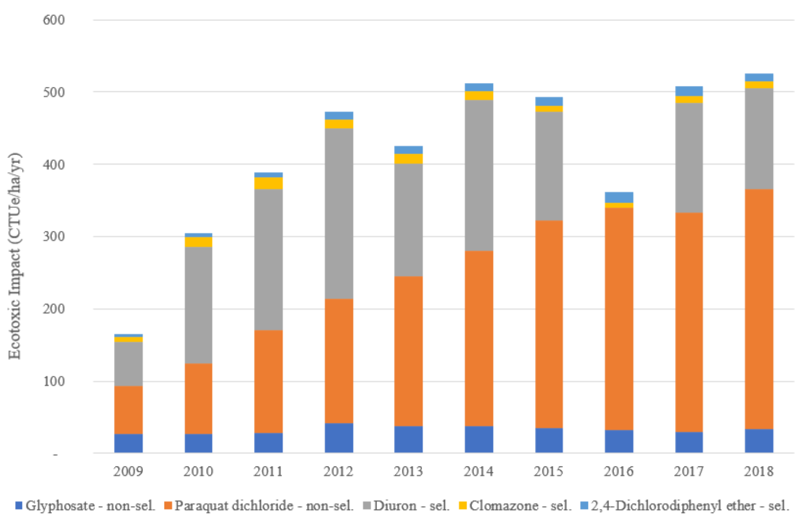

Figure 4.7: Potential freshwater ecotoxicity impact, CTUe per ha and year, for the five largest herbicides.

4.3 Insecticides

The insecticides in the soybean cultivation follow a somewhat different trend from the herbicides. As explained in the method section (Section 3.3), another approach is needed to analyse trends in insecticide use during the studied time period in the soybean cultivation than for herbicides, which results in a higher number of studied insecticide active ingredients than only analysing the insecticides in the largest amounts applied.

4.3.1 Use per hectare and tonne soybean

The amount of applied kilograms of insecticides per hectare and tonne produced soybean can be viewed in Figure 4.8 and 4.9. An increase in A.I over the last ten years can be seen in both cases. The applied amount is considerably lower than for herbicides where an average of around 4 kg/ha and 1.5 kg/tonne can be viewed (Figure 4.4 and 4.5) and the average of the insecticides per hectare and produced soybean is much lower (around 1.2 kg/ha and 0.4 kg/tonne). However, this is not necessarily a good sign and will be further discussed throughout the discussion section.

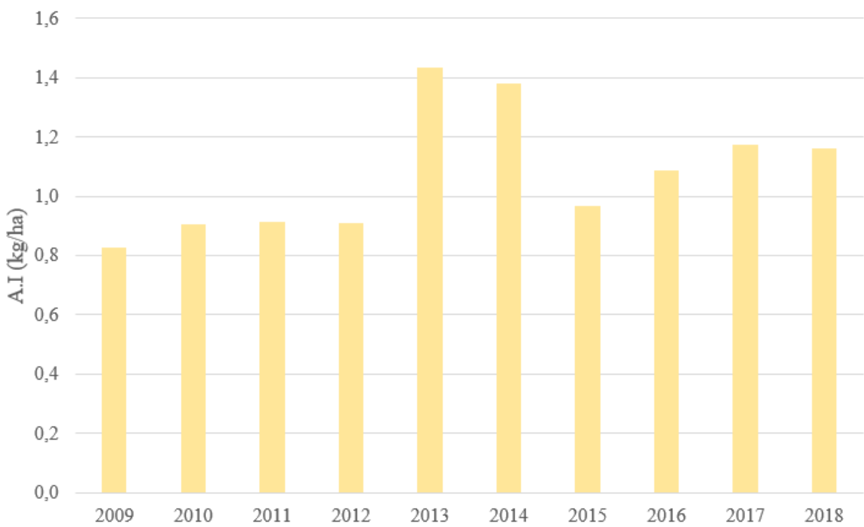

Figure 4.8: Use of insecticides, active ingredient (A.I) kg/ha, in soybeans during the period 2009 - 2018.

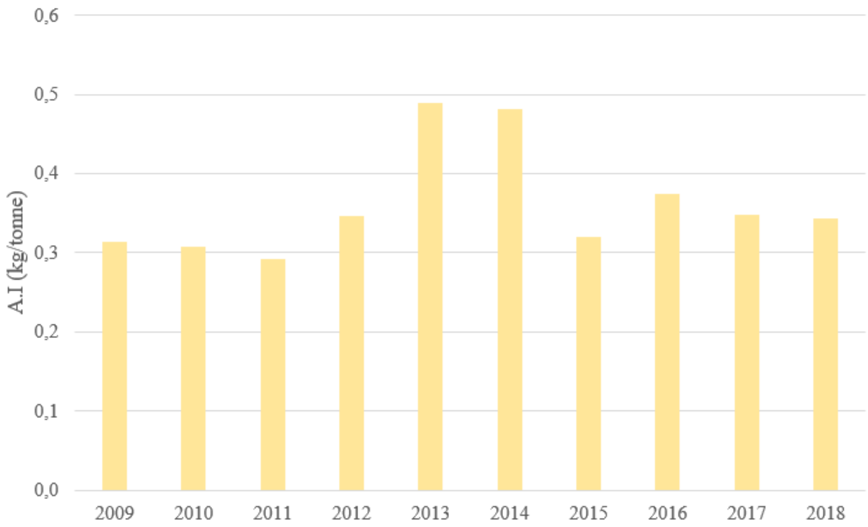

Figure 4.9: Use of insecticides, active ingredient (A.I) kg/tonne soybeans, during the period 2009 - 2018.

4.3.2 Relative trends and qualitative assessments

The relative trends of insecticides show a large increase of all different types of chemical groups - organophosphates, neonicotinoids and pyrethroids - see Figure 4.10 and Figure 4.11. The dip in the organophosphate substance Malathion in 2014 and 2015 is most likely a data gap.

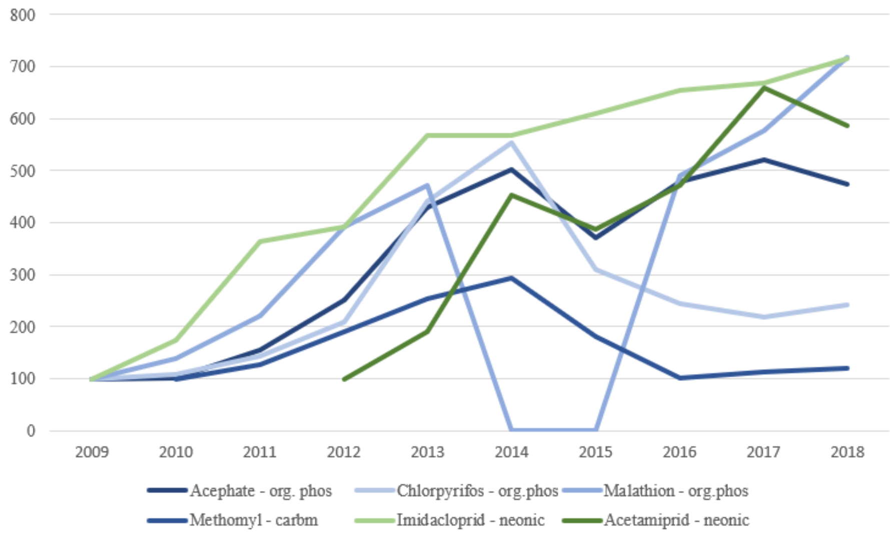

Figure 4.10: Relative trends of various chemical groups of insecticides in soybean cultivation. Use in 2009 is 100.

In Figure 4.11, the trend of the chemical group pyrethroids can be seen, with high tops in the use of Cypermethrin 2011 and 2017. The factor increase of the low dosage insecticide Lambda-Cyhalothrin is around 6.5, a very toxic substance. In general, the neonicotinoids and pyrethroids have increased largely compared to the organophosphates.

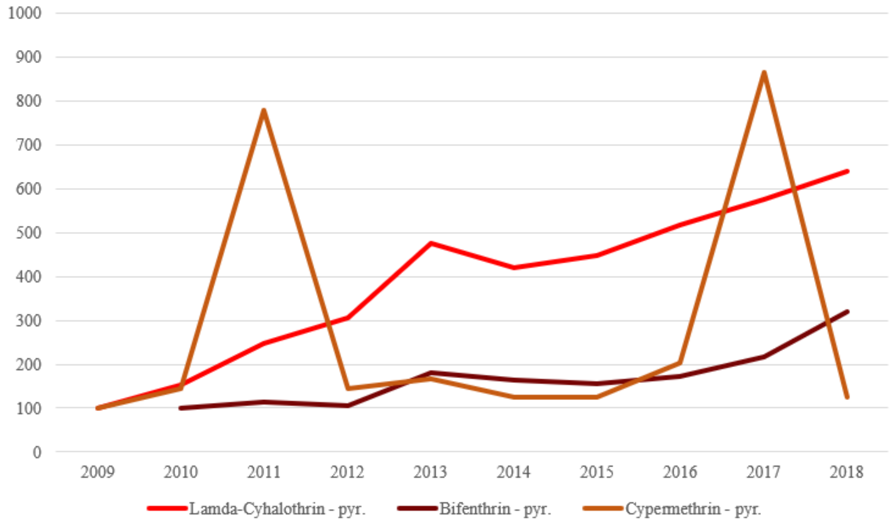

Figure 4.11: Relative trends of pyrethroids in soybean cultivation. Use in 2009 is 100.

In Table 4.2, a qualitative assessment of the insecticides studied can be seen. All of them except Methomyl is classified as highly toxic to bees according to the list of HHP by PAN and all of them are toxic to aquatic organisms and may cause long-term adverse effects for the aquatic environment except for Acephate.

Table 4.2: Qualitative risk assessment of the studied insecticides in the soybean cultivation. Classified using Pesticide Property Database (PPD) and list of Highly Hazardous Pesticides (HHP) by Pesticide Action Network (PAN) [21][53].

Insecticide	Human risk classification	Environmental risk classification
Acephate	Harmful if swallowed.	Hazard to ecosystem services - highly toxic to bees.
Acetamiprid	Harmful if swallowed.	Harmful to aquatic organisms. May cause long-term adverse effects in the aquatic environment.

Bifenthrin	Harmful if swallowed. Toxic if swallowed. Toxic by inhalation. Danger of serious damage to health by prolonged exposure.	Hazard to ecosystem services - highly toxic to bees. Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.
Chlorpyrifos	Toxic if swallowed. Harmful in contact with skin. May cause sensitisation by skin contact.	Hazard to ecosystem services - highly toxic to bees. Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.
Cypermethrin	Harmful if swallowed. Danger of serious damage to health by prolonged exposure. Irritating to respiratory system.	Hazard to ecosystem services - highly toxic to bees. Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.
Imidacloprid	Harmful if swallowed.	Hazard to ecosystem services - highly toxic to bees. Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.
Lambda-Cyhalomethin	Very toxic by inhalation. Toxic if swallowed. Harmful in contact with skin. May cause sensitisation by skin contact.	Hazard to ecosystems services - highly toxic to bees. Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.

Malathion	Harmful if swallowed. May cause sensitisation by skin contact.	Hazard to ecosystems services - highly toxic to bees. Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.
Methomyl	Very toxic if swallowed.	Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.

4.3.3 Freshwater ecotoxicity impacts

The potential freshwater ecotoxicity impacts, calculated as CTUe per ha and year, are presented in different diagrams due to the active ingredients' large differences in aquatic toxicity and thus large differences in the substances characterisation factors. This can be viewed in Figure 4.12, 4.13 and 4.14. It is clear that the difference in toxicity varies with numbers of ten thousands CTUe and the pyrethroids are the most toxic ones. The largest contributor to this is Lamda-Cyhalothrin due to its characterization factor of 139 000 000 kg/CTUe. Comparing the various insecticides in Figure 4.12, which mostly consists of organophosphates with the pyrethroids in Figure 4.14, the difference is enormous. Methamidophos and Endosulfan were banned in 2012 and are listed in Annex III in the Rotterdam Convention due to extreme toxicity towards humans, but they are plotted to show how toxic they are and because the increase in neonicotinoids and pyrethroids are much due to the fact that many organophosphates have been banned.

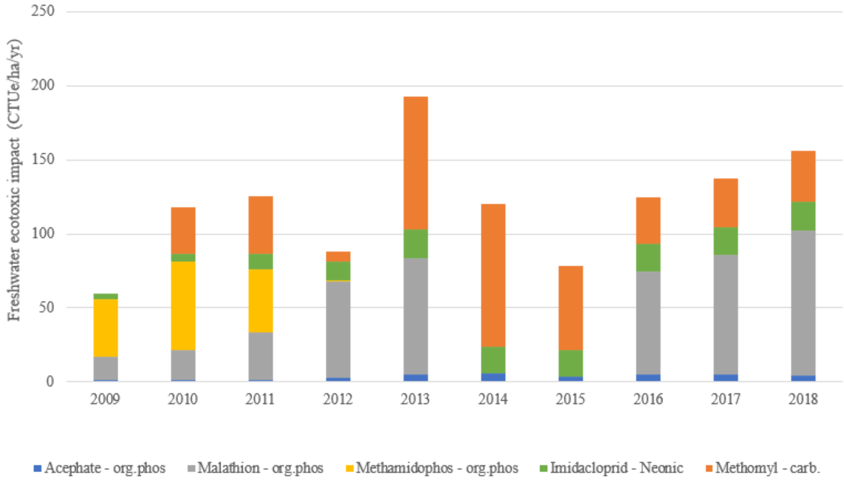

Figure 4.12: Potential freshwater ecotoxicity impact, CTUe per ha and year, for different chemical groups of insecticides.

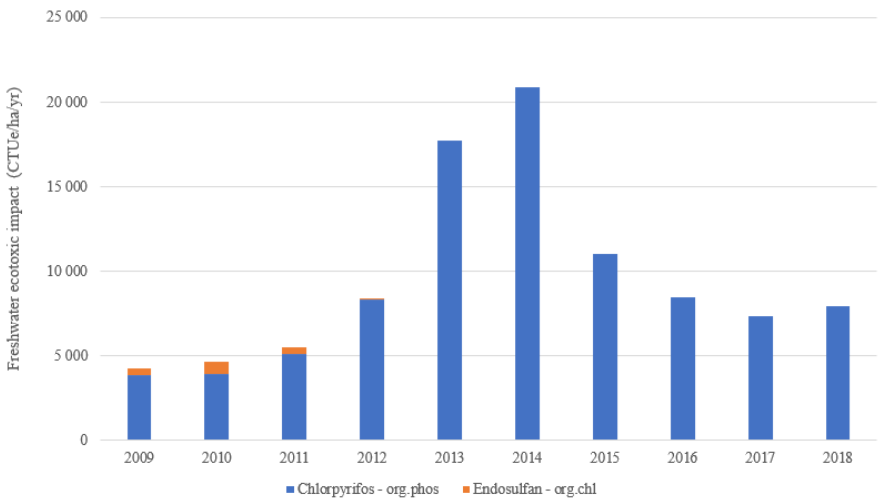

Figure 4.13: Potential freshwater ecotoxicity impact, CTUe per ha and year, for the insecticides Chlorpyrifos and Endosulfan.

Comparing the various insecticides in Figure 4.12, which mostly consists of organophosphates with the pyrethroids in Figure 4.14, the difference is enormous. Furthermore, it is worth noting that the pyrethroids are low dosage insecticides compared to the organophosphates, proving that a larger amount of applied active ingredient does not mean that it will cause the largest potential freshwater impacts.

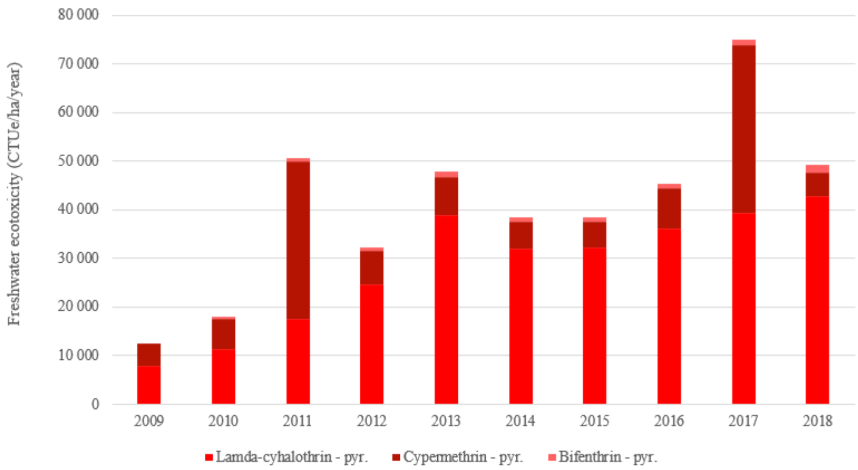

Figure 4.14: Potential freshwater ecotoxicity impact, CTUe per ha and year, for the chemical group pyrethroids.

4.4 Fungicides

The evaluation of the fungicide footprint in the soybean cultivation differs from herbicides and insecticides. Compared to insecticides with low-dosage chemicals, the fungicide use has shifted during the studied period much due to the need of controlling the Asian soybean rust. Therefore, in the trend analysis, also active ingredients with a relatively large increase are included.

4.4.1 Use per hectare and tonne soybean

The fungicide use per hectare and tonne produced soybean can be seen in Figure 4.15 and 4.16. The fungicide use is - in the same way as insecticides - lower than the herbicide use. It is slightly lower than the insecticide use, but still shows an increase in applied fungicides over the studied time period.

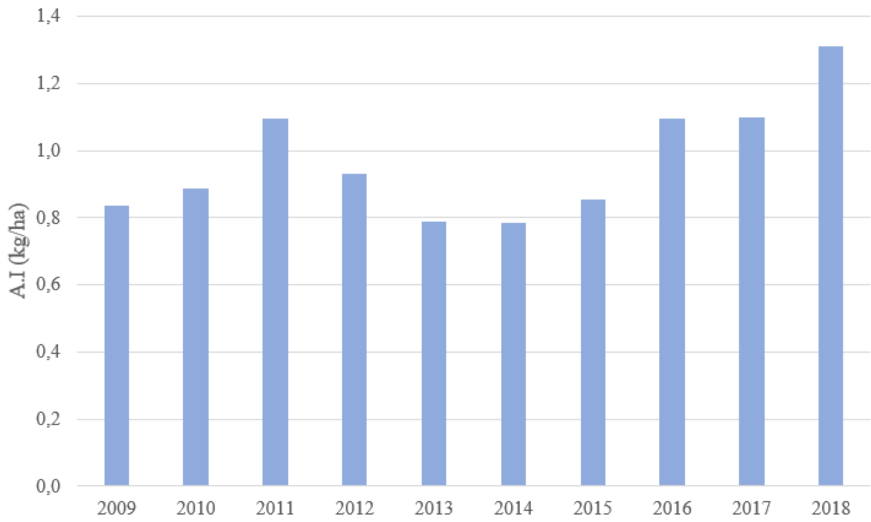

Figure 4.15: Use of fungicides, active ingredient (A.I) kg/ha, in soybeans during the period 2009 - 2018.

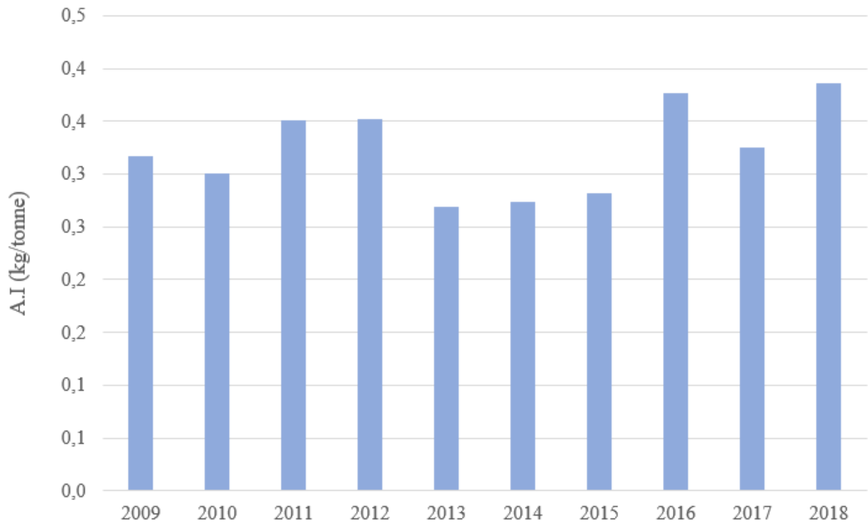

Figure 4.16: Use of fungicides, active ingredient (A.I) kg/tonne soybean, during the period 2009 - 2018.

4.4.2 Relative trends and qualitative assessments

In Figure 4.17, the relative trends of fungicides can be viewed. The three fungicides that have increased most are fungicides with a multi-site activity MoA - Mancozeb, Chlorothalonil and Copper Oxychloride - where Mancozeb has increased with a factor of over 11.

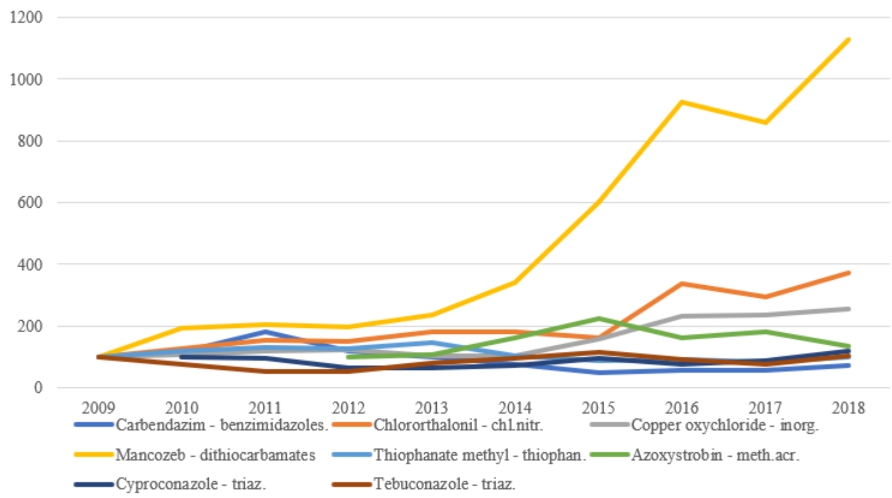

Figure 4.17: Relative trends of the most commonly used fungicides in soybean cultivation. Use in 2009 is 100.

The qualitative assessment of the studied fungicides can be viewed in Table 4.3. One important notion is that many of the fungicides - compared to herbicides and insecticides - have been classified as having a potential impact on fetuses and may cause genetic mutations. This includes Mancozeb, which has had the largest increase in the studied time period. All of them are also toxic to aquatic organisms.

Table 4.3: Qualitative risk assessment of the studied fungicides in the soybean cultivation. Classified using Pesticide Property Database (PPD) and list of Highly Hazardous Pesticides (HHP) by Pesticide Action Network (PAN) [21][53].

Fungicide	**Human risk classification**	**Environmental risk classification**
Azoxystrobin	Toxic by inhalation.	Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.
Carbendazim	May cause heritable genetic damage. May impair fertility. May cause harm to the unborn child.	Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.
Chlorothalonil	Very toxic by inhalation. Risk of serious damage to eyes. May cause sensitisation by skin contact. Irritating to respiratory system. Limited evidence of a carcinogenic effect.	Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.

Copper oxychloride	Harmful by inhalation. Harmful if swallowed.	Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.
Cyproconazole	Possible risk of harm to the unborn child. Harmful if swallowed. Limited evidence of a carcinogenic effect.	Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.
Mancozeb	Possible risk of harm to the unborn child. May cause sensitisation by skin contact.	Very toxic to aquatic organisms.
Tebuconazole	Possible risk of harm to the unborn child. Harmful if swallowed.	Toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.
Thiophanate methyl	Possible risk of harm to the unborn child. Harmful by inhalation. May cause sensitisation by skin contact.	Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment.

4.4.3 Freshwater ecotoxicity impacts

For the fungicide active substances with the largest increase in use during the studied 10-year period potential freshwater ecotoxicity impacts were calculated, see Figure 4.18. In 2011, there was a considerable peek of the use of Carbendazim and together with Chlorothalonil, it accounts for most of the freshwater ecotoxicity.

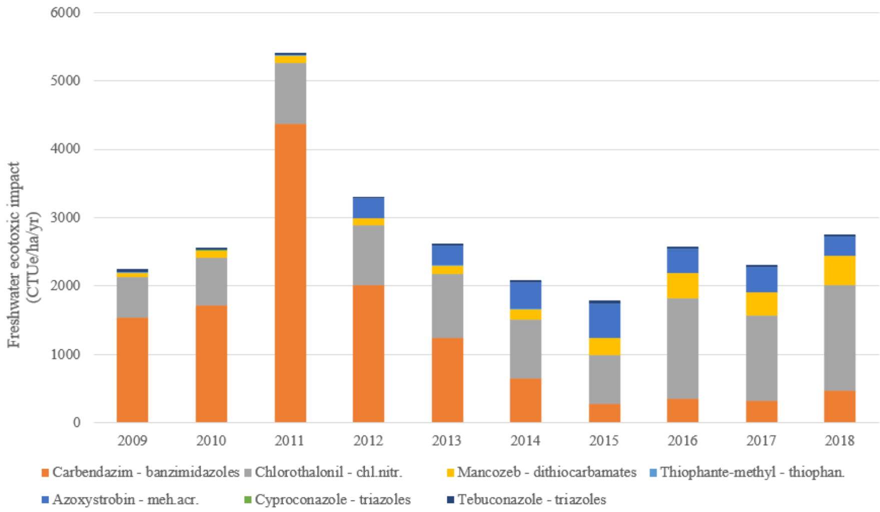

Figure 4.18: Potential freshwater ecotoxicity impact, CTUe per ha and year of commonly used fungicides in soybean cultivation.

4.5 Summary and comparison of results

To summarize and get an overview of some important indicator results from this thesis study, two graphs of two different indicators - the use-indicator (kg A.I/ha) and the impact-indicator (CTUe/ha), are presented in Figure 4.19 and 4.20. While the use indicators suggest that herbicides are the most important pesticide group to consider, the impact indicators (reflecting potential freshwater ecotoxicity impacts) highlight the importance of the insecticides The herbicides are barely visible in this diagram and the fungicides only represent a small part. This is an important result since it shows that amount of applied pesticides is not an indicator that necessarily show how bad a pesticide is for the environment.

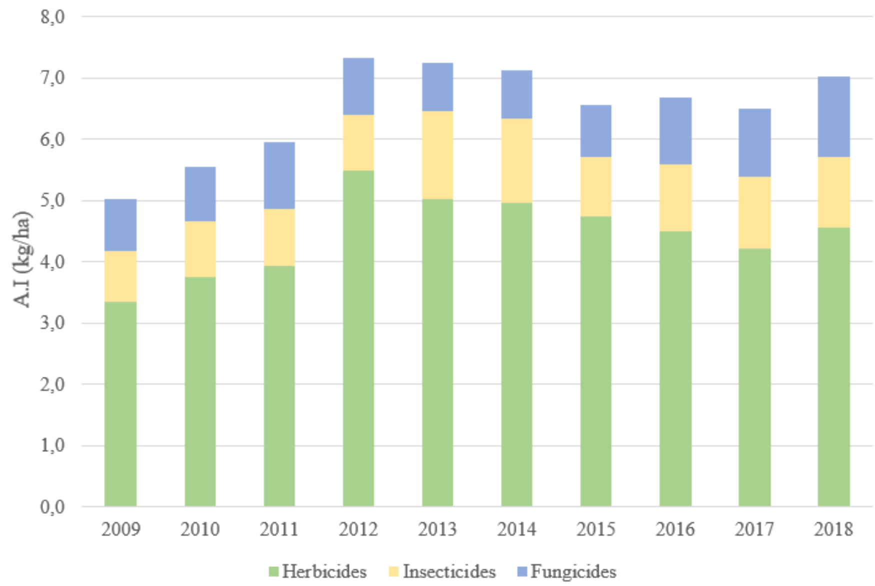

Figure 4.19: Use of pesticides, kg active ingredient (A.I) per ha soybeans, divided between herbicides, insecticides and fungicides, 2009-2018.

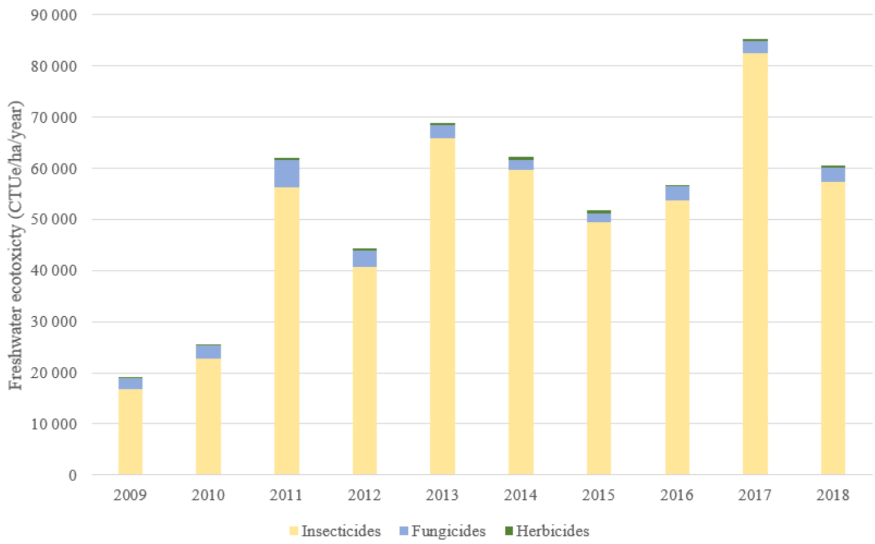

Figure 4.20: Potential freshwater ecotoxicity impact of pesticides use in soybean, CTUe per ha, divided in herbicides, insecticides and fungicides, 2009-2018.

To further establish that the amount applied to the fields is not a good indicator for pesticide footprint, the qualitative assessments shows that the herbicides and insecticides with the largest increase over time are also the ones with the most toxic classifications. The outcome from the qualitative assessments of the most used and/or pesticides having the largest increase in the studied period, support the conclusion that the an indicator showing use of pesticide provide a very incomplete pesticide footprint indicator.

5
Discussion

In this section, the results will be evaluated and discussed, initially about the data mapping and research, the discussion is then divided between herbicides, insecticides and fungicides. After this, the indicators and the pesticide resistance problem will be analysed. The pesticide use, emissions and impacts will then be evaluated by discussing the DPSIR model. Lastly, some of the challenges with calculating pesticide footprints will be stated.

5.1 Data mapping and reporting

The first concern considering Brazil's data reporting on pesticide use is that the numbers from FAOSTAT and the national numbers are not the same. Why is the difference in the reporting an astonishing 162 768 tonnes? While this cannot be answered with certainty, it puts further pressure on researching the use of pesticides since Brazil is one of the largest producer of agricultural commodities and user of pesticides. Speculating in why the numbers have differed, it may be because FAOSTAT has tried to estimate the pesticide use by using calculation models and data from other countries and/or by looking at trends. To ensure future food and freshwater security, biodiversity and human health, pesticide use must be monitored since many pesticides are toxic to both humans and environment. Furthermore, as the data of the total amount of pesticides could be found publicly on the ministry of environment IBAMA, the numbers reported to FAOSTAT should be updated with official national numbers.

Not all information on individual sold active ingredients was published on the IBAMA website. The commercial competition between different farms and companies is protected and not public information. The result of this is that a complete impact assessment cannot be done since information about hundreds of individual active ingredients are not available which complicated the understanding of the pesticide use in Brazil. This can be viewed in Figure 4.1, where an average of 262 active substances are not reported throughout the years, which in volumes represent 10 % of the active ingredient sales. Although the reported A.I accounts for 90 % of the total sales, there is a large uncertainty on what type of pesticide active ingredients the rest of the 10 % are. One idea is that these active ingredients mainly constitutes of low dosage pesticides that are applied with a small amount and low concentrations since they account for a lower amount of the sales but there is no way to be certain. Many low dosage pesticides are very toxic to humans and the environment due to having toxicological effects like endocrine disruption and being toxic to bees so the impacts may be high even if the dose is low.

After further research it was discovered that Brazil may report more thoroughly at regional level than at national level. Comparing a list of active ingredients used in Mato Grosso, one of the bigger soybean cultivation regions, with the collected summary of all active ingredients used in Brazil some differences could be found. One of the differences was that different types of salts and compounds were not fully reported at national/regional level. This included but was not limited to Glyphosate, 2,4-D and Picloram as well as various types of chlorine compounds and bacteria.

One of the most time consuming parts of the thesis was the actual data mapping and classifications of the active substances used in Brazil. The list of all pesticides reported at national level via IBAMA can be viewed in Appendix 1. The sorting and classification took some additional time due to uncertainties about the databases where the research on classification was done. When the used database - Pesticides Property Database - was found, the information was double checked to see if everything was correctly sorted and classified right in terms of herbicides, insecticides and fungicides as well as having properties such as selective or not, or having foliar or seed treatment.

5.2 Calculations of pesticide use and impacts

Some challenges arose during the calculations of use and impacts of pesticides, not only because of reporting issues. The statistics needed to be translated from Portuguese and interpreted before being able to calculate any of the indicators. The assumption that the share of pesticides dedicated to soy is the same from 2014-2018 might result in a higher or lower amount of active ingredient allocated to soy. However, the large increase of the share of non-selective herbicides between 2010 and 2014 captures that the Glyphosate sales have increased during the studied time period, in line with the increased hectares cultivated with the GE soybean variety. The assumption that all insecticides and fungicides are foliar applied on the fields is, apart from the motivation given in Section 3.2, further motivated by previous study trips in Brazil where D.Meyer and C.Cederberg visited soybean plantation sites and got insight in the pesticide management on many farms [29].

Due to the large uncertainties with the LCA tools PestLCI and USEtox, the freshwater ecotoxicity calculations are estimations of the potentially affected fraction of aquatic organisms. This gives an indication of how toxic the studied active ingredients are, even if they are applied in small doses. To be able to do a proper LCIA future research is required, including developing PestLCI and USEtox for tropical climates and data mapping of pesticide use on a regional level since the climate differs throughout Brazil [45]. Since large areas of the soybean cultivation takes place in tropical climates, toxicity impact assessments from pesticide use are very uncertain. This is much due to the fact that emissions cannot be established using the inventory tool PestLCI. Since PestLCI quantifies pesticide emissions in temperate climate using soil, weather and other climate data together with chemical data from the active ingredient substance to calculate the emissions, the tropical climate conditions will most certainly influence the emission. An increase in precipitation, humidity, soil composition and possibly wind should increase vaporization and runoff from the soils and thus resulting in different emissions than for temperate climates. This is under evaluation and development but a lot remains to be done. The pesticide emission estimation was, as previously mentioned, done using rough emissions factors based on JRC Product Environmental Footprint manual [16]. This is a certain and reliable source but, however, the basis for these emission factors are inadequately motivated which further pinpoints that it is an indicator estimation.

5.3 Herbicides

The herbicide use in Brazilian soybean production is by far the largest in terms of amount active ingredient. The non-selective herbicide Glyphosate represent the largest part of this, together with paraquat dichloride. The high Glyphosate use is due to the enormous increase of GE soybean that is tolerant towards this A.I, where over 90 % of the hectares dedicated to soybean are the so called Round-up Ready soybean. The mean value of herbicide use per hectare and produced ton soybean is 4.5 kg and 1.5 kg respectively, where the use per hectare is the most interesting indicator since it indicates how much pressure the fields and landscape are under. These numbers show that the introduction of the GE soybean variety has increased the use of toxic active ingredients.

The relative trends of the most commonly used herbicides (Figure 4.6) show that Glyphosate has had a steady use level compared to the other herbicides, which can be explained by the increasing amount of Round-up Ready soybean in Brazil. Glyphosate is the largest applied active ingredient but has been so since this GE soybean variety was introduced. However, Diuron, 2,4-D and Paraquat dichloride show an enormous increase of a factor 3-7 from 2009 to 2018. While Glyphosate is applied in large amounts, there are weeds that have become resistant towards this active ingredient and other herbicides have been sprayed to combat them. Looking at Figure 2.4 in the background section, the spraying schedule of herbicides show that these substances are sprayed in the pre-planting and in the harvest period of the soybean cultivation. This is because the strategy is to spray everything before planting so that the field is clear of weeds before the soy is sowed, and then spray before harvest to ripen the soybeans that are not ready for harvest yet as well as killing off weeds that has grown during the vegetative state. However, increasing problems with Glyphosate resistant weeds are likely one important reason for this strong increase in these three herbicides. Paraquat dichloride and 2,4-D are also the herbicides with the most toxic classifications in the qualitative assessment with Paraquat dichloride being extremely toxic towards humans. The substance is fatal if inhaled and toxic in contact with skin as well as being very toxic to aquatic organisms and may cause long term effect in aquatic environments. Paraquat dichloride is a substance that is used for suicide in many countries due to being easy accessible, cheap and fatal if ingested or inhaled - an evaluation in South Korea showed that the total suicide rate decreased when a ban on paraquat was adopted [56].

The potential freshwater ecotoxicity of herbicides shown in Figure 4.7 further illustrates that Paraquat dichloride and Diuron are the most toxic herbicides of the ones evaluated. Even if Glyphosate is applied in *much* larger amount, the USEtox characterization factor is so low compared to the other two that it does not show as much potential risk for aquatic organisms.

5.4 Insecticides

The insecticides show an increasing use trend, where the chemical group organophosphates accounts for the largest amount of applied kilograms. When looking at Figure 4.4 where the kilograms of insecticide A.I per hectare are plotted, a large increase of A.I can be seen in 2013, this may be because a problem with some insects increased during that year. For example, a biotype of the Whitefly insect was introduced in Rio Grande do Sul - a large soybean region - in 2013 [31], and may have caused an increase of certain insecticides. These types of specific year occurrences of pests influences how much pesticides the farmers have to use and some years might need more applications of certain pesticides. From 2009-2018, there has been an increase around 0.4 kg of insecticides per hectare which is a substantial amount that contributes to pressure on the fields, especially since there are many low dosage high effect insecticides in the soybean cultivation.

The relative trends on insecticides were divided between various A.I and pyrethroids to give a clearer overview of certain active ingredient results. An important result of these trends is that low dosage high effect insecticides - neonicotinoids and pyrethroids - have increased the most compared to organophosphates (except Malathion, that accounts for the largest increase of organophosphates with a factor 7). One of the reasons for this is that insects have become resistant towards organophosphates. Even if the MoA is the same for all of these insecticides, the chemical groups affects different parts of the muscle and nerve systems, as can be seen in Table 2.1 in the background section [31]. Thus, insects can be resistant towards the site of action that organophosphates affects but still be controlled by neonicotinoids and pyrethroids that accumulate faster and in different internal parts in the insects which results in a higher effect. However, the resistance problem is concerning since there are limited numbers of MoA and developing new ones requires both time and resources. By the time a new MoA arrives on the market, further resistance may have developed [20].

As good as all of the insecticides with the highest increase are highly toxic to bees and aquatic organisms (Table 4.2), meaning that an extensive use of these may cause impacts on ecosystems that today are unknown.

The potential freshwater ecotoxicity of insecticides are without a doubt the highest one of the three pesticide groups, where pyrethroids accounts for the largest potential impact which can be seen in Figure 4.14. The largest contributor to this is the low-dosage insecticide is Lambda-Cyhalothrin. This active ingredient has a CF (for water) of 139 000 000 CTUe/kg which, compared to for example the organophosphate Acephate with a CF of 626 CTUe/kg, explains why the largest share of the toxicity is allocated to Lambda-Cyhalothrin. Furthermore, Malathion has a large impact on freshwater organisms (Figure 4.12) since it is used in such large amounts. Malathion is also one of the active ingredients that has increased the most during the ten year period. Concluding, an increase of the most toxic insecticides for aquatic organisms has occurred during the studied time period.

5.5 Fungicides

The use of fungicide active ingredient per hectare and produced ton soybeans are the lowest compared to the other two classes but still show an increase of over 0.4 kg per hectare from 2009 to 2018. The Asian soybean rust is a severe problem in the Brazilian soybean cultivation [40], and the increase of different fungicides could be a result of the different strategies to try to combat this pathogen fungi that causes large yield losses .

In terms of relative trends the three most increasing fungicides, Mancozeb, Chlorothalonil and Copper oxychloride - seen in Figure 4.17 - all have so called multi-site activity mode of action, meaning that they affect the organism on multiple sites internally. The reason for this increase is that there is a lower chance of fungus developing a resistance towards these types of active ingredients. Usually, these A.I are to a large extent mixed together with low dosage active ingredients to combine the multi-site mode of action with high effect fungicides. Mancozeb - that has increased with a factor of almost 12 over the studied time period - has been evaluated in many studies as being effective towards the Asian rust, mostly in combination with other active ingredients such as the low dosage fungicide Azoxystrobin [34][40]. From the qualitative assessment of fungicides seen in Table 4.3 it can be noted that fungicides are the only one of of the three pesticide groups that are classified to possibly causing genetic mutations and harm to fetuses, which is why some of them have been banned in the EU.

The potential freshwater ecotoxicity of fungicides is higher than the herbicides, but lower than the insecticides. Chlorothalonil, which use increased with a factor of 2, has a high impact on aquatic organisms together with Carbendazim. Carbendazim has not increased much in the studied time period but is one of the most largely used fungicides in kilograms. In 2011, a large increase of this fungicide can be seen, which may be due to a specifically rough year in terms of fungus attacks on the soybeans.

5.6 Indicators for pesticide footprints

The indicator of active ingredient per hectare and produced soybean is clearly not sufficient in terms of environmental impact since herbicides are the most used pesticide group but still accounts for the smallest part of the estimated potential freshwater ecotoxicity. This can be seen when comparing the results in Figure 4.19 and Figure 4.20. However, this indicator still presents important information on how much pressure there is on the fields and on the landscapes since chemicals affect natural crops and environments as opposed to no application at all. One important notion regarding the result of this indicator is that only the amount of pesticide applied to soy is included, while many of they soybean fields are double cropped, meaning that maize is cultivated between the soybean seasons i.e. two commercial crops per year. Maize crops are also sprayed with pesticides, a large part with the herbicide Atrazine (thousands of tonnes nationally, see Appendix 1[12]). Atrazine is banned in the EU and is very toxic toward humans and aquatic environments [6][21]. Therefore, the use of pesticides per hectare during one year is very often higher during one year than the mean of 6.5 kilograms used for soybean seen in Figure 4.19, which means that the pressure on the same hectare is very large during all parts of the year and not only during the soybean cultivation season.

The relative trends of the three pesticide groups are important indicators for changes taking place in the cultivation systems. These results reflect what type of pesticide active ingredients are necessary for controlling the pests and - together with the qualitative assessment - how toxic these are. Unfortunately, almost all of the active ingredients studied in the three pesticide groups are toxic or very toxic to aquatic organisms and may cause long term adverse effects in aquatic environments. Furthermore, all of them are toxic towards humans in some way, either by inhalation, ingestion or skin contact with effects being damage to lungs, skin and possible genetic mutations. The three most increasing herbicides are the ones with the most amount of toxic notations, which is very concerning. The largest increased insecticides and fungicides are also the ones with the highest amount of toxic classifications and many of them are banned in the EU and in Sweden. These qualitative assessment results are important since the quantitative results of LCIA potential freshwater ecotoxicity only reflects aquatic environments and are a rough estimation.

The LCA potential freshwater ecotoxicity is an indication of how toxic the pesticides are to aquatic environments. Even if this is rough estimation due to large uncertainties, the results still give an indication of how toxic each individual active ingredient is due to the characterization factors which is a type of impact indicator developed by USEtox. As discussed, many low dosage insecticides are very toxic to aquatic organisms, which is reflected in their high CFs. This show how important it is to perform some type of impact assessment and not only look at the total amount of sprayed pesticides

5.7 Pesticide resistance

Pesticide resistance is an increasing problem in Brazil and worldwide [31][33]. The study done to understand the trends in pesticide use in Brazil was to the greatest extent focused on looking at resistance trends. The herbicide, insecticide and fungicide resistance action committees (HRAC, IRAC, FRAC) were essential for this investigation, with their combined industry and research knowledge from countries worldwide. The Brazilian IRAC and FRAC webpages provided information on the fungicides used for combating the Asian soybean rust and which insecticides that could be used for battling certain insects that have developed resistance towards certain site of actions that e.g. organophosphates have [31][33].

If the trend of increased pesticide use continues, the question if it will possible to spray effectively against various pests arises. Due to difficulties of finding new MoA and intense use of the same MoA insecticides, the future years may be very difficult for soybean farmers. Large yield losses caused by resistant insects would result in a decrease of harvested soybeans with a further result of decreased export and economic profits. However, before that happens, more low dosage high effect insecticides may be sprayed if the trends of these continues. This will inflict large impacts on aquatic organisms and on bees due to their extreme toxicity. Bees are important pollinators and the effect of toxic insecticides on them will thus affect ecosystems services to an extent not known.

To combine different mode of actions within the three pesticide groups is the best way of avoiding resistance problem. Other ways also include so called "blank windows" - where the fields are not sprayed at all and are allowed to breathe and recover - and have a rotation of crops that does not have the same type of pest problems and thus different pesticides can be used or none at all [31]. Another alternative is to use tillage and not pesticides for weed management, but tillage has been abolished in Brazil (and in other countries) mostly due to the soil erosion tillage causes [57].

5.8 DPSIR

The driver (D) "use of pesticides" is a driving force for the intention of protecting the soybean yield from pests and thus the economic gain from cultivation. The pesticide use is the result of both individual and industrial drivers. The production is part of the food system, and as the demand for meat increases, so does the demand for soybeans as a protein meal to use as feed for the animal industry - individual need. But the soybean cultivation is also a highly industrialized process where the products are harvested and aimed both for the food chain but also for biofuel production.

Pressures from pesticide use in the soybean cultivation are direct and indirect. Direct because they affect organisms directly when sprayed, e.g. weeds and insects. Indirect because when insects that are important for ecosystems other than the cultivated crop field are unable to reproduce or pollinate, those ecosystems and their functions and services are at risk. Since the amount of pesticides used in the soybean cultivation is so high, the emissions will be high too, not because all pesticides are emitted but because it is inevitable that some of them will be released to the surrounding environment. As previously mentioned, the double cropping systems where the fields never rests puts immense pressure on the system, something that has resulted in pesticide resistance. This should not come as a surprise, since evolution has always found a way around anthropocentric influences. The pesticide emissions needs to be further evaluated to be able to give a fair indication on how the pesticides pressure the fields, landscapes and ecosystems.

The states in ecosystems due to pressure from chemical pesticides are largely unknown, especially in developing countries. A study by Albuquerque, AF et al [58], showed that studies on pesticide residues in freshwater systems in Brazil are few and only exists in five of the twenty seven states. In these samples, herbicides were the major ones represented but insecticides were the major concern. This is in line with the results of this thesis, where herbicides are the most used class but insecticides are the most toxic ones. Another study by Stehle et al from 2015 showed that monitoring of insecticide residues in surface waters is severely lacking on a global scale and that 68,5 % of the sites that are monitored exceed the legal regulatory threshold levels [59]. This further shows that more monitoring of pesticide residues are needed to be able to see what state the fields, landscapes and ecosystems are in and thus be able to study the impacts. Hence, Brazil should start to investigate freshwater for pesticide residues by monitoring and sampling more regions, especially the regions with large scale agribusiness where the emissions and residues should be the highest. Regarding the states of humans as a result of pesticide pressure; pesticide poisoning in Brazil became debated when an airplane sprayed pesticides over a rural school in the state of Goiás and 90 children had to be hospitalized immediately [60], but has since then not been evaluated much.

As the states from pesticide use are not to a full extent known, the impacts also remain unknown. In LCIA, the tool for evaluating potential impacts from pesticides - USEtox - only accounts for freshwater toxicity. Judging from the qualitative assessment, the impacts on bees from insecticide use are high. In 2019, BBC published an article about mass deaths of bees in Brazil, where farmers reported that 500 million bees had died in Brazil in three months [61]. Thus, the states of ecosystems reliable on bees can be threatened. The potential freshwater ecotoxicity impacts from the studied active ingredients are high, especially from pyrethroids. Thus, the organisms in freshwater ecosystems in regions were a lot of soybeans are cultivated should be greatly affected by these impacts.

The responses from policy makers have varied. In 2013, the insecticide active ingredients Endosulfan and Metamidophos were banned and phased out due to the high toxicity towards humans [29]. As can be seen in Figure 4.1, the total number of used and approved active ingredient went down from 372 to 317 between 2013 and 2014, and that decreasing trend continued with the number being 310 in 2018. Thus, even if the amount of total pesticide use has increased, the number of pesticides approved and used has gone down. Unfortunately, the current government will probably not continue this trend but on the contrary, might increase the number of approved active ingredients again. Another, more recent, response from pesticide use in Brazil is that the National Health Surveillance Agency in Brazil - ANVISA - tried to re-evaluate Paraquat dichloride since it is classified in toxicological class one - very toxic and it is connected to diseases such as Parkinson's, as well as being know to be fatal to humans [21][53]. This re-evaluation was done in 2015 and the suggestion was to phase out paraquat dichloride [62], but since 2015, the use of paraquat has increased with 3000 tonnes [12]. However, society's response to pesticide use becomes more prominent, with organisations like Greenpeace, Human Right's Watch and Pesticide Action Network investigating the effects of pesticides and take action towards bans and restrictions on the use.

Concluding the DPSIR framework when applied to pesticides; drivers are known except for the use of some individual active ingredients, the states and impacts are to a large extent not known and the impacts that can be quantitatively assessed are estimations which means that further research needs to be done. More responses where this is studied and investigated is needed to be able to give a fair picture of what the pesticide use in the Brazilian soybean cultivation really results in.

5.9 Challenges with pesticide footprints

One of the main challenges with calculating pesticide footprints in Brazilian soybean is that the commercial competition hinders data to be published at state level, which results in unavailability of information about individual active substances. Therefore, the project had to take another direction and use-trends of the largest pesticides were studied together with a qualitative assessment. This resulted in important qualitative toxicity assessments as a complement to the quantitative potential freshwater ecotoxicity.

The next discovery that made this thesis change direction was the information that PestLCI and USEtox had very large uncertainties as LCA tools in tropical climate conditions. The Joint Research Center (JRC) in the European Union ranks USEtox in class 3 when assessing their reliability as a impact assessment (IA) method compared to IA methods used for e.g. climate change that were assessed in class 1 - much more reliable [16]. The article written by Gentil et al [45], also states that PestLCI and USEtox is not developed for tropical climates. Thus, the qualitative assessment of the toxicity became very important to indicate toxicity for humans and the environment.

Another challenge was to understand the relative trends of pesticide use. This required extensive knowledge on why and how pesticides are used in Brazil. This part could not have been done without consulting literature and researchers with an expertise in these questions. To be able to understand the use-trends, one must visit or be in contact with soybean farmers, since the system is complex and varies from year to year. The low-dosage insecticides are easy to miss if only large amounts of applied pesticides are considered. The insight that insecticide resistance had caused so many problems together with the fungi pathogen Asian soybean rust required extensive literature studies that stated known problems in soybean cultivation system specifically. The pathogen fungi Asian soybean rust have caused large problems in the soybean fields and multiple studies have been done on what types of fungicides that are most effective and do not cause resistance problem. All these results and conclusions required time to understand.

Apart from these three major challenges, another challenge was to group insecticides and fungicides into their different MoA and sub-classification, i.e. foliar and/or seed treatment or if they are used for other purposes than in application in agricultural fields. For example, while some active ingredients are classified as having foliar treatment in one country, they might be used for seed treatment in another. Furthermore, they might be registered for being applied both foliar and on seeds but only used for one of the things. The study of this required research time to be able to sure that the active ingredients were used on crops and not in e.g. storage/domestic use and or for rodents.

6

Conclusions and future research

- Brazil's reporting on individual active substances are lacking due to commercial competition.
  - Due to this, a complete life cycle impact assessment cannot be done.
- During the last decade, there has been a large increase of all pesticide groups, i.e. herbicides, insecticides and fungicides.
  - In total and in soybean cultivation, but not as much per hectare and produced ton soybean due to continuously more effective agriculture.
- The amount of used pesticides per hectare and produced soybean is not a sufficient indicator to evaluate the impacts from pesticide spraying.
  - Thus, further studies on human toxicity and ecotoxicity have to be done.
- Pesticide resistance has caused severe problems.
  - Thus, an increase of neonicotinoids and pyrethroids insecticides, multi-site activity fungicides as well as herbicides that battle Glyphosate resistant weeds can be seen.
- The impacts from pesticide use in soybean cultivation are high.
  - On humans and environment, which both qualitative and quantitative methods indicate.

A lot remains to be done to further be able to calculate pesticide footprints of agricultural commodities. Future research could focus on regional data and results to see if pesticide use differ between states in Brazil. This will also give a temporal evaluation since some states have been cultivating soy for decades and other have recently started. The resistance problem might not be as developed in the young cultivation states and thus a different trend in pesticide use for these states may be seen. The pesticide application may also be less there if the problems with pests are not as developed. Doing regional assessments would also help the USEtox evaluation of freshwater ecotoxicity since the climate could be accounted for if the PestLCI is updated to better account for pesticide emissions under tropical conditions.

When evaluating agricultural commodities in future research, pesticide footprints should be included. Due to the large focus on climate aspects of the agribusiness, the impacts from pesticides have been overlooked. For example, in the study done by Nordborg et al from 2017, the results show that chicken meat has a high freshwater ecotoxicity impact, while beef has a lower one. This result is not often seen when doing climate assessments of meat and are due to the fact that conventional chickens are to a great extent fed with soybean meal and soybeans have a large pesticide footprint [46]. More studies are needed to give a more nuanced picture and broaden the analysis of sustainable agriculture systems.

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A

Appendix 1

In this appendix, all of the active ingredients, amount and classification from 2009 to 2018 will be presented. At the end of each table, the total amounts can be viewed. **The amount is in tonnes.**. Some of the substances are marked with symbols, this means that additional information on the classification is found in other sources than Pesticide Property Database. A list of additional databases are shown in the list below together with the related symbol.

- ϵ - Pubchem [43].
- ζ - Cornell university [22].
- ι - Food and Agriculture Organization of the United Nations (FAO) [50].

Table A.1: Herbicides 2009.

Herbicides	**Amount**	**Classification**
2,4-D	12 116,12	selective
Alachlor	43,93	selective
Ametryn	1 624,09	selective
Atrazine	10 133,80	selective
Bentazon	1 017,28	selective
Clomazone	2 712,01	selective
Chlorimuron-ethyl ϵ	106,59	selective
Paraquat dichloride	1 977,19	non-selective
Diuron (DCMU)	2 147,97	selective
Glyphosate + salt	118 484,57	non-selective
Hexazinone	631,00	non-selective
Imazaquin	15,60	selective
Imazethapyr ζ	411,77	selective
Lactofen	259,25	selective
Metsulfuron-methyl	14,28	selective
MSMA ϵ	1 399,88	selective
Nicosulfuron	54,53	selective

Picloram	676,22	selective
Propanil	136,64	selective
Simazine	239,58	selective
Tebuthiuron	960,30	selective
Trifluralin	332,92	selective
Selective	**34 402,75**	-
Non-selective	**121 092,76**	-
Total	**155 495,51**	-

Table A.2: Insecticides 2009.

Insecticides	**Amount**	**Classification**
Abamectin ι	48,63	Foliar
Acefate	5 204,89	Foliar
Bacillus thuringiensis ζ	73,14	Foliar and seed
Baculovirus anticarsia	0,02	-
Cypermethrin	413,03	Foliar
Chlorpyrifos	2 966,39	Foliar and soil
Dicofol	0,14	Foliar
Diflubenzuron	262,33	Foliar
Dimethoate	827,50	Foliar
Endosulfan	2 980,42	Foliar
Flumethrin	100,22	Used on animals
Aluminum phosphide	367,42	Rodenticide
Imidacloprid	1 399,15	Foliar and seed
Lambda cyhalothrin	264,08	Foliar
Malathion	1 057,67	Foliar
Methamidophos	10 774,80	Foliar
Fembutatin oxide	191,33	Foliar
Parathion-methyl	2 691,33	Foliar
Permethrin	301,48	Foliar and seed
Serricornim ϵ	0,02	Pheromone
Sulfur amino	15,23	Domestic

Foliar	**27 682,55**	-
Foliar and seed	**1 773,77**	-
Total foliar and seed	**29 456,32**	-
Other	**482,90**	-
Total	**29 939,22**	-

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Table A.3: Fungicides and other classes 2009.

Fungicides	**Amount**	**Classification**
Benalaxil	11,91	Foliar and seed
Carbendazim	6 712,59	Foliar and seed
Cymoxanil	1 189,55	Foliar and seed
Chlorothalonil	1 964,75	Foliar
Sulfur	11 514,80	Foliar
Epoxiconazole	545,81	Foliar
Fluazinam	339,11	Foliar
Flutriafol	337,15	Foliar
Copper||hydroxide ϵ	1 047,75	Foliar and seed
Mancozeb ϵ	3 590,35	Foliar and seed
Copper oxychloride	3 152,99	Foliar
Propiconazole ϵ	131,63	Foliar and seed
Tebuconazole ϵ	2 676,88	Foliar and seed
Tetraconazole	191,62	Foliar and seed
Thiophanate methyl ϵ	3 754,32	Foliar
Foliar	**21 608,93**	-
Foliar and seed	**15 552,28**	-
Total	**37 161,21**	-
Other	**Amount**	**Class**
Mepiquat chloride	49,93	PGR
Ethephon	409,84	PGR

Polyethylene glycol nonyl phenyl ether	342,19	Wetting agent
Mineral oil	32 634,09	Other
Vegetable oil	13 422,60	Other

Table A.4: Herbicides 2010.

Herbicides	Amount	Classification
2,4-D	19 450,29	selective
Alachlor	44,17	selective
Ametryn	2 858,40	selective
Atrazine	12 811,48	selective
Bentazon	1 064,48	selective
Clethodim	244,50	selective
Clomazone	5 255,42	selective
Chlorimuron-ethyl ϵ	210,03	selective
Paraquat dichloride	3 113,24	non-selective
Diuron (DCMU)	6 123,86	selective
Fenoxaprop-p-ethyl	55,16	selective
Glyphosate	127 585,92	non-selective
Glyphosate - isopropilaminsalt	6 531,37	non-selective
Hexazinone	1 155,16	non-selective
Imazaquin	6,59	selective
Imazethapyr ζ	325,30	selective
Lactofen	303,94	selective
Metsulfuron-methyl	27,56	selective
MSMA ϵ	1 672,78	selective
Nicosulfuron	75,86	selective
Picloram	845,42	selective
Propanil	282,95	selective
Simazine	222,26	selective
Tebuthiuron	2 041,97	selective
Triclopyr	489,79	selective

Trifluralin	1 380,68	selective
Selective	**55 792,89**	-
Non-selective	**138 385,69**	-
Total	**194 178,59**	-

Table A.5: Insecticides 2010.

Insecticide	Amount	Classification
Abamectin ι	58,75	Foliar
Acefate	5 233,44	Foliar
Acetato de (e)-8-dodecenila	0,40	Dispenser/puffer
Bacillus thuringiensis ζ	84,72	Foliar and seed
Baculovirus anticarsia	0,00	-
Bifenthrin	397,78	Foliar
Bromomethane	90,86	Fumigant
Carbofuran	2 178,80	Foliar and soil
Cypermethrin	599,95	Foliar
Chlorpyrifos	*3 191,78*	*Foliar and soil*
Deltamethrin	23,43	Foliar
Dicofol	87,99	Foliar
Diflubenzuron	245,93	Foliar
Dimethoate	988,66	Foliar
Endosulfan	6 083,34	Foliar
Flumethrin	40,12	Used on animals
Aluminium phosphide	411,81	Rodenticide
Grandlure	0,00	Pherome
Imidacloprid	2 441,11	Foliar and seed
Lambda cyhalothrin	404,59	Foliar
Malathion	1 464,41	Foliar
Methamidophos	17 661,77	Foliar
Methomyl	3 350,53	Foliar and soil
Fembutatin oxide	91,64	Foliar
Parathion-methyl	1 743,90	Foliar

Permethrin	320,87	Foliar and seed
Serricornim ϵ	0,01	Pheromone
Sulfur amino	18,85	Domestic
Triflumuron	386,58	Foliar
Foliar	**44 193,27**	-
Foliar and seed	**2 846,69**	-
Total foliar and seed	**47 039,96**	-
Other	**562,05**	-
Total	**47 602,01**	-

Table A.6: Fungicides and other classes 2010.

Fungicide	**Amount**	**Classification**
Captan	729,35	Foliar and seed
Carbendazim	7 629,82	Foliar and seed
Cymoxanil	142,79	Foliar and seed
Cyproconazole	1 707,27	Foliar
Chlorothalonil	2 488,77	Foliar
Sulfur	12 343,12	Foliar
Epoxiconazole	675,56	Foliar
Fluazinam	656,89	Foliar
Flutriafol	546,43	Foliar
Copper||hydroxide ϵ	2 355,71	Foliar and seed
Mancozeb ϵ	6 917,62	Foliar and seed
Copper oxychloride	3 364,24	Foliar
Propiconazole ϵ	120,03	Foliar and seed
Copper-sulfate	264,67	Foliar and seed
Tebuconazole ϵ	2 066,78	Foliar and seed
Tetraconazole	179,42	Foliar and seed
Thiophanate methyl ϵ	4 472,94	Foliar
Thiram	304,18	Foliar and seed
Foliar	**26 255,22**	-
Foliar and seed	**20 710,37**	-

Total	46 965,59	-
Other	**Amount**	**Class**
Cuprous oxide	109,87	Non-pesticidal
Mepiquat chloride	110,85	PGR
Ethephon	801,20	PGR
Nonyl phenyl Ethoxyl	227,08	Surfactant
Polyethylene glycol nonyl phenyl ether	389,34	Wetting agent
Mineral oil	40 967,83	Other
Vegetable oil	**8 488,43**	Other
Sodium dodecylbenzene sulfonate	**107,36**	Other
Total	**51 094,59**	-

Table A.7: Herbicides 2011.

Herbicides	**Amount**	**Classification**
2,4-D	23 116,97	selective
Alachlor	42,39	selective
Ametryn	3 441,88	selective
Atrazine	18 580,93	selective
Bentazon	857,38	selective
Clethodim	354,10	selective
Clomazone	6 171,87	selective
Chlorimuron-ethyl ϵ	247,54	selective
Paraquat dichloride	4 275,38	non-selective
Diuron (DCMU)	6 978,62	selective
Fenoxaprop-p-ethyl	31,84	selective
Glyphosate	128 514,31	non-selective
Glyphosate - isopropilaminsalt	3 383,68	non-selective
Hexazinone	1 560,75	non-selective
Imazaquin	3,00	selective
Imazethapyr ζ	329,84	selective
Lactofen	261,84	selective

Metsulfuron-methyl	36,26	selective
MSMA ϵ	1 515,11	selective
Nicosulfuron	82,94	selective
Picloram	1 485,90	selective
Propanil	143,44	selective
Simazine	1 025,82	selective
Tebuthiuron	3 195,36	selective
Triclopyr	710,23	selective
Trifluralin	1 824,04	selective
Selective	**70 437,29**	-
Non-selective	**137 734,12**	-
Total	**208 171,41**	-

Table A.8: Insecticides 2011.

Insecticides	**Amount**	**Classification**
Abamectin ι	95,19	Foliar
Acephate	8 124,83	Foliar
Bacillus thuringiensis ζ	96,22	Foliar and seed
Baculovirus anticarsia	0,00	-
Bifenthrin	456,08	Foliar
Bromomethane	97,11	Fumigant
Cypermethrin	3 219,22	Foliar
Chlorpyrifos	4 288,36	Foliar and soil
Dicofol	85,36	Foliar
Diflubenzuron	272,46	Foliar
Dimethoate	938,30	Foliar
Endosulfan	3 631,37	Foliar
Flumethrin	95,63	Used on animals
Aluminium phosphide	374,16	Rodenticide
Grandlure	0,00	Pherome
Imidacloprid	5 074,00	Foliar and seed
Lambda cyhalothrin	649,74	Foliar

Malathion	2 334,28	Foliar
Methamidophos	12 838,84	Foliar
Metarhizium anisopliae ι	52,57	Foliar and seed
Methomyl	4 247,09	Foliar and soil
Fembutatin oxide	194,22	Foliar
Parathion-methyl	1 225,79	Foliar
Permethrin	331,03	Foliar and seed
Serricornim ι	0,01	Pheromone
Sulfur amino	18,13	Domestic
Triflumuron	489,51	Foliar
Foliar	**43 090,65**	-
Foliar and seed	**5 553,82**	-
Total foliar and seed	**48 644,47**	-
Other	**585,04**	-
Total	**49 229,51**	-

Table A.9: Fungicides and other classes 2011.

Fungicides	**Amount**	**Classification**
Captan	698,23	Foliar and seed
Carbendazim	12 216,92	Foliar and seed
Cymoxanil	132,05	Foliar and seed
Cyproconazole	1 653,27	Foliar
Chlorothalonil	3 001,41	Foliar
Kresoxim-methyl	37,23	Foliar
Sulfur	14 133,51	Foliar
Epoxiconazole	682,96	Foliar
Fluazinam	1 028,86	Foliar
Flutriafol	564,62	Foliar
Copper||hydroxide ϵ	2 571,59	Foliar and seed
Mancozeb ϵ	7 290,18	Foliar and seed
Copper oxychloride	3 706,01	Foliar
Propiconazole ϵ	223,81	Foliar and seed

Copper-sulfate	797,60	Foliar and seed
Tebuconazole ϵ	1 441,43	Foliar and seed
Tetraconazole	200,77	Foliar and seed
Thiophanate methyl ϵ	4 947,79	Foliar
Thiram	542,28	Foliar and seed
Foliar	**29 755,65**	-
Foliar and seed	**26 114,84**	-
Total	**55 870,50**	-
Other	**Amount**	**Class**
Mepiquat chloride	129,79	PGR
Ethephon	1 244,48	PGR
Polyethylene glycol nonyl phenyl ether	464,76	Wetting agent
Nonyl phenyl Ethoxyl	268,08	Surfactant
Mineral oil	44 561,90	Other
Vegetable oil	7 758,19	Other
Sodium dodecylbenzene sulfonate	52,50	Other
Acetato de (e)-8-dodecenila	0,40	Dispenser/puffer
Acetato de (z)-8-dodecenila	0,62	Ferom - puffer
Total	**54 480,73**	

Table A.10: Herbicides 2012.

Herbicides	**Amount**	**Classification**
2,4-D	32163,99	selective
Alachlor	40,48	selective
Ametryn	4705,76	selective
Atrazine	27139,56	selective
Bentazon	878,53	selective
Clethodim	479,66	selective
Clomazone	4731,45	selective
Chlorimuron-ethyl ϵ	202,51	selective
Paraquat dichloride	5249,54	non-selective

Diuron (DCMU)	8502,78	selective
Fenoxaprop-p-ethyl	49,05	selective
Glyphosate	186483,39	non-selective
Glyphosate - isopropilaminsalt	1293,79	non-selective
Hexazinone	2009,96	non-selective
Imazaquin	10,19	selective
Imazethapyr ζ	324,37	selective
Lactofen	170,21	selective
Metsulfuron-methyl	20,99	selective
MSMA ϵ	1778,80	selective
Nicosulfuron	88,02	selective
Picloram	1625,86	selective
Propanil	71,67	selective
Simazine	89,70	selective
Tebuthiuron	3650,86	selective
Triclopyr	951,88	selective
Trifluralin	1467,41	selective
Selective	**89 143,72**	-
Non-selective	**195 036,67**	-
Total	**284 180,39**	-

Table A.11: Insecticides 2012.

Insecticides	**Amount**	**Classification**
Abamectin ι	141,81	Foliar
Acefate	13080,63	Foliar
Acetamiprid	181,82	Foliar
Bacillus thuringiensis ζ	101,04	Foliar and seed
Baculovirus anticarsia	0,00	"Biopesticide"
Beauveria bassiana ι	0,05	Foliar and seed
Bifenthrin	416,75	Foliar
Bromomethane	70,06	Fumigant
Cypermethrin	591,63	Foliar

Chlorpyrifos	6218,35	Foliar and soil
Dicofol	36,34	Foliar
Diflubenzuron	342,36	Foliar
Dimethoate	715,37	Foliar
Endosulfan	497,78	Foliar
Fipronil	1068,60	Foliar and seed
Flumethrin	84,20	Used on animals
Aluminium phosphide	391,81	Rodenticide
Magnesium phosphide	2,52	Rodenticide
Grandlure	0,00	Pherome
Imidacloprid	5476,11	Foliar and seed
Lambda cyhalothrin	809,87	Foliar
Malathion	4147,18	Foliar
Metamidophos	281,18	Foliar
Metarhizium anisopliae ι	37,44	Foliar and seed
Methomyl	6376,02	Foliar and soil
Parathion-methyl	1 763,44	Foliar
Permethrin	163,82	Foliar and seed
Propargite ϵ	508,11	Foliar
Serricornin ϵ	3612,38	Pheromone
Sulfur amino	18,58	Domestic
Foliar	**36108,63**	-
Foliar and seed	**6847,06**	-
Total foliar and seed	**42955,68**	-
Other	**4179,54**	-
Total	**47 135,23**	-

Table A.12: Fungicides and other classes 2012.

Fungicides	**Amount**	**Classification**
Azoxystrobin	1634,41	Foliar
Captan	634,39	Foliar and seed
Carbendazim	7999,80	Foliar and seed

Cymoxanil	104,24	Foliar and seed
Cyproconazole	1090,87	Foliar
Chlorothalonil	2987,65	Foliar
Sulfur	9678,46	Foliar
Epoxiconazole	839,46	Foliar
Fluazinam	943,65	Foliar
Flutriafol	1044,19	Foliar
Copper||hydroxide ϵ	2566,66	Foliar and seed
Mancozeb ϵ	7134,82	Foliar and seed
Copper oxychloride	3854,88	Foliar
Prochloraz	-0,39	Foliar
Propiconazole ϵ	299,09	Foliar and seed
Tebuconazole ϵ	1430,00	Foliar and seed
Tetraconazole	63,52	Foliar and seed
Thiophanate methyl ϵ	4800,58	Foliar
Thiram	295,37	Foliar and seed
Foliar	**26873,77**	-
Foliar and seed	**20527,88**	-
Total	**47 401,65**	-
Other	**Amount**	**Class**
Mepiquat chloride	62,76	PGR
Ethephon	1554,26	PGR
Polyethylene glycol nonyl phenyl ether	415,21	Wetting agent
Nonyl phenyl Ethoxyl	296,65	Surfactant
Mineral oil	36962,20	Other
Vegetable oil	7770,64	Other
Acetato de (e)-8-dodecenila	0,00	Dispenser/puffer
Acetato de (z)-8-dodecenila	0,00	Ferom - puffer
Total	**47061,72**	**-**

Table A.13: Herbicides 2013.

Herbicides	**Amount**	**Classification**
2,4-D	37 131,43	selective
Alachlor	0,02	selective
Ametryn	4 705,14	selective
Atrazine	28 394,91	selective
Bentazon	1 051,89	selective
Clomazone	5 576,83	selective
Chlorimuron-ethyl ϵ	239,37	selective
Paraquat dichloride	6 792,69	non-selective
Diuron (DCMU)	6 100,96	selective
Fenoxaprop-p-ethyl	81,95	selective
Glyphosate	184 967,70	non-selective
Glyphosate - isopropilaminsalt	988,43	non-selective
Hexazinone	1 254,00	non-selective
Imazaquin	16,64	selective
Imazethapyr ζ	360,45	selective
Lactofen	149,77	selective
Metribuzin	1 044,27	selective
Metsulfuron-methyl	37,10	selective
MSMA ϵ	1 330,31	selective
Nicosulfuron	67,60	selective
Picloram	2 048,93	selective
Propanil	168,22	selective
Simazine	1 038,89	selective
Tebuthiuron	3 653,40	selective
Triclopyr	1 332,01	selective
Trifluralin	1 453,44	selective
Selective	**95 983,53**	-
Non-selective	**194 002,82**	-
Total	**289 986,35**	-

Table A.14: Insecticides 2013.

Insecticides	**Amount**	**Classification**
Abamectin ι	168,29	Foliar
Acefate	22 355,41	Foliar
Acetamiprid	344,97	Foliar
Bacillus thuringiensis ζ	226,53	Foliar and seed
Beauveria bassiana ι	1,37	Foliar
Bifenthrin	720,25	Foliar
Bromomethane	79,62	Fumigant
Carbofuran	1 739,81	Foliar and soil
Cypermethrin	693,36	Foliar

Chlorpyrifos	13 084,62	Foliar and soil
Dicofol	17,82	Foliar
Diflubenzuron	550,00	Foliar
Dimethoate	698,92	Foliar
Endosulfan	0,03	Foliar
Fipronil	1 232,15	Foliar and seed
Flumethrin	80,05	Used on animals
Aluminium phosphide	388,06	Rodenticide
Magnesium phosphide	1,51	Rodenticide
Grandlure	0,00	Pherome
Imidacloprid	7 940,82	Foliar and seed
Lambda cyhalothrin	1 253,51	Foliar
Malathion	4 986,75	Foliar
Metamidophos	0,00	Foliar
Metarhizium anisopliae ι	32,49	Foliar and seed
Methomyl	8 533,26	Foliar and soil
Fembutatin oxide	83,87	Foliar
Parathion-methyl	1 548,53	Foliar
Permethrin ϵ	46,53	Foliar and seed
Propargite	354,89	Foliar
Serricornim ϵ	0,01	Pheromone
Sulfur amino	19,62	Domestic
Foliar	**57 135,68**	-
Foliar and seed	**9 478,53**	-
Total foliar and seed	**66 614,21**	-
Other	**568,87**	-
Total	**67 183,07**	-

Table A.15: Fungicides and other classes 2013.

Fungicides	**Amount**	**Classification**
Azoxystrobin	1 750,69	Foliar
Carbendazim	6 689,84	Foliar and seed
Cymoxanil	136,79	Foliar and seed
Cyproconazole	1 094,16	Foliar
Chlorothalonil	3 537,31	Foliar
Kresoxim-methyl	429,46	Foliar
Sulfur	3 797,92	Foliar
Epoxiconazole	797,23	Foliar
Fluazinam	958,49	Foliar
Flutriafol	668,21	Foliar
Folpete	61,16	Foliar
Copper||hydroxide ϵ	2 426,33	Foliar and seed
Mancozeb ϵ	8 419,01	Foliar and seed

Copper oxychloride	3 214,42	Foliar
Propiconazole ϵ	463,99	Foliar and seed
Copper-sulfate ζ	842,92	Foliar and seed
Tebuconazole ϵ	2 118,56	Foliar and seed
Tetraconazole	119,45	Foliar and seed
Thiophanate methyl ϵ	5 508,41	Foliar
Thiram	974,13	Foliar and seed
Foliar	**21 817,46**	-
Foliar and seed	**22 191,01**	-
Total	**44 008,47**	-
Other	**Amount**	**Class**
Mepiquat chloride	68,41	PGR
Ethephon	1 216,99	PGR
Polyethylene glycol nonyl phenyl ether	450,69	Wetting agent
Nonyl phenyl Ethoxyl	283,35	Surfactant
Mineral oil	28 347,06	Other
Vegetable oil	14318,3451	Other
Acetato de (e)-8-dodecenila	0,27	Dispenser/puffer
Acetato de (z)-8-dodecenila	0,40	Pheromone- puffer
Total	**44 685,50**	**-**

Table A.16: Herbicides 2014.

Herbicides	**Amount**	**Classification**
2,4-D	36 513,55	selective
Alachlor	0,00	selective
Ametryn	2 278,98	selective
Atrazine	13 911,37	selective
Bentazon	1 250,81	selective
Clomazone	5 420,32	selective
Chlorimuron-ethyl ϵ	331,54	selective
Paraquat dichloride	8 404,76	non-selective
Diuron (DCMU)	8 579,52	selective
Fenoxaprop-p-ethyl	138,80	selective
Glyphosate	193 947,87	non-selective
Glyphosate - isopropilaminsalt	929,97	non-selective
Hexazinone	1 381,45	non-selective
Imazaquin	25,06	selective
Imazethapyr ζ	381,50	selective
Lactofen	197,61	selective
Metribuzin	1 034,46	selective
Metsulfuron-methyl	56,30	selective
MSMA ϵ	1 015,99	selective

Nicosulfuron	69,23	selective
Picloram	2 022,89	selective
Propanil	68,50	selective
Simazine	491,78	selective
Tebuthiuron	3 952,54	selective
Triclopyr	1 513,32	selective
Trifluralin	1 594,00	selective
Selective	**81 179,62**	-
Non-selective	**204 664,05**	-
Total	**285 512,13**	-

Table A.17: Insecticides 2014.

Insecticides	**Amount**	**Classification**
Abamectin ι	130,38	Foliar
Acephate	26 190,52	Foliar
Acetamiprid	822,15	Foliar
Bifenthrin	648,47	Foliar
Bromomethane	80,35	Fumigant
Cypermethrin	511,35	Foliar
Chlorpyrifos	16 452,77	Foliar and soil
Dicofol	11,79	Foliar
Diflubenzuron	1 064,97	Foliar
Dimethoate	713,38	Foliar
Endosulfam	-0,12	Foliar
Fipronil	1 058,200	Foliar and seed
Flumethrin	68,54	Used on animals
Aluminium phosphide	482,91	Rodenticide
Magnesium phosphide	4,01	Rodenticide
Grandlure	0,00	Pherome
Imidacloprid	7 951,43	Foliar and seed
Lambda cyhalothrin	1 105,90	Foliar
Metamidophos	0,00	Foliar
Methomyl	9 801,11	Foliar and soil
Fembutatin oxide	0,00	Foliar
parathion-methyl	1 383,66	Foliar
Permethrin ϵ	38,59	Foliar and seed
Propargite ϵ	619,37	Foliar
Sulfur amino	20,42	Domestic
Foliar	**59 455,70**	-
Foliar and seed	**9 048,223**	-
Total foliar and seed	**68 503,928**	-
Other	**652,21**	-
Total	**69 160,15**	-

Table A.18: Fungicides and other classes 2014.

Fungicides	**Amount**	**Classification**
Azoxystrobin	2 652,79	Foliar
Carbendazim	5 141,11	Foliar and seed
Cymoxanil	157,12	Foliar and seed
Cyproconazole	1 234,47	Foliar
Chlorothalonil	3 547,33	Foliar
Kresoxim-methyl	412,49	Foliar
Sulfur	4 965,22	Foliar
Epoxiconazole	631,74	Foliar
Fluazinam	399,12	Foliar
Flutriafol	675,14	Foliar
Copper||hydroxide ϵ	2 241,86	Foliar and seed
Mancozeb ϵ	12 273,86	Foliar and seed
Copper oxychloride	3 284,23	Foliar
Propiconazole ϵ	2 237,46	Foliar and seed
Copper-sulfate ζ	1 116,98	Foliar and seed
Tebuconazole ϵ	2 532,45	Foliar and seed
Tetraconazole	108,15	Foliar and seed
Thiophanate methyl ϵ	3 855,51	Foliar
Thiram	1 101,60	Foliar and seed
Foliar	**21 658,05**	-
Foliar and seed	**26 910,61**	-
Total	**48 568,65**	-
Other	**Amount**	**Class**
Mepiquat chloride	77,89	PGR
Ethephon	1 568,03	PGR
Polyethylene glycol nonyl phenyl ether	442,04	Wetting agent
Nonyl phenyl Ethoxyl	270,27	Surfactant
Mineral oil	25 632,86	Other
Vegetable oil	16 126,71	Other
Total	**44 117,81**	-

Table A.19: Herbicides 2015.

Herbicides	**Amount**	**Classification**
2,4-D	48 013,26	selective
Alachlor	0,00	selective
Ametryn	3 172,44	selective
Atrazine	18 869,47	selective
Bentazon	1 253,01	selective
Bromacil	22,82	non-selective
Clethodim	1 175,54	selective

Clomazone	3 615,80	selective
Chlorimuron-ethyl ϵ	642,78	selective
Paraquat dichloride	10 536,60	non-selective
Diuron (DCMU)	6 613,08	selective
Fenoxaprop-p-ethyl	174,86	selective
Glyphosate	193 945,89	non-selective
Glyphosate - isoprophanyl salt	993,70	non-selective
Hexazinone	1 290,06	non-selective
Imazaquin	19,47	selective
Imazethapyr ζ	390,55	selective
Lactofen	119,31	selective
Metribuzin	923,29	selective
Metsulfuron-methyl	76,40	selective
MSMA ϵ	425,61	selective
Nicosulfuron	65,61	selective
Picloram	2 123,42	selective
Propanil	122,42	selective
Simazine	455,43	selective
Tebuthiuron	4 662,20	selective
Triclopyr	901,22	selective
Trifluralin	1 219,20	selective
Selective	**95 057,19**	-
Non-selective	**206 789,09**	-
Total	**301 823,45**	-

Table A.20: Insecticides 2015.

Insecticides	**Amount**	**Classificaion**
Abamectin ι	181,65	Foliar
Acefate	19 324,66	Foliar
Acetamiprid	705,87	Foliar
Bifenthrin	615,24	Foliar
Bromomethane	79,30	Fumigant
Cypermethrin	517,69	Foliar
Chlorpyrifos	9 187,19	Foliar and soil
Dicofol	-0,04	Foliar
Diflubenzuron	475,38	Foliar
Dimethoate	708,05	Foliar
Fipronil	1 116,52	Foliar and seed
Flumethrin	62,63	Used on animals
Aluminium phosphide	521,42	Rodenticide
Magnesium phosphid	2,32	Rodenticide
Imidacloprid	8 541,55	Foliar and seed
Lambda cyhalothrin	1 182,86	Foliar

Methomyl	6 097,50	Foliar and soil
Novaluron	64,90	Foliar
Fembutatin oxide	0,00	Foliar
Parathion-methyl	1 310,55	Foliar
Permethrin	426,07	Foliar and seed
Propargite ϵ	570,33	Foliar
Sulfur amino	28,96	Domestic
Foliar	**40 941,82**	-
Foliar and seed	**10 084,15**	-
Total foliar and seed	**51 025,96**	-
Other	**694,62**	-
Total	**51 720,59**	-

Table A.21: Fungicides and other classes 2015.

Fungicides	**Amount**	**Classification**
Azoxystrobin	3 643,02	Foliar
Carbendazim	3 217,90	Foliar and seed
Cymoxanil	167,98	Foliar and seed
Cyproconazole	1 662,32	Foliar
Chlorothalonil	3 153,95	Foliar
Kresoxim-methyl	226,81	Foliar
Difenoconazole	711,28	Foliar and seed
Sulfur	4 009,59	Foliar
Epoxiconazole	639,10	Foliar
Fluazinam	436,52	Foliar
Flutriafol	650,86	Foliar
Copper||hydroxide ϵ	1 926,56	Foliar and seed
Mancozeb ϵ	21 574,44	Foliar and seed
Copper oxychloride	4 920,31	Foliar
Copper-sulfate ζ	1 384,10	Foliar and seed
Tebuconazole ϵ	3 112,82	Foliar and seed
Tetraconazole	91,11	Foliar and seed
Thiophanate methyl ϵ	3 276,65	Foliar
Thiram	1 089,46	Foliar and seed
Carboxin	214,98	Seed
Foliar	**22 619,12**	-
Foliar and seed	**33 275,65**	-
Seed	**214,98**	-
Total	**56 109,74**	-
Other	**Amount**	**Class**
Mepiquat chloride	121,59	PGR
Ethephon	1 472,32	PGR

Polyethylene glycol nonyl phenyl ether	470,28	Wetting agent
Nonyl phenyl Ethoxyl	250,00	Surfactant
Mineral oil	25 773,01	Other
Vegetable oil	18 287,12	Other
Sodium dodecylbenzene sulfonate	1 019,19	Other
Total	**47 393,50**	

Table A.22: Herbicides 2016.

Herbicides	**Amount**	**Classification**
2,4-D	53 374,41	selective
Alachlor	0,00	selective
Ametryn	3 312,89	selective
Atrazine	28 615,70	selective
Bentazon	1 277,33	selective
Bromacil	0,00	non-selective
Clomazone	3 455,75	selective
Chlorimuron-ethyl ϵ	263,57	selective
Diquat-dibromide	1 050,92	non-selective
Paraquat dichloride	11 638,19	non-selective
Fenoxaprop-p-ethyl	242,72	selective
Glyphosate	185 602,22	non-selective
Glyphosate - isoprophanyl salt	0,00	non-selective
Hexazinone	1 357,27	non-selective
Imazaquin	8,18	selective
Imazethapyr ζ	377,96	selective
Lactofen	64,06	selective
Metribuzin	3 586,03	selective
Metsulfuron-methyl	79,28	selective
MSMA ϵ	1 262,65	selective
Nicosulfuron	79,06	selective
Picloram	2 515,74	selective
Propanil	190,23	selective
Simazine	555,49	selective
Tebuthiuron	3 037,53	selective
Triclopyr	798,22	**selective**
Trifluralin	1 375,22	selective
Selective	**104 472,00**	-
Non-selective	**199 648,60**	-
Total	**304 120,60**	-

Table A.23: Insecticides 2016.

Insecticides	**Amount**	**Classification**
Abamectin ι	143,94	Foliar
Acefate	24 858,68	Foliar
Acetamiprid	855,50	Foliar
Bifenthrin	686,81	Foliar
Bromomethane	57,33	Fumigant
Cypermethrin	832,61	Foliar
Chlorpyrifos	7 271,08	Foliar and soil
Dicofol	0,00	Foliar
Diflubenzuron	478,87	Foliar
Dimethoate	623,61	Foliar
Fipronil	1 272,74	Foliar and seed
Flumethrin	64,62	Used on animals
Aluminium phosphate	492,26	Rodenticide
Magnesium phosphate	0,84	Rodenticide
Imidacloprid	9 165,97	Foliar and seed
Lambda cyhalothrin	1 364,69	Foliar
Malathion	5 177,64	Foliar
Methomyl	3 431,55	Foliar and soil
Novaluron	62,46	Foliar
Fembutatin oxide	0,03	Foliar
Parathion-methyl	460,24	Foliar
Permethrin	62,92	Foliar and seed
Propargite ϵ	453,95	Foliar
Sulfur amino	33,04	Domestic
Tiodicarbe ϵ	1 957,23	Foliar and seed
Foliar	**46 701,65**	-
Foliar and seed	**12 458,86**	-
Total foliar and seed	**59 160,51**	-
Other	**648,09**	-
Total	**59 808,60**	-

Table A.24: Fungicides and other classes 2016.

Fungicides	**Amount**	**Classification**
Azoxystrobin	2 659,25	Foliar
Captan	713,67	Foliar and seed
Carbendazim	3 912,51	Foliar and seed
Cymoxanil	157,88	Foliar and seed
Cyproconazole	1 330,70	Foliar
Propamocarb hydrochloride ζ	423,22	Foliar
Chlorothalonil	6 620,14	Foliar
Sulfur	5 516,62	Foliar

Epoxiconazole	800,31	Foliar
Fluazinam	1 166,38	Foliar
Flutriafol	677,94	Foliar
Folpet	77,38	Foliar
Copper||hydroxide ϵ	1 248,05	Foliar and seed
Mancozeb ϵ	33 232,94	Foliar and seed
Copper oxychloride	7 256,65	Foliar
Propiconazole ϵ	529,39	Foliar and seed
Copper-sulfate ζ	1 268,58	Foliar and seed
Tebuconazole ϵ	2 404,20	Foliar and seed
Tetraconazole	41,26	Foliar and seed
Thiophanate methyl ϵ	3 424,36	Foliar
Thiram	786,69	Foliar and seed
Foliar	**29 952,96**	-
Foliar and seed	**44 295,17**	-
Total	**74 248,12**	-
Other	**Amount**	**Class**
Mepiquat chloride	116,17	**PGR**
Ethephon	1 273,77	PGR
Polyethylene glycol nonyl phenyl ether	396,97	Wetting agent
Nonyl phenyl Ethoxyl	245,69	Surfactant
Mineral oil	27 801,09	Other
Vegetable oil	17 259,26	Other
Sodium dodecylbenzene sulfonate	1 907,26	Other
Total	**49 000,21**	-

Table A.25: Herbicides 2017.

Herbicides	**Amount**	**Classification**
2,4-D	57389,35	selective
Alachlor	0	selective
Ametryn	2795,24	selective
Atrazine	24730,9	selective
Bentazon	1263,77	selective
Clethodim	2219,06	selective
Clomazone	4559,9	selective
Chlorimuron-ethyl ϵ	268,37	selective
Paraquat dichloride	11756,39	non-selective
Diuron (DCMU)	6999,47	selective
Fenoxaprop-p-ethyl	183,87	selective
Glyphosate	173150,75	non-selective
Glyphosate - isoprophanyl salt	0	non-selective
Glyphosate - aminosalt ϵ	1137,65	non-selective

Haloxyfop-P-methyl	690	selective
Hexazinone	1566,02	non-selective
Imazaquin	6,54	selective
Imazethapyr ζ	588,79	selective
Lactofen	81,02	selective
Mesotrione	297,74	selective
Metribuzin	1602,33	selective
Metsulfuron-methyl	94,81	selective
MSMA ϵ	1517,02	selective
Nicosulfuron	69,64	selective
Picloram	3127,41	selective
Propanil	345,96	selective
Simazine	307,97	selective
Sulfentrazone	1185,95	selective
Tebuthiuron	4092,41	selective
Triclopyr	1041,92	selective
Trifluralin	1940,41	selective
Selective	**117 399,85**	-
Non-selective	**187 610,81**	-
Total	**305 010,66**	-

Table A.26: Insecticides 2017.

Insecticides	**Amount**	**Classification**
Abamectin ι	190,77	Foliar
Acefate	27057,66	Foliar
Acetamiprid	1199,49	Foliar
Bifenthrin	865,03	Foliar
Bromomethane	43,64	Fumigant
Cypermethrin	3570,28	Foliar
Chlorpyrifos	6471,19	Foliar and soil
Diafenthiuron	870,09	Foliar
Dicofol	0	Foliar
Diflubenzuron	427,2	Foliar
Dimethoate	703,01	Foliar
Endosulfan	0	Foliar
Fenpyroximate	6,54	Foliar
Fipronil	1368,43	Foliar and seed
Flumethrin	74,47	Used on animals
Aluminium phosphide	532,59	Rodenticide
Magnesium phosphid	1,3	Rodenticide
Imidacloprid	9364,57	Foliar and seed
Lambda cyhalothrin	1523,87	Foliar
Malathion	6094,65	Foliar

Methomyl	3766,44	Foliar and soil
Novaluron	66,33	Foliar
Fembutatin oxide	0	Foliar
Parathion-methyl	0	Foliar
Permethrin ϵ	83,34	Foliar and seed
Pyriproxyfen	154	Foliar
Propargite	252,97	Foliar
Sulfur amino	31,95	Domestic
Thiodicarb ϵ	1284,52	Foliar and seed
Foliar	**53219,52**	-
Foliar and seed	**12100,86**	-
Total foliar and seed	**65320,38**	-
Other	**683,95**	-
Total	**66 004,33**	-

Table A.27: Fungicides and other classes 2017.

Fungicides	**Amount**	**Classification**
Azoxystrobin	2933,78	Foliar
Carbendazim	3748,26	Foliar and seed
Cymoxanil	150,2	Foliar and seed
Cyproconazole	1473,28	Foliar
Chlorothalonil	5771,99	Foliar
Kresoxim-methyl	127,94	Foliar
Difenoconazole	1190,03	Foliar and seed
Sulfur	7392,44	Foliar
Epoxiconazole	834,51	Foliar
Fluazinam	1021,51	Foliar
Flutriafol	637,67	Foliar
Imazalil	4,27	Foliar and seed
Mancozeb ϵ	30815,09	Foliar and seed
Copper oxychloride	7443,62	Foliar
Procymidone	337,15	Foliar and seed
Propiconazole ϵ	695,1	Foliar and seed
Copper-sulfate ζ	1156,78	Foliar and seed
Tebuconazole ϵ	2064,6	Foliar and seed
Tetraconazole	4477,19	Foliar and seed
Thiophanate methyl ϵ	3124,45	Foliar
Thiram	751,04	Foliar and seed
Foliar	**30761,19**	
Foliar and seed	**45389,71**	
Total	**76 150,90**	
Other	**Amount**	**Class**

Mepiquat chloride	163,3	PGR
Ethephon	1178,02	PGR
Polyethylene glycol nonyl phenyl ether	334,37	Wetting agent
Nonyl phenyl Ethoxyl	310,7	Surfactant
Mineral oil	26777,62	Other
Vegetable oil	7275,93	Other
Sodium dodecylbenzene sulfonate	4385,06	Additive
Total	**40425**	-

Table A.28: Herbicides 2018.

Herbicides	Amount	Classification
2,4-D	48 921,25	selective
Alachlor	0,00	selective
Ametryn	4 077,26	selective
Atrazine	28 799,34	selective
Clethodim	3 081,14	selective
Clomazone	4 544,29	selective
Chlorimuron-ethyl ϵ	235,28	selective
Paraquat dichloride	13 199,97	non-selective
Diuron (DCMU)	6 609,51	selective
Fenoxaprop-p-ethyl	167,15	selective
Fluroxipyr-meptyl	397,34	selective
Glyphosate	195 056,02	non-selective
Glyphosate - isoprophanyl salt	0,00	non-selective
Glyphosate - aminosalt ϵ	1 450,53	non-selective
Haloxyfop-P-methyl	738,91	selective
Hexazinone	1 284,65	non-selective
Imazaquin	2,88	selective
Imazethapyr ζ	698,10	selective
Lactofen	113,52	selective
Mesotrione	319,53	selective
Metribuzin	729,81	selective
Metsulfuron-methyl	98,90	selective
MSMA ϵ	1 585,68	selective
Nicosulfuron	80,04	selective
Picloram	3 566,69	selective
Propanil	241,30	selective
Quizalofop-p-ethyl	45,04	selective
Simazine	351,45	selective
Sulfentrazone	1 564,48	selective
Tebuthiuron	3 770,64	selective
Triclopyr	1 647,68	selective
Trifluralin	2 329,61	selective

Selective	**114 716,80**	**-**
Non-selective	**210 991,18**	**-**
Total	**325 707,98**	**-**

Table A.29: Insecticides 2018.

Insecticides	**Amount**	**Classification**
Abamectin ι	256,15	Foliar
Acephate	24 656,79	*Foliar*
Acetamiprid	1 065,12	Foliar
Azadirachtin ι	8,34	Foliar and soil
Bifenthrin	1 273,91	Foliar
Cyantraniliprole	260,71	Foliar, soil seed
Cypermethrin	520,45	Foliar
Chlorantraniliprole ϵ	1 202,87	Foliar and seed
Chlorpyrifos	7 157,96	Foliar and soil
Diafenthiuron	1 276,11	Foliar
1_2-Dibromoethane ϵ	1 293,45	Fumigant
Diflubenzuron	485,44	Foliar
Dimethoate	721,76	Foliar
Fipronil	1 689,71	Foliar and seed
Flumethrin	84,75	Used on animals
Aluminium phosphide	652,81	Rodenticide
Magnesium phosphide	1,12	Rodenticide
Imidacloprid	10 021,22	Foliar and seed
Lambda cyhalothrin	1 690,44	Foliar
Lufenuron	175,35	Foliar
Malathion	7 590,74	Foliar
Methomyl	4 016,67	Foliar and soil
Fembutatin oxide	0,05	Foliar
Parathion-methyl	0,00	Foliar
Permethrin ϵ	109,84	Foliar and seed
Pyriproxyfen	109,10	Foliar
Propargite	306,81	Foliar
Sulfur amino	34,04	Domestic uses
Diatomaceous earth	794,89	Organic material
Thiodicarb ϵ	1 627,79	Foliar and seed
Foliar	**51 311,18**	**-**
Foliar and seed	**14 912,14**	**-**
Total foliar and seed	**66 223,32**	**-**
Other	**2 861,05**	**-**
Total	**69 084,37**	-

Table A.30: Fungicides and other classes 2018.

Fungicides	**Amount**	**Classificaton**
Azoxystrobin	2 226,49	Foliar
Captan	678,57	Foliar and seed
Carbendazim	4 843,97	Foliar and seed
Cymoxanil	137,19	Foliar and seed
Cyproconazole	2 051,85	Foliar
Chlorothalonil	7 293,69	Foliar
Kresoxim-methyl	136,11	Foliar
Difenoconazole	1 953,38	Foliar and seed
Sulfur	10 409,69	Foliar
Epoxiconazole	799,92	Foliar
Fluazinam	1 681,12	Foliar
Flutriafol	588,15	Foliar
Copper||hydroxide ϵ	1 433,20	Foliar and seed
Iprodione ϵ	129,24	Foliar and seed
Mancozeb ϵ	40 549,92	Foliar and seed
Copper oxychloride	8 018,65	Foliar
Procymidone	600,91	Foliar and seed
Propiconazole ϵ	795,05	Foliar and seed
Copper-sulfate ζ	1 116,43	Foliar and seed
Tebuconazole ϵ	2 764,94	Foliar and seed
Thiophanate methyl ϵ	3 685,51	Foliar
Thiram	1 061,57	Foliar and seed
Foliar	**36 891,20**	
Foliar and seed	**56 064,36**	
Total	**92 955,56**	
Other	**Amount**	**Class**
Mepiquat chloride	470,47	PGR
Ethephon	1 416,94	PGR
Mineral oil	9 112,53	Other
Vegetable oil	2 945,23	Other
Total	**13 945,17**	-

Table A.31: CFs for the commonly used herbicides in the Brazilian soybean production. **Important notion:** The CFs for Paraquat dichloride is the CFs for Paraquat. This is because it is the Paraquat ion that is sprayed upon the crops, but Paraquat dichloride salt is how this herbicide is formulated. The salt is dissolved and the ion Paraquat is sprayed on the soybeans. To be sure that this is done correctly, the CTUe/ha/yr is multiplied with 0.7 since 30 % of the molecule weight is chloride. So the impact is from the paraquat ion, which has a lower weight than the paraquat dichloride.

Herbicide AI	CF emission to rural air at the continental scale (CTUe/kg)	CF emission to freshwater at the continental scale (CTUe/kg)
2,4-D - selective	46,5	861
Clomazone - selective	278	7780
Diuron - selective	5510	60000
Glyphosate - non-selective	62	321
Paraquat dichloride - non-selective	7530	119000

Table A.32: CFs for the commonly used insecticies in the Brazilian soybean production.

Insecticide AI	CF emission to rural air at the continental scale (CTUe/kg)	CF emission to freshwater at the continental scale (CTUe/kg)
Acephate - organophosphate	50,3	626
Bifenthrin - pyrethroid	61300	6580000
Chlorpyrifos - organophosphate	8390	6230000
Cypermethrin - pyrethroid	379000	50300000
Endosulfan - organochlorine	3080	594000
Imidacloprid - Neonicotiniod	880	3200

Lambda-Cyhalothrin - pyrethroid	556000	139000000
Malathion - organophosphate	1240	62200
Metamidophos - organophosphate	835	9940
Methomyl - Carbamate	2230	28900

Table A.33: CFs for the commonly used fungicides in the Brazilian soybean production.

Fungicide AI	**CF emission to rural air at the continental scale (CTUe/kg)**	**CF emission to freshwater at the continental scale (CTUe/kg)**
Azoxystrobin - methoxy-acrylates	13200	770000
Carbendazim - benzimidazoles	25800	740000
Chlorothalonil - multi-site activity	39400	1140000
Cyproconazole-triazoles	319	4610
Mancozeb - multi-site acitivity	2590	52600
Tebuconazole - triazoles	2450	68600
Thiophanate-methyl - thiophanates	172	7410