Identifying Inefficiencies in the Food System: How to Feed 9.7 Billion People in 2050.

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Abstract

The use of pesticides in agriculture is harmful to both human health and the environment. However, it is still argued that increasing the use of pesticides is required to feed the growing population. By 2050, 9.7 billion people will inhabit Earth, begging the question of how everyone will be fed despite 702 - 828 million people already suffering from food insecurity.

This paper identifies two parts of the food system as inefficiencies: the meat industry and food waste. It suggests that if meat consumption is reduced by 5% and 50%, between 115 and 127 million people and between 1.15 and 1.27 billion more people could be fed, respectively. Similarly, if food waste were reduced by 5% and 50%, 169 million and 1.69 billion people would be fed, respectively. To feed the population in 2050 whilst simultaneously achieving a reduction in pesticides requires significant changes in meat consumption and food waste patterns. To achieve a 10%, 25% and 50% reduction in pesticides, meat consumption and food waste need to decrease by 57%, 66% and 82%, respectively. In light of these results, the paper suggests that, although reducing meat consumption and food waste will have positive impacts on feeding the population, it needs to be combined with shifts in the food system, such as moving toward a food sovereignty paradigm.

Keywords: pesticides, food waste, meat industry, reducing pesticides, feeding the world, food sovereignty

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Introduction

The use of pesticides has increased dramatically in the last thirty years. Between 1990 and 2019. The total use of all pesticides per year increased by over 900,000 tonnes, from 1,685,000 tonnes to approximately 2,654,000 tonnes in 2019 (FAOSTAT, 2019a). According to the UN Food and Agricultural Organisation (FAO), the definition of a pesticide is " any substance, or mixture of substances of chemical or biological ingredients intended for repelling, destroying or controlling any pest, or regulating plant growth" (FAO, 2014 p10). Synchronically, the population is increasing drastically, with future predictions reaching over 9.7 billion people inhabiting Earth by 2050 (Max & Rodés-Guirao, 2013). As a result, food consumption will increase further, and consequently, increased food production is necessary. Since the Green Revolution, agricultural intensification - the increased production of crops on a given land area resulting from more agricultural inputs (Pingali, 2012) - has led to a vast increase in food production. Despite this, an estimated 702 - 828 million people still suffer from food insecurity (FAO et al., 2022). Food security is when a person "lacks regular access to enough safe and nutritious food for normal growth and development and an active and healthy life" (FAO et al., 2022).

A crucial part of agricultural intensification is the use of pesticides, where the benefits and adverse effects are increasingly discussed in the literature. Many authors and research papers discuss the need for pesticides and the positive outcomes of pesticide use, particularly the argument for increased yields (Cooper & Dobson, 2007; Mahmood et al., 2016; Popp, Peto & Nagy, 2013). On the contrary, the adverse effects of pesticides, including environmental damage and harm to human health, are discussed simultaneously (Willem Erisma et al., 2016). The negative impacts of pesticides are not new to the literature. However, the argument that we would not be able to feed the world without pesticides ensures their continued use.

Therefore, this paper aims to debunk the notion that pesticides are essential for feeding the world's population by addressing two components of the food system; food waste and the meat industry. Food waste and the meat industry can both be considered inefficient in providing calories for human consumption to the human food system. Thus, this paper will argue that reducing food waste and livestock farming, resulting in reduced meat consumption will have more significant effects for feeding the world than increasing pesticide use and agricultural outputs. In essence, it will argue that further intensification of agriculture is not necessary for feeding the world and will look at how this would be possible for feeding the 2050 population.

In this paper, the following research question will be addressed: **"Is pesticide use in intensive agriculture the best and most efficient way to feed the planet now and in 2050?"** To answer this question, the existing literature on the benefits and adverse effects of pesticides will be discussed, followed by the literature that addresses the inefficiencies in the meat industry and the issue of food waste. This will be followed by a series of calculations using data from the Food and Agricultural Organization (FAO) to see how reducing livestock farming - therefore, meat consumption - and food waste influence how many people can be fed with our current agricultural outputs. The results will be discussed in the wider context of feeding the population, why pesticides are continually supported, and how this can be changed.

It should be noted that throughout this paper, when "reducing feed crops" is referred to, it implies a reduction in meat consumption, and when "reducing meat consumption" is referred to, it implies a reduction in feed crops.

The Benefits of Pesticides

Pesticides undeniably have benefits for the goal of intensifying agriculture. As a result of rapid population growth, pesticides have been used to increase crop yields to keep up with the copious number of people needing to be fed (Popp, Peto & Nagy, 2013). Pesticides kill pests and diseases in crops, which are estimated to be responsible for 20-40% of crop loss pre-harvest (Oerke, 2006; Bromilow, 2005). Thus, reducing crop losses, increasing crop yields, and increasing crop productivity (Aktar, Sengupta & Chowdhury, 2009). To put the economics of pesticide use into perspective, Popp (2011) argues that the net return of pesticides – including external and secondary costs – is US$4 for each dollar spent on pesticides. However, it should be noted that this economic benefit does not necessarily only refer to food production. Products such as tobacco are pesticide intensive (McDaniel, Solomon & Malone, 2005), and thus economically efficient without contributing to the food system.

Reducing crop losses keeps a consistent food supply in the market and controls food prices (Damalas, 2009). It should also be noted that the economic return is not necessarily representative of the external costs associated with pesticide use, such as the impacts on human health, which will be discussed in later sections.

Pesticides can also keep invasive species of plants and pests out of forest and wildlife habitats (Mahmood et al., 2016). Additionally, to avoid agricultural expansion happening at the expense of forests and natural habitats, pesticides can intensify and increase the existing agricultural outputs (Popp, Peto & Nagy, 2013).

Other benefits of pesticides in literature are that pesticides can control diseases in humans, for example, malaria (Rose, 2001). After an extensive literature review, Cooper & Dobson (2007) argue that there are 26 primary benefits and 31 secondary benefits associated with pesticide use, including those already mentioned. The primary benefits are categorised under controlling pests and plant vectors, controlling human/livestock disease vectors and nuisance organisms, and preventing or controlling organisms that harm other human activities and structures. The secondary benefits are categorised under community benefits, national benefits and global benefits. The figure used to list these benefits are in Appendix 1.

The only question remains is whether these benefits surpass the adverse effects covered in the following sections.

Impacts of Pesticides on the Environment

Pesticides present significant externalities toward the environment. Pimentel (1995) argued that less than 0.1% of pesticides reach their target organisms. This number may have increased over the last nearly thirty years due to the development of application techniques. However, the fact remains that a significant portion of pesticides do not reach their target organisms and thus have effects on the surrounding environment. Pesticides impact organisms such as natural pest predators, pollinators and earthworms (Gill & Garg, 2014). The toxic nature of pesticides has caused considerable damage to entire species and ecosystems (Aktar, Sengupta & Chowdhury, 2009; Tudi et al., 2021). For example, populations of honey bees are declining, which, despite being an issue for the bees themselves, presents further problems for agriculture because bees pollinate around ⅓ of crops (Mahmood et al., 2016). Similarly, populations of birds have declined by 20-25% since pre-agricultural times due to pesticide ingestion and the killing of earthworms, on which birds feed (Mahmood et al., 2016). Furthermore, every year, a few thousand domestic animals are poisoned by accidental ingestion of pesticides, as well as farm animals such as cows and goats (Pimentel, 2005).

Beyond the non-target organisms, pesticides leach into the soil and groundwater supplies (Tudi et al., 2021), altering and negatively impacting terrestrial and aquatic biodiversity and the microbes residing in the soil (Mahmood et al., 2016; Willem Erisma et al., 2016). Furthermore, Tsiafouli and colleagues (2015) found that intensive agriculture reduces soil biodiversity because they negatively impact the diversity of soil food webs, reducing the number of species living in the soil and the diversity of these species, as well as reducing the number of the soil biota. These are all characteristics that make up the biodiversity of the soil (Tsiafouli et al., 2015).

The final issue to be addressed here is that of pesticide resistance. Pests can quickly evolve resistance to the chemicals introduced to them through pesticides (Hawkins, Bass, Dixon & Neve, 2019). Pesticide resistance costs the US billions of dollars annually (Palumbi, 2001). Not only does this have economic impacts, but sociopolitical, individual and community impacts, too (Gould, Brown, & Kuzma, 2018). However, pesticide resistance and many other impacts of pesticides – including human health - are often not considered when cost-benefit analyses of pesticide use are conducted (Pimentel, 2005).

Impacts of Pesticides on Human Health

Pesticides can directly enter the human body through four primary ways: dermal exposure (Anderson & Meade, 2014), oral exposure (Damalas & Eleftherohorinos, 2011), respiratory exposure (Damalas & Eleftherohorinos, 2011) and eye exposure (Kim, Kabir & Jahan, 2017; Gilden, Huffling & Sattler, 2010).

Exposure to pesticides has extremely harmful effects on the human body. The literature showing links between pesticides and human health detriments is overwhelming. The primary issue is that several people have unintentionally died due to accidental poisoning (Carvalho, 2017). In addition to this, Mostafalou & Abdollahi (2013) provided an extensive literature review, presenting hundreds of studies linking pesticide exposure to chronic diseases for humans. These include cancers (Alavanja, Hoppin & Kamel, 2004; Dich Zahm, Hanberg & Adami, 1997) ranging from – but not limited to – leukaemia, brain, bone, breast, and prostate to kidney, lung, and stomach. Studies also show pesticide exposure leads to reproductive disorders (Gilden, Huffling & Sattler, 2010; Fucic, 2021) and birth defects (Winchester, Huskins & Ying, 2009).

Furthermore, there are studies showing associations between pesticide exposure and neurodegenerative diseases such as Parkinson's and Alzheimer's Disease (Parrón et al., 2011), and cardiovascular disease (Zago, 2021). With more than 1000 active ingredients used under the umbrella term of pesticides (Mostafalou & Abdollahi, 2013), it is unsurprising that there are so many associated health risks. Additionally, the health effects of each of these active ingredients are often studied and connected to one or more diseases alone. However, the interaction between these ingredients is understudied and highly complex, which can lead to unforeseeable or even amplified effects (Hernández, Gil & Lacasaña, 2017).

Overall, the impacts on human and environmental health are a call for concern. Therefore, the following section will look at the two inefficiencies that this research chooses to address: the meat industry and food waste. The purpose of this is to establish how we can feed the population by changing or reducing these inefficiencies instead of using more pesticides with such harmful effects.

Inefficiencies in the Food System

Given all of the consequences of the use of pesticides, it leaves two questions: are the benefits of pesticides truly outweigh the harm they cause? Are pesticides and agricultural intensification the only way to feed the planet? To determine how to increase the number of people with access to food without intensifying agriculture, the inefficiencies of the food system need to be identified. This section discusses the inefficiency of the meat industry and the current amount of food waste.

The Meat Industry

Based on data from the FAO, currently, 46% of habitable land is occupied by agriculture. Of this, 77% of the land is used for livestock (including land used for feed crops and grazing land), and 23% is used for crops (Ritchie & Roser, 2013). Consequently, despite the vast majority of agricultural land being used for livestock, it only contributes to 18% of the global calorie supply and 37% of the global protein supply. The remaining 82% of the global calorie and 63% of the global protein supply comes from plant-based food (Ritchie & Roser, 2013). Whilst contributing less than ⅕ of the global calorie supply, livestock grazing changes soil structures by inducing compaction, degrading the soil for future crops (Lai & Kumar, 2020).
This makes one question whether livestock occupying 77% of agricultural land is the most efficient way to produce food.

Feed crops consist mainly of cereal crops, such as corn, soybeans, sorghum and oats (AFIA, n.d.; USDA, n.d.). The highest consumer of feed crops in the US are cattle, followed by hogs and broiler chickens. All of the crops that are used for feed crops can be consumed directly by humans. According to the United States Department of Agriculture, feed crops use around 40% of domestically grown corn (USDA, n.d.). Similarly, in Brazil, 17% of the 23% of soybeans that are domestically processed go toward feed crops (Kuepper, Steinweg & Piotrowski, 2019). Considering this, Cassidy and colleagues (2013) found that only 4% of the calories grown in feed crops reach the food system through animal products. Furthermore, Alexander and colleagues (2017) found (in line with estimates from Gustavsson et al., 2013) that the highest inefficiencies in the food system come from livestock production, with 87.2% of the total calories being lost in production. When talking about calories lost, this refers to the number of calories available for human consumption through animal products relative to the number of calories needed throughout the process of cultivating animal products. Furthermore, calories are also lost in processing meat and take into account the fact that not all parts of animals are consumable. Considering the three papers, it is fair to assume that the caloric loss lies between 87% and 96%.

Meat consumption and production have increased dramatically in the last fifty to sixty years. Meat and dairy production is four times higher than in 1961 (Ritchie, Rosado & Roser 2017). The increase in meat consumption has driven land use change (Alexander et al., 2015) to what it is today. Stopping meat production and consumption entirely is completely unrealistic, and the purpose of this paper is not to endorse that. However, reducing meat consumption could be a factor that significantly changes current land use patterns, thus leading to lower pesticide use. Reducing meat consumption has positive implications towards the environment, biodiversity, human health and climate change (Godfray et al., 2018; Machovina, Feeley & Ripple, 2015).

Reducing meat consumption is realistic. Alexander et al. (2017) did a study to assess the land use required if the entire world adopted the standard diet of the people in each country in the world. They found that if the global population adopted an Indian diet – primarily whole grains and vegetables – only 45% of the current agricultural land would be utilised to meet the demand. On the contrary, if the typical diet of the United States – primarily processed foods with high meat consumption – were to be adopted, we would require 178% more land than what we are using (Alexander et al., 2017). This proves that reducing meat consumption would allow us to produce more food without intensifying agriculture further and driving more agricultural outputs from the land we are already using.

Food Waste

Food waste has become an increasingly popular topic over the last two decades. Gustavsson et al. (2011) found that approximately 1.3 billion tonnes of food is lost or wasted annually. This equates to around ⅓ of edible food, grown and produced for human consumption. This accounts for all stages of the supply chain- from field to fork.

The amount of food wasted and where these losses occur most differs per region. They found that in high-income countries, such as European and North American countries, around 280-300 kg/year per capita of food is lost. Of this, 95-115kg/year per capita is wasted by consumers. In contrast, low-income countries such as African and South East Asian countries see a per capita loss of 120-170 kg/year, with only 6-11 kg/year of consumer waste per capita. Essentially, in high income countries, majority of food waste occurs at consumer level, whilst in low income countries, majority of food waste occurs at production and storage and handling (Gustavsson et al., 2011).

The environmental, economic and social impacts of food waste on the environment are detrimental. Around 6% of global emissions come from uneaten and wasted food (Poore & Nemecek, 2018). Aside from this, the environmental impact of land use change, soil degradation and eutrophication caused by cultivation for food that eventually becomes waste are lesser discussed but still relevant (Tonini, Albizzati & Astrup, 2018). One could go as far as to argue that given ⅓ of food is wasted, ⅓ of the resources that go directly into food for human consumption are wasted, and ⅓ of the emissions produced from the agricultural production of food for human consumption are "wasted". Aside from the environmental concern, the economic burden of food waste is a call for consideration. All of the food wasted costs close to US$1 trillion (FAO,F, 2014). In Europe alone, food waste costs the economy €143 billion annually (Stenmarck et al., 2016). Understandably, some food waste is unavoidable, for example, from processing (Teigiserova, Hamelin & Thomsen, 2019). However, avoidable food waste needs to be addressed. Can avoidable food waste be food eaten elsewhere? And thus aid in providing food to more people without increasing agricultural outputs and intensifying agriculture through the use of pesticides?

Given the inefficiencies in the food system, this paper sets out to analyse if more people could be fed by reducing these inefficiencies and comparing how that would look if we reduced the use of pesticides.

Methods

This study aims to answer the following research question: **"Is pesticide use in intensive agriculture the best and most efficient way to feed the planet now and in 2050?"**

To achieve this, two separate factors will be assessed against the impacts on yields of reducing or eliminating pesticide use. These entities are i) converting feed crops for animal consumption into food for human consumption and ii) reducing food waste. The objective of this is to understand how many people can be fed by ultimately decreasing meat consumption and reducing food waste. This will then be compared with the number of people who would not be fed if pesticides were reduced and, therefore, crop yields lost.

These methods consist of analysing data extracted from the FAO food balance tables (FAOSTAT, 2019b) and the FAO statistics on pesticide use (FAOSTAT, 2019a). All of the data was collected for the year 2019, and all calculations were made on a global scale, meaning only the FAO selection World (total) was used. All agricultural commodities with available data from the FAO food balance sheets were considered.

Reducing Feed Crops

Two scenarios were considered; if agricultural commodities used for feed crops were reduced by 5% and 50%. These scenarios are calculated assuming that production remains the same, but the products are used for food for human consumption rather than feed crops.

The first step was to calculate the number of tonnes of feed crops that would be available by reducing feed crops. This was calculated by multiplying total feed crops (tonnes) by 0.05, which will be referred to as 'the 5%'. The number of calories in the 5% was calculated using a conversion rate determined by dividing the total calories of food supply for human consumption by the total tonnes of food produced for human consumption. This is a limitation that will be discussed in the limitations section of this paper.

The number of people that these calories would feed was calculated using the yearly caloric needs of a person (821,250 kcal/year). The yearly caloric needs of a person were based on the average of men's and women's caloric needs as said by the NHS (2000 per day for women and 2500 per day for men).

By reducing feed crops, it is assumed that animal products available for human consumption will decrease too. Here, a range is considered such that Cassidy et al. (2013) calculated that only 4% of calories produced from feed crops are reflected in the food system as animal products, and Alexander et al. (2015) estimated that 87.2% of calories from feed crops are lost in the production of animal products. Thus, two values are considered: 4% and 12.8% of the calories produced from feed crops are available for human consumption through animal products.

To calculate the number of people not fed by meat products that the 5% of feed crops would have produced, the number of calories in 5% of feed crops was multiplied by 0.04 and .012, respectively and then divided by the per capita yearly caloric needs.

Finally, the difference in potential people fed by the feed crops and the number of people not fed by the meat products gave the net increase of people that can be fed by converting the feed crops into food for human consumption.

This was repeated, but replacing 5% with 50%. The calculations can be seen in table 1 below.

Table 1: Calculations for reducing meat consumption

Calculation number	Purpose	Calculation
1	Number of tonnes in 5% reduction of feed crops	= Total feed crops * 0.05
2	Number of calories in 5%	= Calculation 1 * average calories in 1 tonne of crops of food for human consumption
3	Number of people the 5% of calories feeds	= Calculation 2 / 821,250
4	The number of people not fed by meat products that 5% would have produced (given 4% calories represented in the food system)	= Calculation 3 * 0.04
5	The number of people not fed by meat products that 5% would have produced (given 12.8% calories represented in the food system)	= (Calculation 3 * 0.12
6	The net number of people fed by feed crops (given 4% calories represented in food system)	= Calculation 3 - Calculation 4
7	The net number of people fed by feed crops (given 12.8% calories represented in food system)	= Calculation 3 - Calculation 5
* from calculation 3, 5% was replaced with 50% for the second scenario.		

Reducing Food Waste

The first step to understanding the true impact of food waste is to establish how many people all of the food grown for human consumption would feed if there was no waste or losses after harvest. This was done by dividing the total number of calories available for human consumption by 821,250 kcal. To assess the impact of reducing food waste, the same two scenarios are considered as for feed crops: How many people can be fed by 5% of food waste and 50% of food waste? This is based on the assumption that the wasted food would be available before the opportunity for it to be wasted. The first step was calculating how many calories would be left for consumption after the ⅓ loss – as found by Gustavsson et al. (2011) – by multiplying the total food supply (kcal) by ⅔ and dividing that by 821,250 kcal to see how many people are fed. Then, this was taken away from the total number of people and all of the calories available for human consumption to see how many people were not fed by the wasted calories. This number was multiplied by 0.05 and 0.5 to find the number of people they could feed for the two scenarios. The calculations can be seen in table 2 below.

Table 2: Calculations for Food Waste.

Calculation number	**Purpose**	**Calculation**
8	Number of people fed if no food waste lost or wasted	= All food grown for human consumption / 821,250
9	Calories available for consumption after ⅓ loss	= All food grown for human consumption * ⅔
10	Number of people fed by the calories left	= Calculation 9 / 821,250
11	Number of people not fed by calories waste	= Calculation 8 - Calculation 10
12	Number of people fed with 5% reduction	= Calculation 11 * 0.05
Calculation 12 was repeated, replacing 5% with 50%.		

Reducing Pesticides

The same two scenarios were considered as above; 5% reduction and 50% reduction in pesticide use. Based on Oerke's (2006) work, the calculations were made that pesticides reduce crop loss pre-harvest by 20-40%. Thus, a range is considered. The number of calories that would be lost as a result of the yield loss was calculated by multiplying the yield loss rate (20% or 40%) by the reduction in pesticide rate (5% or 50%). This result was then divided by 821,250 kcal to establish how many people are not fed by the yield loss resulting from the pesticide reduction. The calculations are made before considering food waste. The calculations can be seen in table 3 below.

Calculation number	**Purpose**	**Calculation**
14	Calories left for consumption after 5% reduction in pesticides	= Number of calories available for human consumption * 0.2 OR 0.4
15	Number of people not fed by the reduction	= Calculation 14 / 821,250
Calculations were repeated, replacing 5% with 50%.		

Table 3: Calculations for Reducing Pesticides

How would the Population of 2050 be Fed?

This section aims at gauging the percentage reduction of meat consumption and food waste required to feed the projected 2050 population, which is 9.7 billion people (Max & Rodés-Guirao, 2013). This is calculated in scenarios of reducing pesticide use by 0, 10%, 25% and 50%. For this section, an average is taken, in line with Bromilow (2005), that the yield loss rate is 30% without pesticides, instead of the 20-40% range. Furthermore, an average of 8.4% of calories represented in the food system as meat products from feed crops is taken instead of the 4-12.8% range.

With meat consumption, it is assumed that with yields reducing due to pesticide reduction, the net number of people fed by converted feed crops to human food is reduced by the same percentage. However, there is no evidence to suggest that if yields are reduced, food waste will be reduced. Thus, for each scenario, the number of people fed per percentage of reduced food waste remains constant whilst decreasing accordingly for meat consumption.

For all of the calculations done in this section, the number of people fed, as calculated in the previous section, is used. For reducing pesticides, the number of people not fed by a 1% reduction was calculated by multiplying the number of people currently fed (accounting for ⅓ food waste) by the 30% loss, and then by 1%. This value was multiplied by 0, 10, 25 and 50 for each scenario. For meat consumption, the first step was calculating the number of people fed by a 1% reduction by taking the average of the range used in the section "Reducing Feed Crops" above and applying 1% instead of the 5% or 50% that was applied in the calculations. This number was then multiplied by 30% for the yield reduction and the percentage applied to pesticide reduction (0%, 10%, 25% and 50%). Finally, this number was taken away from the original 1% to get the number of people fed, accounting for the reduction in yields from the pesticide reduction. Finally, for food waste, the number of people fed by a 1% decrease in food waste was calculated as described in the "Reducing Food Waste" section above, but applying 1% instead of 5% and 50%. Table 4 shows the calculations for this section.

The equation below was formulated to estimate the reduction in food waste and meat consumption needed to feed 9.7 billion people given the percentage reduction in pesticides as per scenario. The equation is as follows:

9,700,000,000 = Z - Y(1% decrease in pesticides) + X(1% food waste reduction + 1% feed crop reduction, adjusted as per pesticide reduction)

Such that Z = the number of people who are already fed. Y = the given percentage of pesticide reduction (0%, 10%, 25% and 50%). X = the % reduction required of both food waste and feed crops to achieve feeding 9.7 billion people. As mentioned above, the number of people fed from feed crops converted into human food is adjusted for the yield loss from pesticide reduction.

Table 4: Calculations for feeding the population in 2050

Calculation number	Purpose	Calculation
16	Number of people not fed by 1% reduction in pesticides	= Calculation 10 * 0.3 * 0.01
17	The number of people not fed by a 10% reduction of pesticides	= Calculation 16 * 0.1
18	Number of people not fed by 1% feed crop reduction	= Calculation 3 / 5
19	Number of people fed by feed crops converted to human food after accounting for reduction in feed crops	= Calculation 18 - (Calculation 18 * 0.3 * 0.1)
20	Number of people fed by 1% reduction of food waste	= Calculation 12 / 5
21.	The coefficient for X (1% Reduction of food waste and meat consumption)	= Calculation 19 + Calculation 21
All calculations from number 17 were repeated, but replacing 10% with 25% and 50%.		

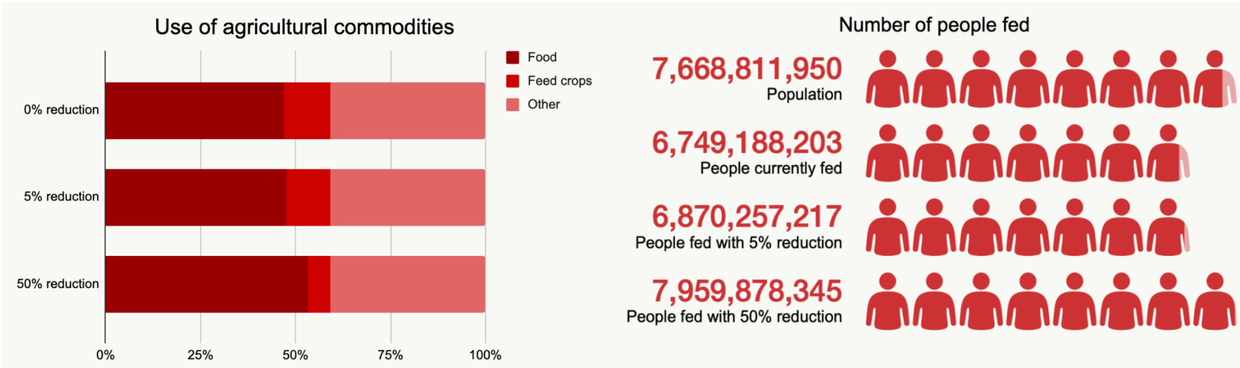
Results

The overall results of this research suggest that reducing feed crops and reducing food waste would increase food availability for human consumption. However, the extent to which yields would be lost if pesticides were reduced is also great.

Reducing Feed Crops

As mentioned, two scenarios for reducing feed crops were considered; 5% reduction and 50% reduction. If feed crops were reduced by 5%, and those crops were redirected to food for human consumption, the number of people who wouldn't have been fed by the meat products produced from the feed crops lies between 5.29 and 16.9 million people. This is based on the assumption that between 4% and 12,8% of the calories from the feed crops are reflected in the food system as meat products. The number of people who could be fed by 71 million tonnes of feed crops in the 5% feed crops was calculated at 132 million people. Thus, the net number of people that the feed crops could feed lies between approximately 115 and 127 million people.
When the same calculations are applied to the 50% redirection of feed crops for animal consumption to food for human consumption, between 1.15 billion and 1.27 billion people could be fed. This considers the people who would not have been fed by the meat products that the feed crops would have otherwise produced. The results can be depicted in Figure 1 below.

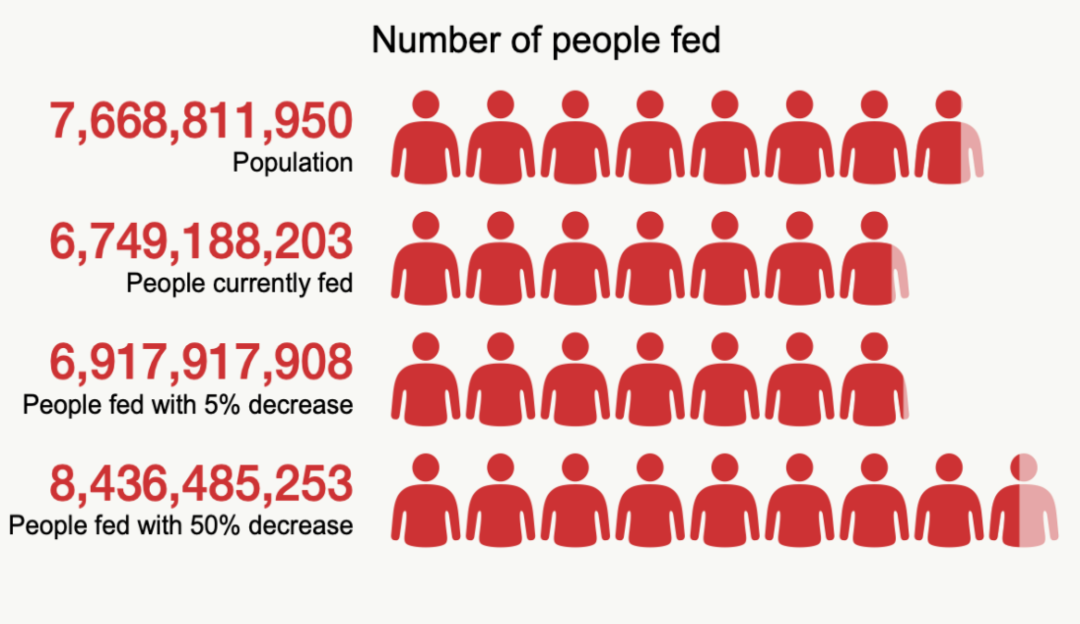
Figure 1: 5% and 50% scenarios of reducing meat consumption



Reducing Food Waste

If all food produced for human consumption was consumed and nothing was wasted pre-harvest, some 10,1 billion people could be fed. However, the number of calories left for human consumption after accounting for Gustavsson and colleagues' (2011) research that ⅓ of food for human consumption is wasted or lost is 5,542,770,811,366,670.00 kcal. This can feed around 6,75 billion people – approximately 88% of the population. The number of tonnes that are lost is wasted is around 1,8 billion tonnes, and the number of people that are not fed by the ⅓ loss is around 3,74 billion people. Based on the above calculation, if food waste was reduced by 5%, an additional 169 million people could be fed. Furthermore, if food waste is reduced by 50%, some 1.69 billion additional people could be fed. These results are based on the assumption that the food is distributed before it has the opportunity to be wasted. The results can be depicted below in Figure 2.

Figure 2: 5% and 50% reduction in food waste.



The Impacts of Pesticide Reduction

The impacts of reducing pesticide use vary. Based on Oerke's (2006) findings that pesticides save 20 - 40% of crop yields, the number of people affected by a reduction of pesticide use on crops varies greatly. If pesticides were reduced by 5% and a 20% crop loss occurred, the number of calories lost would mean that 101 million people would not be fed. If, under the same assumption that crop loss is 20%, pesticides were reduced by 50%, around 1 billion people would not be fed. On the premise that 40% of crops are lost, if pesticides were decreased by 5%, this would result in some 202 million people not being fed. If pesticides were reduced by 50%, and the 40% loss occurred, around 2.02 billion people would not be fed. As said earlier, the variation in results differs hugely, with the number of people affected doubling depending on the impacts of reducing pesticides.

Feeding the 2050 population

Using the equation stated in the methods (the specific equations with numbers can be found in appendix 2) and letting Y = 0%, 10%, 25% and 50%, it is found that to feed 9,7 billion people in 2050 and achieve a pesticide reduction simultaneously, significant shifts in food waste and meat consumption need to occur. A 100% reduction in pesticides is not feasible, nor was this research expecting it to be, by only considering meat consumption and food waste. In fact, the results find that anything above a 50% reduction would require more than an 82% reduction in both food waste and meat consumption. However, to achieve a 25% reduction in pesticides, meat consumption, and food waste would need to reduce by 66% each after the reduction to still feed 9.7 billion people. Furthermore, a 10% reduction in pesticides would require a 57% reduction in feed crops and meat consumption.

All of the calculations and results are based on the assumption that the number of tonnes of agricultural commodities produced does not increase nor decrease from the year the data was collected – 2019.

Discussion

This research aimed to establish the impact on how many people could be fed by reducing feed crops and food waste. It was found that reducing food waste and feed crops – essentially reducing meat consumption – can have considerable positive implications for feeding the population. This is based on the assumption that this food is redirected for direct human consumption. What can this look like? This section of the paper addresses shifting diets and reducing food waste, why the use of pesticides continues and how the food sovereignty paradigm can help feed the population.

Shifting Diets and Reducing Food Waste

If pesticide use remained constant and feed crops were reduced by 5% and 50%, between 115 and 127 million people and 1.15 billion and 1.27 billion people (around the population of India), respectively. Next to this, for someone who eats meat three times a day, seven days a week, a 5% reduction in meat consumption would only require them to not eat meat for 1 out of those 21 meals per week. This is not unreasonable or unrealistic.

These findings expand on the research done by Cassidy et al. (2013) and Alexander et al. (2017), who prove the inefficiency of the meat industry in supplying calories to the food system for human consumption. Besides providing calories to the food system, the meat industry contributes 14.5% of all human-induced greenhouse gas emissions (Gerber et al., 2013). This is likely to have increased in the last decade, considering global meat production has increased from 315.6 million tonnes in 2013 to 357.4 million tonnes in 2021 (Ritchie, Rosado & Roser, 2017).

If food waste were reduced by 5% and 50%, an additional 169 million people and 1.69 billion people (more than the entire population of China) would be fed, respectively. To fit this into the scope of pesticides, it was essential to calculate the extent to which yields would be compromised if pesticides were reduced. This study found that reducing pesticides by 5% and 50% would result in a reduction of people fed by between 101 million and 202 million and 1.01 billion and 2.02 billion people, respectively. Although it may seem obvious that reducing food waste would result in more people being fed, the extent of this, when conceptualised as in figure 2, is shocking. The results of this study are in line, however slightly exceeding that of the FAO (Gustafsson et al., 2013), stating that all of the food wasted could feed 2 billion people. As meat consumption, food waste contributes considerably to greenhouse gas emissions. 8-10% of greenhouse gas emissions are attributed to food waste (United Nations Environment Programme, 2021).

With a total of nearly ¼ of greenhouse gas emissions coming from both food waste and the meat industry provide further incentive for a reduction in both of these categories.

What do these numbers mean? Even if pesticides are not reduced, this study proves that by reducing meat consumption and food waste by half, we could feed 126% of our population (9.65 billion people) on a diet consisting of, on average, 2250 calories per day - the average of what the NHS (NHS, n.d.) suggests. Thus ensuring that **further** intensification of agriculture is barely necessary to feed the projected population in 2050. However, feeding the population in 2050 whilst simultaneously reducing pesticides is a little more complicated, yet still achievable. The results show that to achieve a 10%, 25% and 50% reduction in pesticide use, meat consumption and food waste would need to be reduced by 57%, 66% and 82%, respectively.

Nonetheless, the calculations show that there is almost a 1 to 1 ratio of reduction of pesticides to reduction of food waste alone. The number of calories available for human consumption would increase slightly, if not remain constant, if every 1% reduction in pesticides happened concurrently with a 1% decrease in food waste.

Continued Support of Pesticides

The changes that would be required in food waste and meat consumption are drastic. However, drastic changes are needed to feed a drastically growing population. Expanding agriculture is not possible because, as stated previously, agriculture already utilises 46% of habitable land (Ritchie & Roser, 2013). Further expansion would come at the expense of forests, natural ecosystems and even space for humans to live. Thus, efficiently using current agricultural land is essential, but at what expense? Since the green revolution, this has meant a severe intensification of agriculture through the use of pesticides (Pingali, 2012), which is blindly supported by many entities, regions and organisations in the name of food security, regardless of the negative impacts that were discussed in the prior sections of this paper. For example, the United States, a country that is a front-runner in agricultural production of crops such as corn and rice, still allow the use of 72 chemicals that are either being phased out or are banned in the EU due to their toxicity to humans and the environment (Donely, 2019). Although most countries have strict regulations on the use of pesticides, many pesticides that are banned are still used. A report published by the Pesticide Action Network, Europe, found that 14 of the 24 active ingredients studied were permitted for use 236 times between 2019 and 2022 for “emergency situations” (PAN Europe, 2023). Some of the chemicals used are detrimental to human health and the environment. Yet countries such as Austria, Finland and Denmark still approved their use multiple times. On the contrary, countries like Malta and Bulgaria did not approve of the emergency use of these toxic chemicals once. If Austria can approve these "emergency situations" twenty times in one year, one can either question the severity of all twenty emergencies or the legitimacy of the law.

In addition to policy, pesticide use is still supported by stakeholders that benefit economically. The pesticide industry has a considerable market share. In 2020, the market for crop protection chemicals was US$ 57.13 billion. It is estimated that this will grow to US$81.74 billion in 2028 (Fortune Business Insights, 2021). With such a market size, there would undoubtedly be resistance to reducing pesticides from the stakeholders profiting from the industry.

As proven in this study, eradicating pesticides is not feasible. Feeding the population in 2050 whilst achieving a significant reduction in the use of pesticides cannot happen with only a reduction in meat consumption and food waste. However, there are 4 billion of the 11 billion tonnes of agricultural commodities that are not used for either feed or food or are counted in pre-harvest losses (FAOSTAT, 2019b). Therefore, compromises and redirection from other sectors, such as biofuels, can further aid in feeding the world. However, perhaps considering a different way of looking at the food system is necessary to feed the population sustainably in 2050. Considering we are already producing enough food to feed more than enough people, the production seems not to be the issue

Food Sovereignty

Food sovereignty is a concept that has been gaining attention in research as researchers, policymakers, and firms worldwide battle the issue of how to meet the demands of the growing population. Food sovereignty is an alternative idea to food security that demonstrates how crucial it is for local communities to be in charge of their own food systems (Patel, 2009). Although the end goal of food sovereignty and food security is the same; ensuring adequate access to food for everyone, food sovereignty differs in its underlying principles and approaches to achieving this. The definition of food sovereignty is as follows:

> "The right of peoples to healthy and culturally appropriate food produced through ecologically sound and sustainable methods, and their right to define their own food and agriculture systems. It puts the aspirations and needs of those who produce, distribute and consume food at the heart of food systems and policies rather than the demands of markets and corporations. It defends the interests and inclusion of the next generation. It offers a strategy to resist and dismantle the current corporate trade and food regime, and directions for food, farming, pastoral and fisheries systems determined by local producers and users. Food sovereignty prioritizes local and national economies and markets and empowers peasant and family farmer-driven agriculture, artisanal fishing, pastoralist-led grazing, and food production, distribution and consumption based on environmental, social and economic sustainability. Food sovereignty promotes transparent trade that guarantees just incomes to all peoples as well as the rights of consumers to control their food and nutrition. It ensures that the rights to use and manage lands, territories, waters, seeds, livestock and biodiversity are in the hands of those of us who produce food. Food

sovereignty implies new social relations free of oppression and inequality between men and women, peoples, racial groups, social and economic classes and generations." (Nyéléni Forum for Food Sovereignty 2007).

Given this definition, why is food sovereignty relevant to feeding the population in 2050? Implementing food sovereignty takes an inclusive and holistic approach. It dives beyond the concept of ensuring that people have "sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" as per the definition of food security (World Food Summit, 1996). Whilst food sovereignty aims to achieve this, too, the emphasis is on reducing reliance on international trade by promoting local food production (Via Campesina, 2003). This approach removes the corporate control over the food system, highlighting and encouraging local autonomy (Patel, 2009). Food sovereignty does not look to eliminate trade but rather to reduce it to ensure all people are fed before the food is traded (Via Campesina, 2003). However, researchers stress that the food sovereignty movement needs to develop the position of trade within the concept (Burnett & Murphy, 2014).

Food sovereignty works hand in hand with agroecological farming practices, which limit the use of chemicals, and replaces them with biology (Watts & Williamson, 2015). Agroecology contends that utilising social and ecological diversity can increase productivity and climate change resilience (Wittman, 2011). This narrative is essential for ensuring that land favours future production and environmental sustainability. Some may argue that food sovereignty is not feasible because the shifts it argues for require addressing and changing a system that is the norm and has deeply embedded roots. However, with finite resources and land and planetary boundaries that do not allow for agriculture to intensify further, it is a framework that should be seriously considered by policymakers.

Limitations

Like most research, this study is not free of limitations. With most agricultural data, all of the data used in this study were estimates. Gathering exact data on agricultural production is extremely difficult. Thus, it should be kept in mind and acknowledged that all of the results from this paper are estimates from estimated data. This can lead to a phenomenon called "dustbowl empericism" (Sam, 2013). This occurs when results are based on empirical observations with no theoretical framework.

Furthermore, this paper aims to prove simply the number of people that can be fed in different scenarios. These calculations are rudimentary and can encapsulate feeding the population from a global perspective based on a number of assumptions. This is essential in proving that increasing pesticide use and intensification of agriculture are not necessary to feed our growing population. However, using data from only a global level does not consider where and on which crops pesticides are used most and, thus, where intervention is required. Along the same lines, using averages on a global level can be ambiguous. For example, using an average of how many calories are produced per tonne of agricultural commodities is a disadvantage because, for example, one tonne of corn has a different amount of edible calories than one tonne of sugar cane. Although this paper proves that reducing feed crops would contribute to food for human consumption, it does not give a clear direction of where changes in crops or inputs should occur to achieve as much food grown for direct consumption as possible and which regions this impacts the most. Another limitation associated with this study is that it does not take into account the macronutrient requirements of people, nor how this is represented in agricultural commodities around the world.

The assumptions used in this study may pose some disadvantages. For example, the statistic used from the FAO (Gustavsson et al., 2011) stating that ⅓ of food is wasted includes losses pre-harvest. However, this is already accounted for in the data for food available for human consumption. Therefore, it is possible that the estimations for food waste, as calculated in this study, are overestimates. Furthermore, using the assumption that, on average, a person consumes 2250 calories per day may be inaccurate, as caloric needs differ per region, age and environmental surroundings (National Research Council, 1989). Similarly, this paper and the data do not consider over-consumption as food waste.

Another limitation regarding assumptions is the assumption that 20-40% of yields would be lost if it weren't for pesticides. The paper this estimate (Oerke, 2006) comes from is from 2006, and it is possible that this may have changed in the last 13 years. Furthermore, the two papers used by Cassidy et al. (2013) and Alexander et al. (2017) vary threefold in their calculations for the percentage of calories represented in the food system as animal products.

Future research

Based on the limitations above, future research could consider replicating the methods on a continent or country level to get a better understanding of where intervention and policy could be most effective. Furthermore, analysing the impact of changing the use of different crops or crops groups could build upon the research presented in this paper by understanding which crops would make the most significant difference in calories for human consumption. For example, by analysing the effect on the number of people fed by corn that is converted from feed crops to human food. This study provides good, however, more broad results that can be built upon in more specific studies in the future.

The final point to discuss for future research is the implementation of food sovereignty. Currently, countries such as Venezuela, Mali, Bolivia, Ecuador, Nepal and Senegal have food sovereignty implemented in their constitution (Wittman, Desmarais & Wiebe, 2010). However, perhaps a quantified, universal framework for measuring food sovereignty and its impact on providing food for the people of a specified country as this does not exist yet.

Conclusion

This research set out to answer the research question, **“Is pesticide use in intensive agriculture the best and most efficient way to feed the planet now and in 2050?”**
To achieve this, extensive literature research was conducted, followed by a series of calculations that set out to estimate the number of people that could be fed by reducing meat consumption, food waste and pesticides by 5 and 50%. These calculations were then put into an equation to see the percentage reduction of food waste and meat consumption required to feed the population in 2050 if pesticides were reduced by 10%, 25% and 50%.

To answer the question, reducing meat consumption and food waste can significantly affect feeding the population. It shows that further intensification of agriculture and increased use of pesticides is not necessary to feed the population today nor in 2050. However, reducing pesticides whilst feeding the population in 2050 is more difficult. Feeding the population whilst reducing pesticides by 50% and lower is possible with reductions in food waste and meat consumption by 82%. Although it is possible, it is difficult, therefore, the paper calls for changes in other aspects of agricultural production to assist in feeding the population in 2050. Furthermore, research in an alternative food system such as food sovereignty is essential in feeding the growing population.

References

Aktar, W., Sengupta, D., & Chowdhury, A. (2009). Impact of pesticides use in agriculture: their benefits and hazards. *Interdisciplinary toxicology*, *2*(1), 1.

Alavanja, M. C., Hoppin, J. A., & Kamel, F. (2004). Health effects of chronic pesticide exposure: cancer and neurotoxicity. *Annu. Rev. Public Health*, *25*, 155-197.

Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D., & Rounsevell, M. D. (2017). Losses, inefficiencies and waste in the global food system. *Agricultural systems*, *153*, 190-200.

Alexander, P., Rounsevell, M. D., Dislich, C., Dodson, J. R., Engström, K., & Moran, D. (2015). Drivers for global agricultural land use change: The nexus of diet, population, yield and bioenergy. *Global Environmental Change*, *35*, 138-147.

Anderson, S. E., & Meade, B. J. (2014). Potential health effects associated with dermal exposure to occupational chemicals. *Environmental health insights*, p.*8*, EHI-S15258.

AFIA (n.d.). Animal Feed Consumption. Retrieved 27 May, 2023 from https://www.afia.org/feedfacts/feed-industry-stats/animal-food-consumption/

Bromilow, R. (2005). PESTICIDES. Encyclopedia of Soils in the Environment, 188-195. https://doi.org/10.1016/B0-12-348530-4/00110-7

Burnett, K., & Murphy, S. (2014). What place for international trade in food sovereignty?. Journal of Peasant Studies, 41(6), 1065-1084.

Carvalho, F. P. (2017). Pesticides, environment, and food safety. *Food and energy security*, *6*(2), 48-60.

Cassidy, E. S., West, P. C., Gerber, J. S., & Foley, J. A. (2013). Redefining agricultural yields: from tonnes to people nourished per hectare. *Environmental Research Letters*, *8*(3), 034015.

Cooper, J., & Dobson, H. (2007). The benefits of pesticides to mankind and the environment. *Crop Protection*, *26*(9), 1337-1348.

Damalas, C. A. (2009). Understanding benefits and risks of pesticide use. *Sci. Res. Essays*, *4*(10), 945-949.

Damalas, C. A., & Eleftherohorinos, I. G. (2011). Pesticide exposure, safety issues, and risk assessment indicators. *International journal of environmental research and public health*, *8*(5), 1402–1419.

Dich, J., Zahm, S. H., Hanberg, A., & Adami, H. O. (1997). Pesticides and cancer. *Cancer causes & control*, *8*, 420-443

FAO, IFAD, UNICEF, WFP & WHO. (2022). The State of Food Security and Nutrition in the World 2022. Repurposing food and agricultural policies to make healthy diets more affordable. Rome, FAO.

FAOSTAT. (2019a). *Pesticide Use.* Retrieved 25 March 2023 from https://www.fao.org/faostat/en/#data/RP

FAOSTAT (2019b). *Food Balances (2010-)*. Retrieved 25 March 2023 from https://www.fao.org/faostat/en/#data/FBS

FAO, F. (2014). Food wastage footprint full-cost accounting. Food Wastage Footprint.

Food and Agriculture Organization of the United Nations (2014), International Code of Conduct on the Distribution and Use of Pesticides.

Fortune Business Insights. (2021). Crop Protection Chemicals Market Size, Share & COVID-19 Impact Analysis, By Type (Herbicides, Insecticides, Fungicides, and Others), By Source (Synthetic Chemicals and Biologicals), By Mode of Application (Foliar Spray, Soil Treatment, Seed Treatment, and Others), By Crop Type, and Regional Forecast, 2021-2028. Retrieved 4 June, 2023 from https://www.fortunebusinessinsights.com/industry-reports/toc/crop-protection-chemicals-market-100080#

Fucic, A., Duca, R. C., Galea, K. S., Maric, T., Garcia, K., Bloom, M. S., ... & Vena, J. E. (2021). Reproductive health risks associated with occupational and environmental exposure to pesticides. *International Journal of Environmental Research and Public Health*, *18*(12), 6576.

Gilden, R. C., Huffling, K., & Sattler, B. (2010). Pesticides and health risks. *Journal of Obstetric, Gynecologic & Neonatal Nursing*, *39*(1), 103–110.

Gill, H. K., & Garg, H. (2014). Pesticide: environmental impacts and management strategies. *Pesticides-toxic aspects*, *8*(2014), 187.

Godfray, H. C. J., Aveyard, P., Garnett, T., Hall, J. W., Key, T. J., Lorimer, J., ... & Jebb, S. A. (2018). Meat consumption, health, and the environment. Science, 361(6399), eaam5324.

Gould, F., Brown, Z. S., & Kuzma, J. (2018). Wicked evolution: Can we address the sociobiological dilemma of pesticide resistance?. *Science*, *360*(6390), 728-732.

Gustafsson, J., Cederberg, C., Sonesson, U., & Emanuelsson, A. (2013). The methodology of the FAO study: Global Food Losses and Food Waste-extent, causes and prevention"-FAO, 2011.

Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R., & Meybeck, A. (2011). Global food losses and food waste.

Hawkins, N. J., Bass, C., Dixon, A., & Neve, P. (2019). The evolutionary origins of pesticide resistance. *Biological Reviews*, *94*(1), 135-155.

Hernández, A. F., Gil, F., & Lacasaña, M. (2017). Toxicological interactions of pesticide mixtures: an update. Archives of toxicology, 91, 3211-3223.

IFOAM Organics International. (2017). Organic Agriculture and Pesticides. Retrieved 29 March 2023 from: https://www.ifoam.bio/organic-agriculture-pesticides.

IFOAM Organics International. (n.d.). Definition of Organic Agriculture. Retrieved 29 March 2023 from: https://www.ifoam.bio/why-organic/organic-landmarks/definition-organic.

Kim, K. H., Kabir, E., & Jahan, S. A. (2017). Exposure to pesticides and the associated human health effects. *Science of the total environment*, *575*, 525-535.

Kuepper, B., Steinweg, T., & Piotrowski, M. (2019). Feed and Livestock in Brazil, China, EU Consume Most Cerrado Soy. Washington DC. www. chainreactionresearch. Com.

Lai, L., & Kumar, S. (2020). A global meta-analysis of livestock grazing impacts on soil properties. PLoS One, 15(8), e0236638.

Machovina, B., Feeley, K. J., & Ripple, W. J. (2015). Biodiversity conservation: The key is reducing meat consumption. *Science of the Total Environment, 536,* 419-431.

Mahmood, I., Imadi, S. R., Shazadi, K., Gul, A., & Hakeem, K. R. (2016). Effects of pesticides on environment. *Plant, soil and microbes: volume 1: implications in crop science*, 253-269.

Max & Rodés-Guirao (2013). "Future Population Growth". Published online at OurWorldInData.org. Retrieved March 28, 2023, from https://ourworldindata.org/future-population-growth

McDaniel, P. A., Solomon, G., & Malone, R. E. (2005). The tobacco industry and pesticide regulations: case studies from tobacco industry archives. Environmental health perspectives, 113(12), 1659-1665.

Mostafalou, S., & Abdollahi, M. (2013). Pesticides and human chronic diseases: evidences, mechanisms, and perspectives. *Toxicology and applied pharmacology*, *268*(2), 157-177.

NHS. (n.d.). *What should my daily intake of calories be?* Retrieved on 29 March 2023 from: https://www.nhs.uk/common-health-questions/food-and-diet/what-should-my-daily-intake-of-calories-be/

National Research Council. (1989). Diet and health: implications for reducing chronic disease risk.

Oerke, E. C. (2006). Crop losses to pests. *The Journal of Agricultural Science*, *144*(1), 31–43.

Palumbi, S. R. (2001). Humans as the world's greatest evolutionary force. *Science*, *293*(5536), 1786-1790.

Parrón, T., Requena, M., Hernández, A. F., & Alarcón, R. (2011). Association between environmental exposure to pesticides and neurodegenerative diseases. *Toxicology and applied pharmacology*, *256*(3), 379-385.

Patel, R. (2009). Food sovereignty. The journal of peasant studies, 36(3), 663-706.

Pimentel, D. (1995). Amounts of pesticides reaching target pests: environmental impacts and ethics. *Journal of Agricultural and environmental Ethics*, *8*, 17-29.

Pimentel, D. (2005). Environmental and economic costs of the application of pesticides primarily in the United States. *Environment, development and sustainability*, *7*, 229-252.

Pimentel, D., & Burgess, M. (2014). An environmental, energetic and economic comparison of organic and conventional farming systems. *Integrated Pest Management: Pesticide Problems, Vol. 3*, 141-166.

Pingali, P. L. (2012). Green revolution: impacts, limits, and the path ahead. *Proceedings of the national academy of sciences*, *109*(31), 12302-12308.

Popp, J. (2011). Cost-benefit analysis of crop protection measures. *Journal für Verbraucherschutz und Lebensmittelsicherheit*, *6*(Suppl 1), 105-112.

Popp, J., Pető, K., & Nagy, J. (2013). Pesticide productivity and food security. A review. Agronomy for sustainable development, 33, 243-255.

Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science, 360(6392), 987-992.

Ritchie & Roser (2013) - "Land Use". Published online at OurWorldInData.org. Retrieved 29 March 2023 from: 'https://ourworldindata.org/land-use'

Ritchie, Rosado & Roser (2017) - "Meat and Dairy Production". Published online at OurWorldInData.org. Retrieved 31 March 2023 from: 'https://ourworldindata.org/meat-production'

Rose, R. I. (2001). Pesticides and public health: integrated methods of mosquito management. *Emerging infectious diseases*, *7*(1), 17.

Stenmarck, Â., Jensen, C., Quested, T., Moates, G., Buksti, M., Cseh, B., ... & Östergren, K. (2016). Estimates of European food waste levels. IVL Swedish Environmental Research Institute.

Teigiserova, D. A., Hamelin, L., & Thomsen, M. (2019). Review of high-value food waste and food residues biorefineries with focus on unavoidable wastes from processing. Resources, Conservation and Recycling, 149, 413-426.

Tonini, D., Albizzati, P. F., & Astrup, T. F. (2018). Environmental impacts of food waste: Learnings and challenges from a case study on UK. Waste Management, 76, 744-766.

Tsiafouli, M. A., Thébault, E., Sgardelis, S. P., De Ruiter, P. C., Van Der Putten, W. H., Birkhofer, K., ... & Hedlund, K. (2015). Intensive agriculture reduces soil biodiversity across Europe. *Global change biology*, *21*(2), 973-985.

Tudi, M., Daniel Ruan, H., Wang, L., Lyu, J., Sadler, R., Connell, D., ... & Phung, D. T. (2021). Agriculture development, pesticide application and its impact on the environment. *International journal of environmental research and public health*, *18*(3), 1112.

Sam M.S. (2013) DUSTBOWL EMPIRICISM. PsychologyDictionary.org, https://psychologydictionary.org/dustbowl-empiricism/

USDA (n.d.). Feed Grains Sector at a Glance. Retrieved 27 May 2023 from https://www.ers.usda.gov/topics/crops/corn-and-other-feed-grains/feed-grains-sector-at-a-glance/#:~:text=The%20major%20feed%20grains%20are,of%20corn%20in%20the%20world.

Via Campesina. (2003). Food sovereignty. Via Campesina.

Watts, M., & Williamson, S. (2015). Replacing chemicals with biology: phasing out highly hazardous pesticides with agroecology.

Willem Erisman, J., van Eekeren, N., de Wit, J., Koopmans, C., Cuijpers, W., Oerlemans, N., & J. Koks, B. (2016). Agriculture and biodiversity: a better balance benefits both. AIMS Agriculture and Food, 1(2), 157–174. https://doi.org/10.3934/agrfood.2016.2.157

Winchester, P. D., Huskins, J., & Ying, J. (2009). Agrichemicals in surface water and birth defects in the United States. *Acta paediatrica*, *98*(4), 664-669.

Wittman, H., Desmarais, A., & Wiebe, N. (2010). The origins and potential of food sovereignty. Food sovereignty: Reconnecting food, nature and community, 1-14.

Wittman, H. (2011). Food sovereignty: a new rights framework for food and nature?. Environment and Society, 2(1), 87-105.

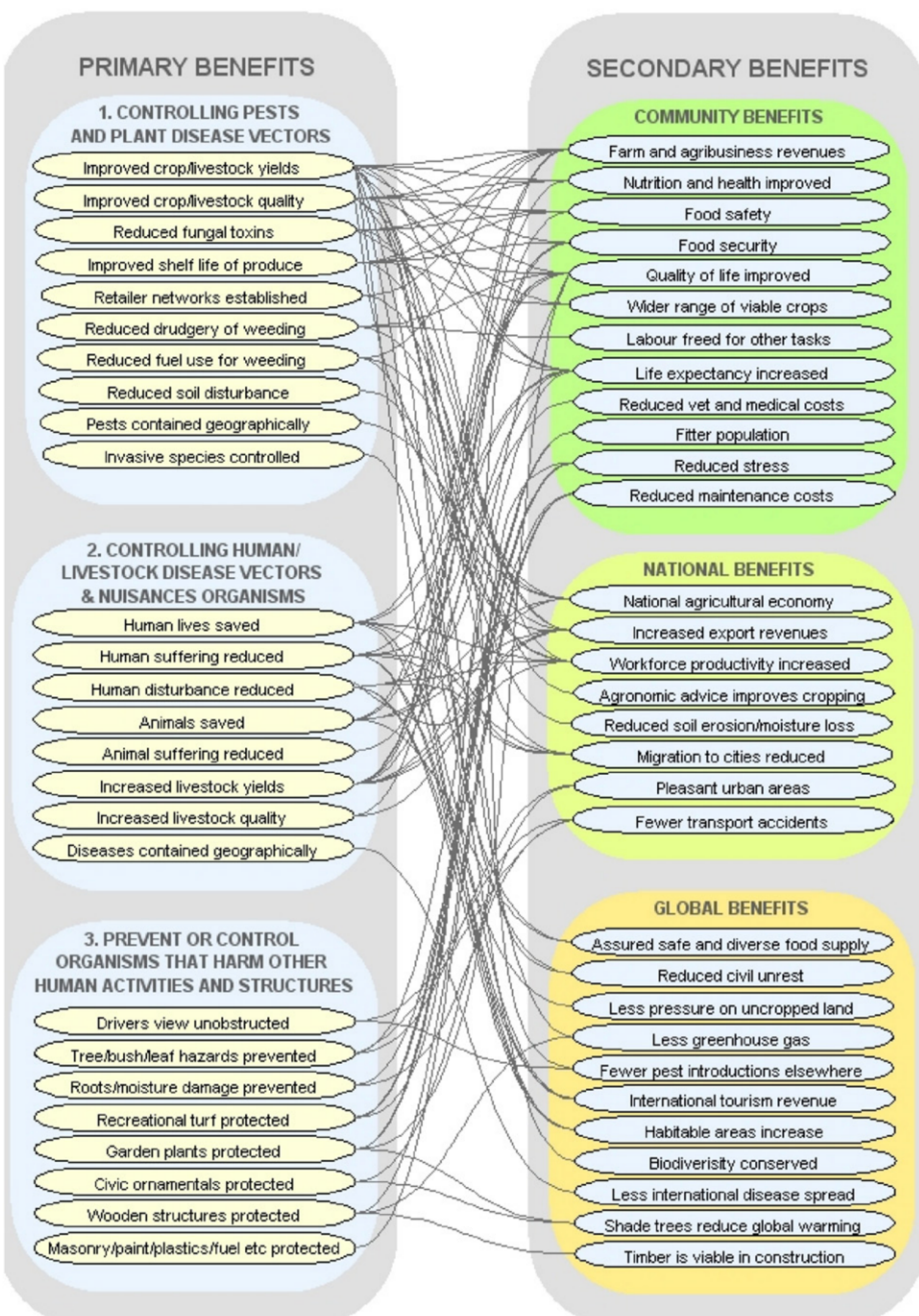
World Food Summit (1996). Declaration on World Food Security. Rome.

Zago, A. M., Faria, N. M., Favero, J. L., Meucci, R. D., Woskie, S., & Fassa, A. G. (2020). Pesticide exposure and risk of cardiovascular disease: A systematic review. *Global Public Health*, 1-23.

Appendices

Appendix 1

Cooper & Dobson's (2007) primary and secondary benefits of pesticides



Appendix 2

The equations used for estimating how to feed the population in 2050. Where x is the percentage decrease required for meat consumption and food waste, after adjusting meat consumption for yields lost from pesticide reduction. 6,749,188,202.58 is the number of people currently fed according to calculations in the "Reducing Food Waste" section of the methods.

9,700,000,000 = Z - Y(1% decrease in pesticides) + X(1% food waste reduction + 1% feed crop reduction, adjusted as per pesticide reduction)

1. Pesticide reduction of 10%:

   9,700,000,000 = 6,749,188,202.58 - 303,713,469 + 56,220,951X

2. Pesticide reduction of 25%:

   9,700,000,000 = 6,749,188,202.58 - 759,283,627 + 53,612,763X

3. Pesticide reduction of 50%:

   9,700,000,000 = 6,749,188,202.58- 1,518,567,345 + 49,265,782X