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Beyond the Bin

Reducing Food Loss and Waste to Conserve Land
and Water Resources

Bachelor thesis in Global Systems Engineering

ALICE CARLSSON, ALICIA SJÖBLOM, ELLA PETER,
LISA HELLSTRÖM, OLIVIA ENGLUND, VENDELA HANSSON

DEPARTMENT OF SPACE EARTH AND ENVIRONMENT
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ALICE CARLSSON, ALICIA SJÖBLOM, ELLA PETER, LISA HELLSTRÖM,
OLIVIA ENGLUND, VENDELA HANSSON

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Supervisor: Chandrakant Singh

Examiner: Martin Persson

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Department of Space, Earth and Environment

Chalmers University of Technology

SE-412 96 Gothenburg

Sweden

Telephone: +46 31 772 1000

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Abstract

With a growing global population and shrinking resources for food production, feeding the world while ensuring future food security is becoming increasingly challenging. Among such challenges, food loss and waste (FLW) pose a significant threat to global sustainability, contributing to environmental degradation and resource depletion. With approximately one-third of all food going to lost or waste, the impact of FLW on natural resources intensifies, underscoring the urgent need for effective reduction strategies. While FLW in general is a quite well-explored area, its specific influence on deforestation and water usage has received limited attention.

By using FLW, commodity-driven deforestation and water-use statistics, our research aims to bridge this knowledge gap and stimulate further exploration in this domain. The objective of this thesis extends to pinpointing the specific regions, agriculture commodity groups, and food supply stages that can help identify preventable deforestation and water usage through the reduction of FLW. By doing so, we can explore possible solutions to reduce FLW that have the greatest potential impact on minimising deforestation and water usage.

Our thesis reveals specific regions, commodity groups and food supply stages for further investigation and targeted interventions. Regions such as "East Asia", "Africa", and "South America", and commodity groups like "cereals" and "oil crops" contribute majorly to FLW. The distribution between supply stages varies geographically and between commodity groups, thus appropriate solutions to reduce FLW differ. Our results also reveal that reducing FLW has the potential to substantially alleviate the strain on forests and water resources with 2.32 million hectares and 1467 teralitres annually. We want to further emphasise that the implementation of solutions must be adapted according to the local contexts, considering factors such as food security and socio-economic dynamics. Thus, our findings can guide policymakers, researchers, and stakeholders in designing targeted, context-specific strategies to effectively reduce FLW and minimise its burden on our land and water resources.

Keywords: *Food Loss and Waste, FLW, sustainability, deforestation, water usage*

Sammandrag

Med en växande global befolkning och begränsade resurser för livsmedelsproduktion blir det allt svårare att tillgodose världens matbehov och samtidigt säkerställa en framtida livsmedelstrygghet. Bland sådana utmaningar utgör matförluster och matsvinn ett märkbart hot mot hållbar utveckling och orsakar miljöförstöring och resursutarmning. Det uppskattas att ungefär en tredjedel av all mat som produceras inte når slutkonsumenten, vilket intensifierar matförlusters och matsvinnns påverkan på naturresurser och understryker det brådskande behovet av effektiva strategier för att minska matförluster och matsvinn. Även om matförluster och matsvinn generellt sett är ett väl utforskat område har dess specifika påverkan på avskogning och vattenanvändning fått begränsad uppmärksamhet.

Genom att använda data om matförluster och matsvinn, råvarudriven skogsavverkning och vattenanvändning, syftar detta kandidatarbete till att fylla kunskapsluckan och väcka intresse för vidare forskning inom området. Syftet med arbetet är vidare att lokalisera de specifika regionerna, matvarugrupperna och matförsörjningsstadierna (eng. food supply stages) i vilka en minskning av matförluster och matsvinn skulle kunna bidra till störst minskning av avskogning och vattenförlust. Genom detta kan vi undersöka möjliga lösningar för att minska de matförluster och matsvinn som har störst potential att, i sin tur, minska avskogning och vattenanvändning.

Våra resultat belyser specifika regioner, matvarugrupper och matförsörjningsstadier för ytterligare undersökning och riktade interventioner. Regionerna "Östasien", "Afrika" och "Sydamerika", samt varugrupperna "spannmål" och "oljeväxter" är särskilt relevanta att betrakta. Fördelningen mellan matförsörjningsstadierna varierar också, både geografiskt och mellan råvarugrupper, varpå det krävs olika typer av lösningar för att minska matförlusterna. Resultatet påvisar att en minskning av matförluster och matsvinn har potential att avsevärt lindra påfrestningen på skogar och vattenresurser med 2,32 miljoner hektar och 1467 teraliter årligen. Implementering av lösningar måste anpassas efter de lokala förutsättningarna med hänsyn till faktorer såsom säker tillgång till livsmedel och socioekonomiska villkor. Därigenom kan våra resultat vägleda beslutsfattare, forskare och intressenter i utformning av riktade, kontextspecifika strategier för att effektivt minska matförluster och matsvinn, samt minimera dess påverkan på mark- och vattenresurser.

Nyckelord: *matförlust, matsvinn, hållbarhet, avskogning, vattenförbrukning*

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Glossary

- **Deforestation:** "The conversion of forest to other land use independently whether human-induced or not".[1] However, in this thesis the term refers to agricultural induced deforestation.
- **Food loss:** Food loss pertains to the inadvertent wastage or degradation of sustenance occurring throughout agricultural operations, storage, transportation, and distribution, resulting in its failure to reach the latter stages of the food supply chain. This encompasses spoilage, impairment, or misplacement of food items attributable to technical limitations, inefficiencies within the food production and supply infrastructure, or deficiencies in labour and handling practices along the earlier parts of the food supply chain. [2] [3] [4]
- **Food waste:** Food waste refers to food of satisfactory quality being unconsumed, and thus, discarded due to neglect or deliberate disposal. Food waste occurs in the latter stages of the food supply chain, encompassing retail, food services and consumers. [2] [3] [5]
- **Food Loss and Waste (FLW):** Food loss and waste is the food that is lost, or wasted, throughout the whole food supply chain.
- **Food Supply Chain:** The linked sequence of operations aimed at producing, processing, distributing, and consuming food [3].
- **Food Supply Stage:** Specific stage in the food supply chain.
- **Region:** Due to there being ambiguous definitions of the word *Region*, there is a point in stating that the meaning utilised in this thesis is: A number of neighbouring countries that are aggregated into one region.
- **Water Loss:** The water used in the production of food that is later lost or wasted. In this thesis also synonym to avoidable water usage by minimising FLW.

1 Introduction

Food is a prerequisite for human life to exist, yet food is constantly lost or wasted throughout its supply chain around the world. Out of the roughly 4 billion tonnes of food produced annually around the globe, an estimate of about a third is being lost or wasted [6]. Simultaneously, the strain on the food system is ever growing as a consequence of an increasing population size and changing eating habits [7]. In order to meet this ever increasing food demand, arable lands are expanded over previously forested regions, leading to biodiversity losses while also removing large carbon sinks and, as a consequence, releasing carbon dioxide into the atmosphere which increases global warming [8]. Large forests are, besides being carbon sinks, also responsible for regulating the water cycle. In the long run, deforestation also leads to decreasing precipitation [9], further affecting biodiversity, the water cycle and in turn, an efficient use of the arable lands, thus endangering the global food security [10].

1.1 Background

Food loss and waste (FLW) is acknowledged as one of the largest issues facing humanity, economically, environmentally, and socially. As it is a broad phenomena to discuss and study, it has been divided into two more unequivocal categories called upstream FLW and downstream FLW. The upstream supply chain includes everything from primary production up to, and including, wholesale, whereas the downstream supply chain includes everything from retail to consumer (also including restaurants and caterers etc.). In 2022, about 735 million people faced hunger [11], while simultaneously, around 13% of the food produced was lost in the upstream supply chain and about 17% of food was wasted in the downstream supply chain [12].

The terminology of FLW has a standardisation of what it represents: “any food intended for human consumption that ultimately is never eaten by humans” [4], or “the edible parts of plants and animals that are produced or harvested for human consumption but that are not ultimately consumed by people” [2]. However, loss and waste are quite different, even though they may be generalised when considering their larger systemic effects on the economy and environment. Food loss refers to the food being lost in the upstream supply chain due to lack of labour or storage, careless handling damaging the produce, or bad transportation resulting in produce not reaching retailers, amongst others. Food waste, on the other hand, includes the food that is more or less consciously wasted in the downstream supply chain by retailers,

restaurants, caterers or household consumers. [2] [3] [4] [5]

A keystone for both preserving and expanding food production lies in securing access to arable land while avoiding strain on natural resources [5]. This includes the cultivation of land and the creation of arable areas through deforestation, as well as water supply. Without either, or both, food may not be grown. As the population increases so does the demand for food, thus exerting pressure on land availability. In turn, this creates a difficult balance between finding arable land to produce an ever growing amount of food and stagnating deforestation to preserve biodiversity and lessen the effects on global warming.

Furthermore, there are obstacles concerning the already existing arable lands used for food production. About 28% of the agricultural land in the world is used to produce food which is later lost or wasted [8], leading to almost a third of the arable land being cultivated unnecessarily. Note that this does not only result in unnecessary cultivation contributing to avoidable greenhouse gas emissions and lessening the utility of these lands, but also in wild lands being converted into agricultural lands through deforestation [8]. Considering that around 80% of all deforestation is made with the intention to cultivate the land gained [13], a lot of deforestation could be prevented through a reduction of FLW.

Closely tied to problems with availability of arable land is the availability of water for agricultural purposes. Great amounts of fresh water are required to ensure a stable food production, and about 72% of the global freshwater withdrawal is used for this purpose [14]. The demand on fresh water for agriculture is ever-growing as it is closely tied to the increasing food demand. Simultaneously, the sources for fresh water are dwindling, aggravating an already arduous situation and endangering future food security.

On top of the substantial fresh water consumption, agriculture is also one of the greatest pollution factors to fresh water due to synthetic pesticides and fertilisers [15]. The food lost and wasted along the food supply chain is equivalent to about 24% of the total freshwater withdrawal used for agriculture [16]. Furthermore, water scarcity is a continuously growing challenge leaving 2.4 billion people in water-stressed countries [14].

In addition to water being scarce, a paramount part of the challenge of hunger lies in dietary gaps, including both quality, nutritional value, and caloric density. The food wasted throughout the food supply chain is generally the most calorie dense and nutritional foods, thus also reducing the amount of calories and average quality of the consumed food [4]. Thus, in order to aid

one of the greatest social adversities of today, a reduction in FLW is essential.

Addressing the intertwined challenges of land and water availability demands innovative approaches in order to manage the agricultural resources more efficiently. In this thesis we examine how reducing FLW has potential to reduce the strain on the Earth system, with a focus on deforestation and water usage.

1.2 Previous Research

The interdisciplinary research field of FLW is becoming an increasingly relevant area of study. A brief search for *Food loss and waste* on Google Scholar yields over 4 million results, indicating it is a relatively well-explored research domain. The complexity and breadth of the FLW research field provides a widespread scope for investigating various aspects. In addition to the inherently problematic nature of FLW, several key aspects have been explored in numerous articles, such as methods and solutions for reducing FLW. This includes both technical solutions across different food supply stages as well as policy, legislation, and strategic interventions. The economic aspect of FLW is a thoroughly investigated area, alongside other aspects such as the link between FLW and food security, as well as FLW and nutrition. Some articles also delve into the correlation between greenhouse gases and FLW. However, there is a notable gap in research concerning the link between FLW and deforestation, which is significant as it contextualises the issue of FLW in relation to the additional problem of deforestation. Similarly, the connection between FLW and water consumption on a global scale remains relatively underexplored, which is also a very important aspect to investigate considering the world's water scarcity. Our study can thus contribute to raising awareness of the major issues resulting from FLW and possibly facilitate the estimation of the negative consequences of FLW on the Earth's limited resources, to some extent. Therefore, the study addresses several knowledge gaps that can increase the understanding of, and lead to further research on, FLW in general and its connection to deforestation and water consumption.

Lipinski, et al. [2] have written an article that adopts a solution-oriented perspective. The article discusses several technical solutions for reducing FLW in various stages of food production, such as evaporative coolers, specific plastic bags and specifications for food date labelling. Additionally, the article addresses several recommendations for reducing FLW. For instance, they discuss FLW targets at both national and global levels, as well as the implementation of a FLW measurement protocol aimed at increasing accurate and consistent FLW data worldwide.

Another article, written by Zhu, et al. [17], investigates the connection between FLW and greenhouse gases. More specifically, they examine the impact of policies and technological developments on reducing greenhouse gas emissions resulting from FLW. Gatto and Chepeliev [18] have written an article that approaches the topic from a nutritional and environmental perspective.

Marston et al. [19] have delved into a similar aspect as this thesis aims to do. Their study investigated the correlation between FLW and water scarcity on a global scale, while also discussing the potential impacts of FLW policies and water wastage. Their findings, amongst others, highlight the significant variation avoidable water usage by minimising FLW across different dietary patterns and geographical locations. Furthermore, they conclude that reducing FLW has the potential to improve both food and water scarcity issues.

1.3 Aim, Objectives and Research Questions

In this thesis, we investigate food loss and waste (FLW) throughout the global supply chain, across regions and commodity groups, in order to gain knowledge about their pressures and effects on our planet and its resources. To specify, region in this thesis refers to a number of neighbouring countries that are aggregated into one region, see section 2.3.3 for further explanation.

We explore a hypothetical scenario where reducing FLW might have led to a corresponding decrease in deforestation and water loss. However, it is important to clarify that in this scenario, deforestation and water use is not directly linked to FLW, since these are effects of the food production, not the FLW.

1.3.1 Aim and Objectives

The aim of this project is to examine FLW throughout its supply chain to assess the impact on land and water resources at a national and regional level. Specifically, we wish to convert the amount of FLW of commodity groups into equivalents of deforestation and water loss. The results from this project will reveal opportunities for reducing the pressures on the Earth's resources, such as deforestation and water usage. In addition the goal is to identify leverage points for potential interventions within the food supply chain in order to minimise food wastage, and in turn lessen deforestation and water usage.

Our intention is to elucidate pathways for mitigating the environmental effects of FLW, while simultaneously optimising the use of resources, by unravelling the complex dynamics governing the FLW system. This project strives

to delve into the complexity of FLW by applying a recent meta-analysis of FLW combined with cutting-edge data concerning deforestation created by increasing arable land, and the water footprint due to similar processes. We want to investigate what the distribution of FLW looks like geographically (limited to regions and nations), as well as in which commodity groups FLW has the highest connection to deforestation and water loss, and where in the supply chain the FLW occurs.

1.3.2 Research Questions

This thesis is divided into two research questions:

1. What does the impact on deforestation and water resources due to production of food, which is later lost or wasted, look like across different geographical regions, commodity groups and food supply stages?
2. What type of solutions are relevant for reducing food loss and waste in consideration to regions, commodity groups, and food supply stages with the largest potential to reduce deforestation and water losses?

1.4 Scope

The scope consists of both the limitations and system boundaries of this thesis. The limitations comprise of restraints due to the situation in which this thesis is created, and system boundaries are restrictions created by the authors to achieve a feasible project with focus on specific areas. To illustrate our system in focus, figure 1 clarifies where the boundaries are drawn, as well as what is included or excluded in our thesis.

One limitation for this thesis concerns the restrictions of the studied data, including constraints in time and geographical location. The studied data, attained from different databases, has varying scopes, definitions and other variations. There may be various definitions of commodities or supply stages in the different datasets, risking inadequacies when merging the data. There is a necessity for gap-filling, driven by the limited data, which in turn adds a layer of complexity that could impact the outcome of the results.

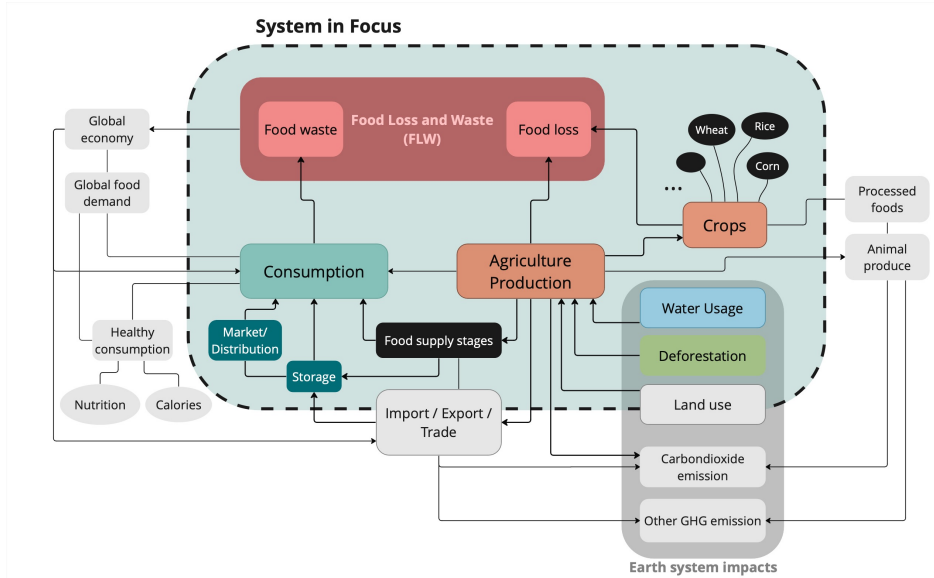


Figure 1: *Illustration defining our system in focus. The dashed line makes out the system boundary, and the grey boxes are topics not covered, or only slightly discussed, while still related to the topics of our thesis.*

The data used in this thesis and its limitations in both time and geography will guide the more fixed temporal and spatial boundaries of the report. The temporal boundaries are set to 2001-2020 for all data except for the data concerning water, which is set to 2001-2016, since there was only available data up until 2016. For the spatial boundaries, we have chosen to not go into more detail than on a national level, meaning we will rather look at a global and regional perspective.

Furthermore, the topic of FLW is interdisciplinary and could be studied from many different perspectives. We have chosen to study the environmental impacts of FLW, and exclude e.g. economic and nutritional aspects. Deforestation and water usage will be the primary aspects studied as environmental features. Another boundary will be the focus on primary crops, and thereby the exclusion of processed foods and animal products.

2 Method

This section portrays the different steps taken throughout the thesis as means towards receiving the results. Our thesis is based on data of FLW in percent from FAO. However, due to the data being inconclusive both geographically and over different time periods, as well as for different commodities, there was a need of extensive gap-filling and data handling. We utilised different techniques relevant to each case in order to get a representative dataset. The data was processed and handled in the programming language Python. At appropriate times, OpenAI’s ChatGPT was used as a supplementary tool for programming. Figure 2 illustrates the flow of processing the different datasets.

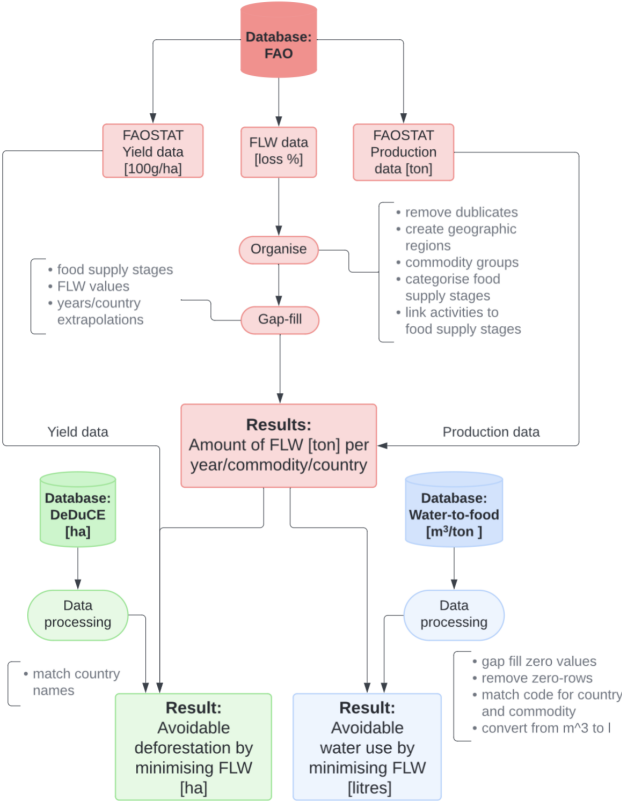


Figure 2: Flowchart of the data analysis. Red covers data from FAO-Food Loss and Waste and FAOSTAT, green covers deforestation data from DeDuCE, and blue covers water use data from Water-To-Food.

In order to link FLW to deforestation and water usage, further data handling was necessary. Datasets for production and yield, also from FAO, were retrieved. To convert the loss percentage into the amount of FLW in tonnes, the Production data was used. To convert FLW in tonnes into hectares land use, the Yield data was utilised. Additionally, data from the DeDuCE model was employed alongside this to correlate land use with the deforested area, in order for this project to determine how much deforestation could be avoided by reducing FLW. Similarly, the amount of water that could have been saved by reducing FLW was determined by using the amount of FLW in tonnes and data from Water-To-Food.

2.1 Databases

In this thesis, we have used the following databases and datasets; FAOSTAT, Food Loss and Waste, DeDuCE and Water-To-Food.

FAOSTAT, a database by FAO, provides extensive statistics about food, agriculture, fisheries, forestry, natural resources management and nutrition. The database covers over 245 different countries and includes data from as far back as 1961. For our thesis, we used FAOSTAT's "Crops and livestock products" dataset which includes data on primary crops, processed crops, primary livestock, processed livestock and live animals. Where we specifically used the data for "Crops, primary".[20]

The Food Loss and Waste database, again by FAO, is a collection of data encompassing both FLW for products, stages in the value chain, and geographical areas. The data has been gathered from various sources including scientific articles, academic publications, and other open databases such as FAOSTAT. The database has compiled information from over 700 different publications and reports, resulting in more than 29,000 data points. However, due to the data being sourced from multiple external sources, the homogeneity of FLW assessment of the database cannot be guaranteed, and FAO emphasises that public users are responsible for assessing its relevance, accuracy, and suitability for their purposes.[21]

Furthermore, we used a dataset created with *The Deforestation Driver and Carbon Emission* (DeDuCE) model, which represents an integrated approach, and combines remote sensing datasets with agricultural statistics to provide a detailed view of agriculture and forestry-induced deforestation. Simplified, the dataset includes deforestation attributed to specific commodities, by country and year while also associating carbon emissions resulting from agriculture and forestry at the national level. [22]

Lastly, Water-To-Food [23] is a database which contains data on water consumption for different commodities, by country and year. In this thesis the dataset called "Unit Water Footprint of Production" was used for crops. It provided information on the water used to produce one unit of primary crops at the producer stage, measured in cubic meters per tonne. The unit Water Footprint of a crop is the ratio between the water use for the crop and the crop yield and is measured in cubic metres per tonne. The water use for the crop is a function of the evapotranspiration of the crop. [24]

2.2 Processing FLW Data

The FLW data used from FAO covers FLW in percentage for each commodity by country, year and food supply stage. The loss percentage is stated as a share of the domestic production for a country, export and import is thus not accounted for. Therefore, the food exported to other countries and later lost or wasted, will still be attributed to the production country. When exploring the FLW data we noticed that there were several data points for the same commodity, country, year, activity and food supply stage, but with different loss percentages. To remove duplicates, a choice was made to use an average of the loss percentage of the duplicates. The data contains values of loss occurring in different activities. An activity is a specific action in a food supply stage. A problem was that sometimes a commodity, country and year had multiple data points in the same food supply stage, because there were different activities in this stage. For the later steps of the data processing, only one data point was desired for each food supply stage corresponding to one country, commodity and year. To deal with this problem we looked at all activities for each food supply stage and made an assumption on which were additive and which were not. If the activities were non-additive the maximum loss percentage of the activities were kept and then summed together with the rest of the activities until there was only one data point left for each commodity, year, country and food supply stage.

2.2.1 Supply Stages and Activities

Since the FLW dataset [21] had a lot of missing data points, gap-filling was necessary. In order to be able to gap-fill, some categorisations needed to be made. Firstly it was decided to aggregate the existing food supply stages into fewer stages in order to simplify the gap-filling process. This aggregation is illustrated in table 1. The FLW dataset from FAO had 19 categories of food supply stages, where each stage contained different activities in which food could be lost or wasted. For example the stage "Harvest", could contain

activities such as "Drying". In the data frame, there were some data points with missing food supply stage values. To ensure that all data points had a specified food supply stage, some assumptions were made. For example, in cases where activity was "Shelling, Threshing" the food supply stage would be labelled "Harvest", and the activity "Grading, Sorting" would be labelled as "Grading" in food supply stage. It was also found that 46 rows in the dataset had missing values for both the food supply stage and the activity. Filling them by guessing would introduce significant uncertainty. Therefore, with consideration to the small amount of rows (46 out of approximately 25,000), these data points were removed from the dataset. After this process, all rows in the dataset had a specified food supply stage which was necessary in order to continue working with the data. The original supply stages and our aggregation can be seen in table 1.

Agricultural Production	Post-harvest	Manufacturing	Distribution and Retail	Storage	Consumption
Pre-harvest Harvest Farm Collector	Post-harvest	Processing Packing Grading	Transport Export Trader Distribution Retail Wholesale Market	Storage	Households Food services

Table 1: *The 19 supply stages from FAO aggregated into the 6 broader stages used in this thesis.*

In the original dataset there were 19 food supply stages, as previously mentioned. When creating this aggregation, some assumptions had to be made since there was a lack of specific definitions of the terms used. Upon further examination of these food supply stages, it was noted that the stage "Stacking" only had one data point within our time frame (2001 to 2020) for Mexico, crop beans, 2016, with a percentage food loss of 2.1%. It seemed reasonable to exclude this single point in the future due to its low loss percentage and insignificant contribution to the overall analysis. In the dataset, one food supply stage was labelled as "Whole supply chain", which was disregarded as a separate food supply stage and separated from the others. The values from this stage were later used for the gap-filling.

As previously mentioned, some assumptions and oversights were made when assembling our 6 supply stages. Amongst others, "Storage" is a supply stage

in its own, but it is also important to note that storage exists partially in all supply stages. Thus, some small amounts of FLW in other stages may occur in storage, but will not be ascribed to the "Storage" stage. It is also possible that storage loss or waste could be accounted for twice as a result of this, thus creating duplicates for some data points. However, we consider these cases so small in comparison to the deviations which could have occurred as a result of aggregation into other stages. Thus, it was a trade-off with a basis in least amount of deviations. Furthermore, the stage "Post-harvest" is a broad stage containing everything from after harvest, up to consumption. Thus, the "Post-harvest" stage may also create duplicates, and will contribute to uncertainties of where in the food supply chain the FLW occurs. Similarly to the storage-case, the trade-offs for the "Post-harvest", in comparison to other stage aggregations, was made since other aggregations could create greater deviations, thus not creating the best final results. Below are explanations of the 6 stages used in this thesis, and the stages from the FAO data included in each of these.

Agricultural Production

All losses occurring during pre-harvest, harvest, collector and farming in general.

- Pre-harvest includes losses during the growth of the commodity such as drought, floods and vermin.
- Harvest encompasses losses due to outdated techniques and machines causing bruising and more severe damage.
- Losses connected to collectors include any handling resulting in bruising and more severe damage.
- Farming is a general term which may contain data on all the stages above, only comprising one value. Farming may also encompass other smaller stages apart from the bigger ones mentioned above.

Post-harvest

FAO defines "Post-harvest" losses as: "All quantity losses (food and non-food) along the Food Supply Chain for all utilisation (food, feed, seed, other) up to but excluding the retail to consumption level." [3] Note that the definition of "Post-harvest" for FLW may deviate from the definition for "Post-harvest" as a general term. Thus, the definition cited above is specified for "Post-harvest" connected to FLW.

Manufacturing

All losses which ensue in processing, grading and packaging of commodities.

- Processing incorporates losses due to inefficient processing techniques and machines, human errors, vermin and microorganic infestations.
- Grading carries active loss choices due to laws, market demands (including aesthetic appeal and freshness) and faulty grading, as well as bruising and more severe damage during handling.
- Packaging covers losses due to bruising and more severe damage of the commodities in the process of packaging, as well as faulty packaging in itself.

Distribution and Retail

All losses of commodities transpiring in transport, export, trading, distribution, retail, market and wholesale.

- Transport includes all losses occurring due to bruising and more severe damage as a cause of careless transportation, bad infrastructure, bad packaging harming the commodities during transport and bad cooling/ventilation etc. during transport.
- Export covers losses as a result of bad packaging, standards and regulations, changes in market demand, and infrastructural issues including, amongst others, transportation and storage availability.
- Trader incorporates losses as a cause of market and price fluctuations, freshness and aesthetic demands, quality laws, market accessibility and storage, handling and transportation.
- Distribution encompasses losses due to negligent transportation and packaging during distribution, poor inventory management, inadequate storage conditions and expiration dates forcing distributors, by law, to discard commodities.
- Retail carries losses due to careless transportation and packaging within the retail sector, legal mandates requiring the disposal of commodities due to expiration dates and inadequate inventory management and storage conditions.
- Market includes losses as a cause of consumer preferences, overstocking, expiration dates, human errors in handling, bad storage and displaying.
- Wholesale encompasses losses due to consumer preferences, overstock-

ing, expiration dates, human errors in handling, bad storage, packaging and labelling.

Storage

FLW in the food supply stage "Storage" occurs as a result of bad packaging, lack of cooling and ventilation in storage spaces, bad inventory management and handling procedures, lack of management, vermin and microorganic infestations, contamination and cross-contamination.

Consumption

All wastage of commodities in households and food services.

- Household encompasses everything wasted in the specific households, not including food services the household may utilise. Waste may occur due to consumer preferences, over consumption, expiration dates, human error in handling, bad packaging and storage, inefficient food preparation, leftover management, handling of perishable goods and lack of awareness.
- Food services covers waste in restaurants, caterers, institutional food services, etc. Waste in this stage happens due to overproduction and over-consumption, portion sizes, consumer preferences, spoilage, contamination and cross-contamination, food safety concerns, inefficient food preparation, expiration dates and plate waste.

2.2.2 Grouping Commodities and Countries

In order to be able to gap-fill food supply stages in the FLW data, there was a need of grouping the commodities into specific commodity groups. When categorising commodities into commodity groups, FAO's method description for the dataset was used [3]. It clearly states the commodity groups and which commodities each group contains. However, a problem arose as a few commodities in the dataset were not included in the method description. For example "peppermint" was missing, and thus, it was assigned the commodity group "stimulants" in accordance with categorisations used by other organisations. To filter the data and only get the primary (non-processed) crops, the production dataset from FAOSTAT including the desired commodities was used. The final grouping of commodities into commodity groups is listed in appendix A.

Furthermore, a grouping of countries into regions was made. Firstly the data was divided into continents and smaller sub-regions according to the

M49 standard [25]. M49 is a list of codes for countries and areas used by The United Nations Statistics Division. At first, the smaller sub-regions seemed more productive to study, but some of the sub-regions had very few data points which resulted in another aggregation. Since Asia held a lot of data points, it was decided a partition into two parts of Asia would be appropriate, especially since Asia is large and has varying climate. In our division "East Asia" includes the sub-regions "South-Eastern Asia" and "Eastern Asia", while "Rest of Asia" includes the sub-regions "Western Asia", "Southern Asia" and "Central Asia". For the remaining data, the already defined regions were used since many of the sub-regions did not individually hold enough points to be parted. The following regions were used: "Africa", "East Asia", "Europe", "North America", "Oceania", "Rest of Asia", "South America", and the countries included in each region can be seen in figure 3 as well as listed in appendix B. Note that Mexico is assigned to "South America" due it being included in the sub-region "Latin America and the Caribbean".

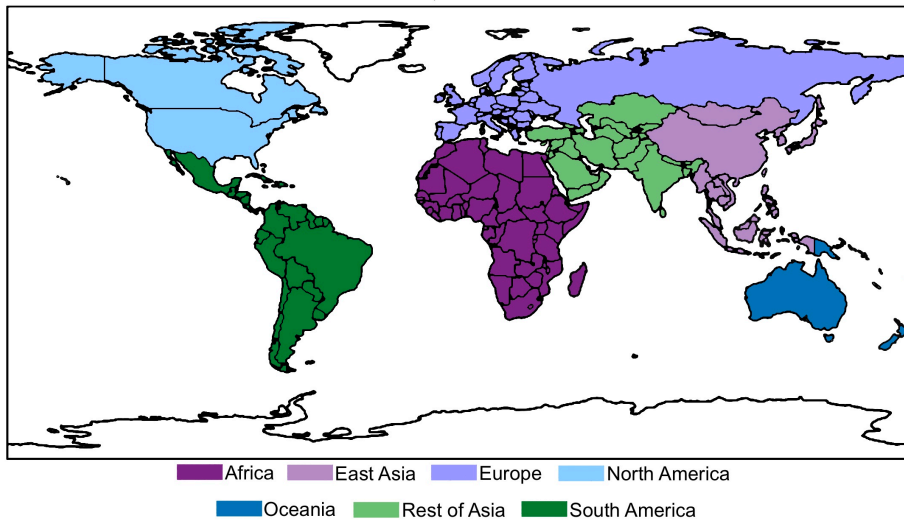


Figure 3: This image illustrates all the countries and regions included in the thesis after gap-filling. The gap-filling, including the extrapolation, will be explained in detail in section 2.2.3

2.2.3 Gap-Filling

As with most collected data, some data points in the FLW dataset were missing due to various methods of data collection as well as a lack of studies in specific country or commodity contexts. Therefore there was a need for extensive gap-filling. An example of how the gap-filling worked is illustrated in figure 4.

The goal of the gap-filling was to have a value for each country, commodity, year and stage, to later be able to sum up the whole supply chain for each point. The first step of gap-filling was to study a specific country, commodity and supply stage, and if a value was missing for a year, gap-filling was done with the average FLW percentage from all 20 years for the same country, commodity and stage. This filled all the gaps in all the stages that exist for the country, commodity and stage combination any time in the data.

There were still a few points missing after this step, and, thus, the next part was to gap-fill from the same commodity, country and year, with average values from the region. For values still missing, an average from the commodity group was used (same year, stage and region). After this, we used the commodity, year and stage with a world average. And finally, for values still missing, an average from the world with the same commodity group and stage was used. A few values were still missing after this, and a decision was made that if the value does not exist in the entire world, for any year in the commodity group and stage, then it is presumed to be insignificant and thereby set to zero.

After the previous step, a sum was created over the supply chains for each country, commodity and year to get a total value of all the loss in the whole supply chain. After summarising, we noticed a lot of the FLW percentages were very high, with some being above 100%. In order to handle the unreasonably high values of the loss percentage, we set maximum and minimum limits for each commodity group. To obtain these limits the data points for the "Whole supply chain" stage in the FLW-data were used. This is visualised in a box plot, see figure 5. The maximal limit were determined by the upper whisker limit and the minimum limit by the lower whisker limit. Values outside of these limits were set to the maximum if they were higher, or the minimum if they were lower. In addition to compiling the loss throughout the value chain, a share of the the loss in each of the 6 food supply stages were derived, to later be able to study the data further.

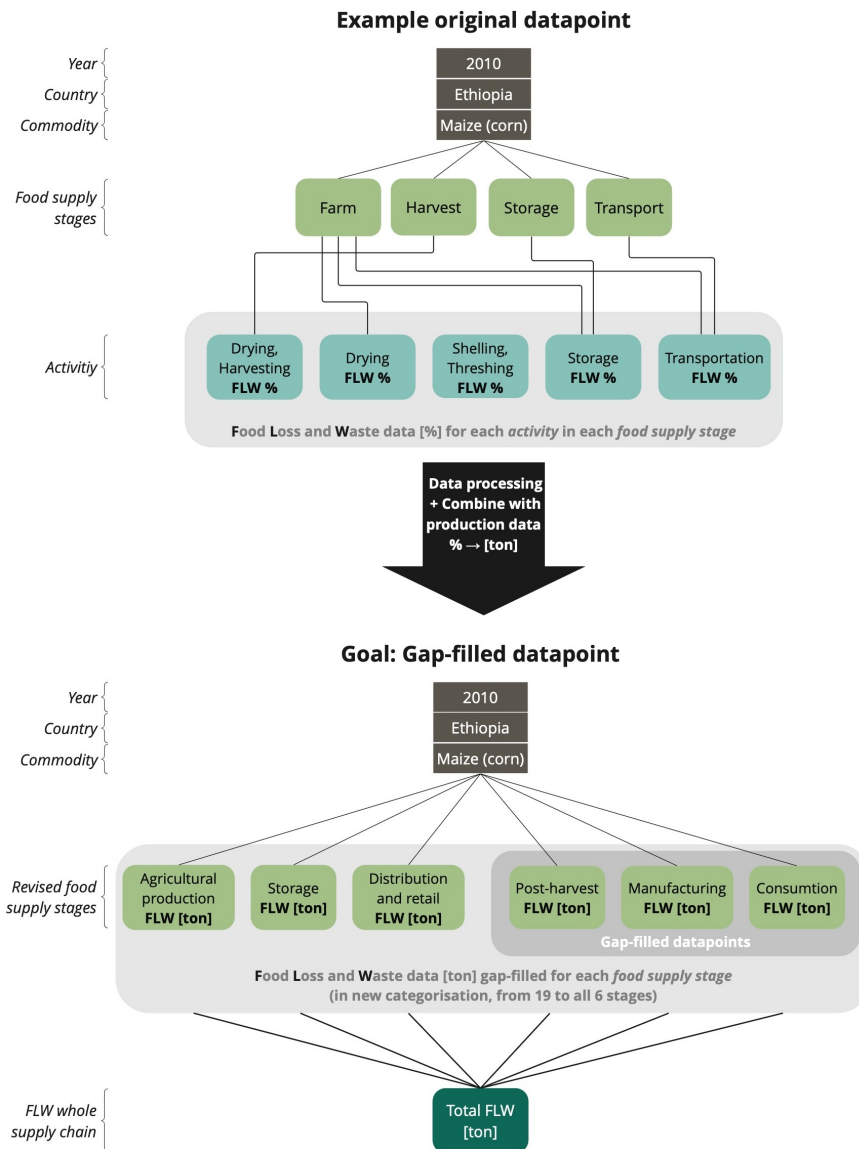


Figure 4: An example data point illustrating how the data is processed and how it looks in its final stage. The most important takeaway is the transformation from FLW given by activities in food supply stages, to FLW given directly from the food supply stage. With the production data from FAOSTAT the FLW values are translated from percentages to weight in tonne.

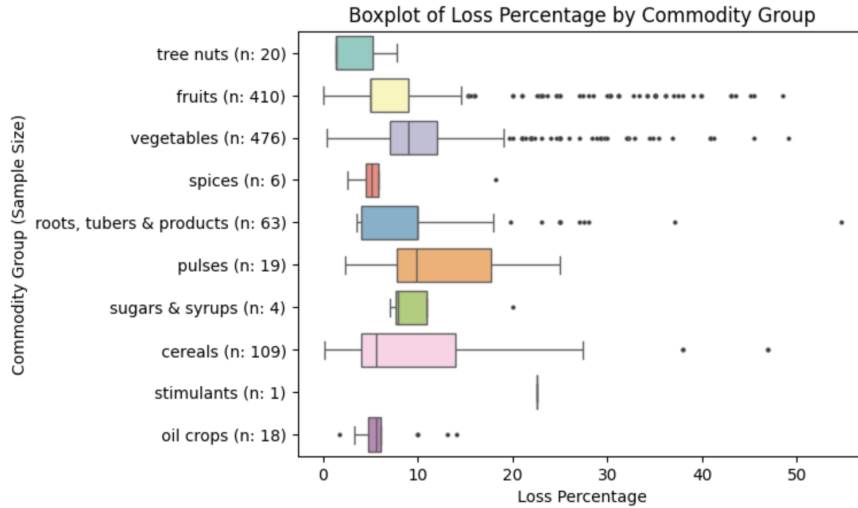


Figure 5: Box plot of the loss percentage for the "Whole supply chain", within each commodity group. The dots show the outliers, determined with the interquartile range method.

The first steps of gap-filling left us with data points for all the commodities and countries that were, to some extent, present in the dataset from the beginning. This left a number of countries and commodities out of the analysis, which led to deficiencies in our results. To take care of the missing data, a choice was made to use extrapolation in order to get FLW data for all the primary crop production existing in the production dataset. In order to reach this goal, we commenced by finding which data points were missing from the FLW data, but existed in the production data. If one country-commodity combination existed in the production data, but not in the FLW data, a FLW data point was created for this combination. To estimate the FLW for a specific commodity within a country, the average FLW percentage for the commodity group within the respective region was utilised. If a value within the region did not exist, a world average was used.

Region	Original FLW Dataset			Post Gap-Filling and Extrapolation		
	Data Points	Commodities	Countries	Data Points	Commodities	Countries
Africa	6563	41	44	36 933	127	50
Rest of Asia	821	70	17	28 000	128	27
Europe	249	27	10	38 311	112	37
South America	140	36	22	30 451	128	34
Oceania	44	12	3	5003	102	8
East Asia	147	22	11	15 614	121	16
North America	915	53	2	2759	91	2

Table 2: *FLW data before and after gap-filling for all regions.*

Commodity group	Original FLW Dataset			Post Gap-Filling and Extrapolation		
	Data Points	Commodities	Countries	Data Points	Commodities	Countries
Cereals	6631	11	79	18 955	15	167
Oil crops	96	9	12	15 539	21	168
Vegetables	924	23	45	42 606	27	172
Fruits	848	29	53	40 700	36	173
Roots and tubers	201	5	33	9695	7	172
Spices	20	2	3	5707	9	106
Pulses	99	9	21	11 801	11	161
Sugars and syrups	15	2	4	2910	3	131
Tree nuts	44	6	4	5670	9	110
Stimulants	1	1	1	3488	5	88

Table 3: *FLW data before and after gap-filling for all commodity groups.*

Tables 2 and 3 show the number of data points, as well as countries and commodities, covered before and after gap-filling and extrapolation. It is important to note that the data before gap-filling has separate data points for each of the 6 supply stages, while the data after only hold total values for the whole supply chain. As shown in the tables, the gap-filling significantly expands the dataset. This is done in order to be able to draw conclusions about the global FLW as well as finding total values of deforestation and water usage for the whole world. See appendix A for all commodities existing in each commodity group in the FLW data before data processing and after data processing (including gap-filling), and appendix B for all countries existing before and after data processing in each region.

During the extrapolation an issue emerged concerning the country Sudan. Since Sudan was split into South Sudan and Sudan 2011, it was necessary to handle the concerned data differently in the different datasets. We made the decision to handle Sudan as one country through the entire time period, despite it being divided for a small time period in one of the datasets. This choice was made to simplify further data analysis since the DeDuCE model also kept Sudan as one country.

2.3 Linking Food Loss and Waste to Deforestation

In order to find the amount of deforestation that could potentially have been avoided if there had been no FLW, the FLW percentage needed to be converted into weight (tonnes). Since FLW is stated as a percentage of the domestic production, these values are multiplied by values for the corresponding production in tonnes from FAOSTAT to achieve this.

The FAOSTAT Yield dataset describes how much area is needed to produce 100 grams of a commodity in a country. By dividing the FLW in tonnes with the values for yield, we attain the area used to produce food which is later lost or wasted. The DeDuCE dataset includes the deforestation attributed to different commodities. The deforested area is compared to the land area used for production of food which is later lost or wasted. If the land use is smaller than the total deforestation, the deforestation is set to the land use. However, if the land use is larger than the total deforestation, the amount of deforestation preventable through the reduction of FLW is set to the total deforestation. To clarify, all the deforestation could, in that case, have been avoided.

2.4 Linking Food Loss and Waste to Water Usage

To calculate the avoidable water usage by minimising FLW, the data for FLW in tonnes was used. This dataset, derived from merging the percentage loss from the FLW database with the FAOSTAT production dataset, was also employed in the deforestation analysis. While the water data used ISO2 country codes and FAO commodity codes, the data for FLW in tonnes used M49 country codes and CPC commodity codes. The codes in the water data were converted to the other codes with the help of two different datasets containing these codes, [25] and [26], enabling the merging of the two datasets.

Rows with all zeros across all years for a particular country and commodity were considered indicative of commodities not being grown in that country

and were therefore excluded, i.e. deleted. In cases where data existed for some years but not others for a given country-commodity pair, missing values were filled using the average of the available years for that pair. Following these adjustments, the water data was multiplied with the FLW data in tonnes for each country, commodity, and year combination to get the amount of water used for producing the food that is later lost or wasted (reported in litre).

3 Results

In this section we will present the FLW statistics across regions, commodity groups and supply stages and link it to avoidable deforestation and water usage by minimising FLW.

3.1 Food Loss and Waste

After processing and gap-filling the data from the FLW dataset, we find an annual FLW of approximately 1.87 billion tonnes between 2001 and 2022 (totalling 37.3 billion tonnes) (figure 6). To attain these numbers we summed all values for FLW seen in figure 6 and divided this sum by 20 (for the studied years). Since the FLW data is reported as percentages of domestic production, the FLW for one crop is assigned to the production country. This means that even if a large amount could be exported and wasted in another country, it still contributes to the FLW in the production country in our results.

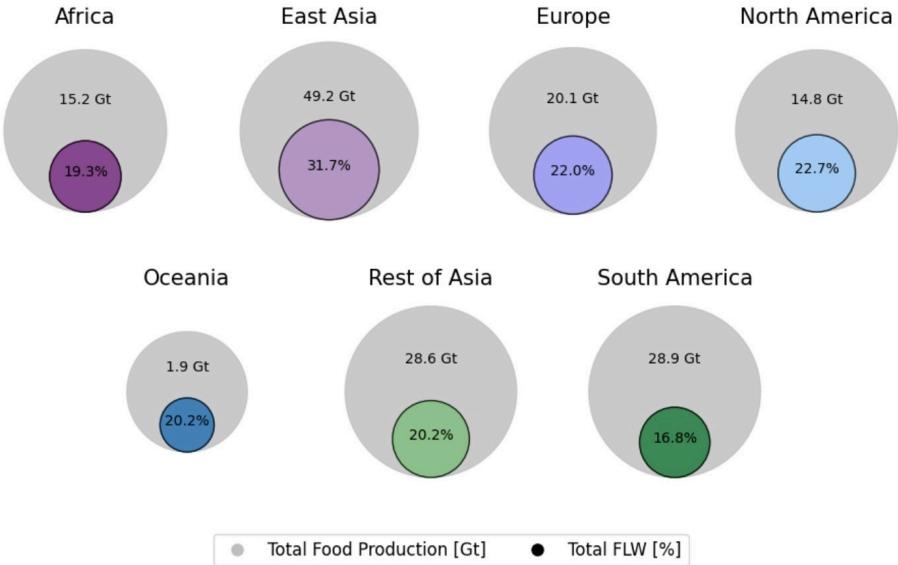


Figure 6: Total food production (Gt) over the years 2001-2020 and FLW (%) for each region.

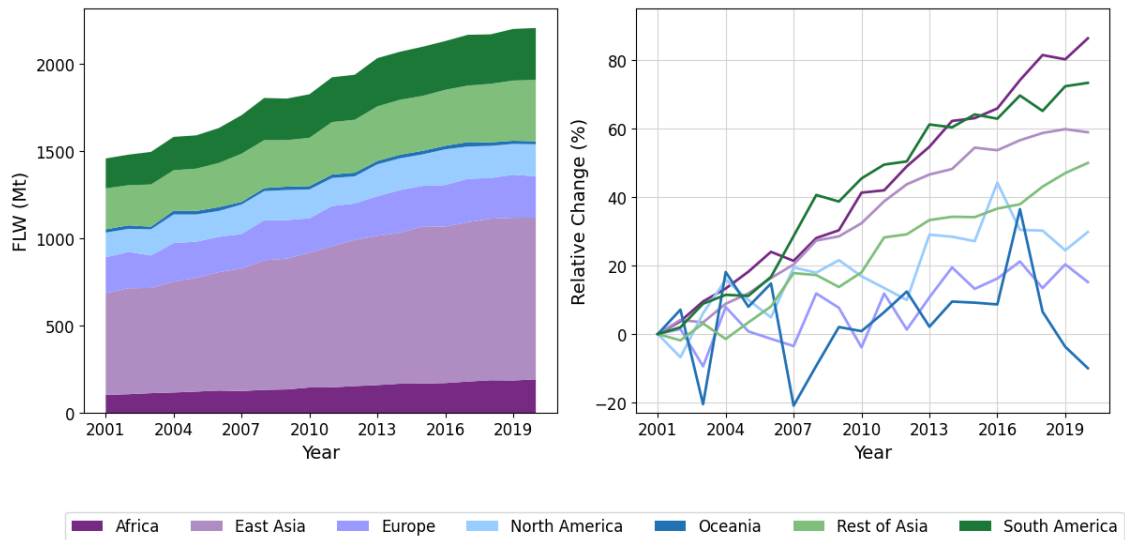


Figure 7: *FLW in weight (Mt) across regions over time (left) and relative change (%) from the starting point of 2001 (right).*

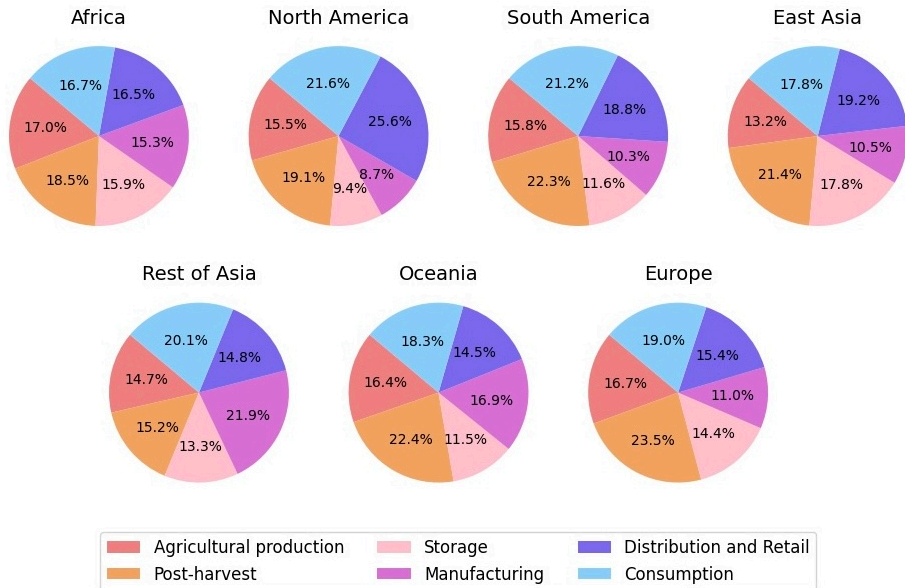


Figure 8: *Pie charts showing FLW weight shares (%) across supply stages for each region and all the years. For a box plot showing the distribution of data, see appendix C.*

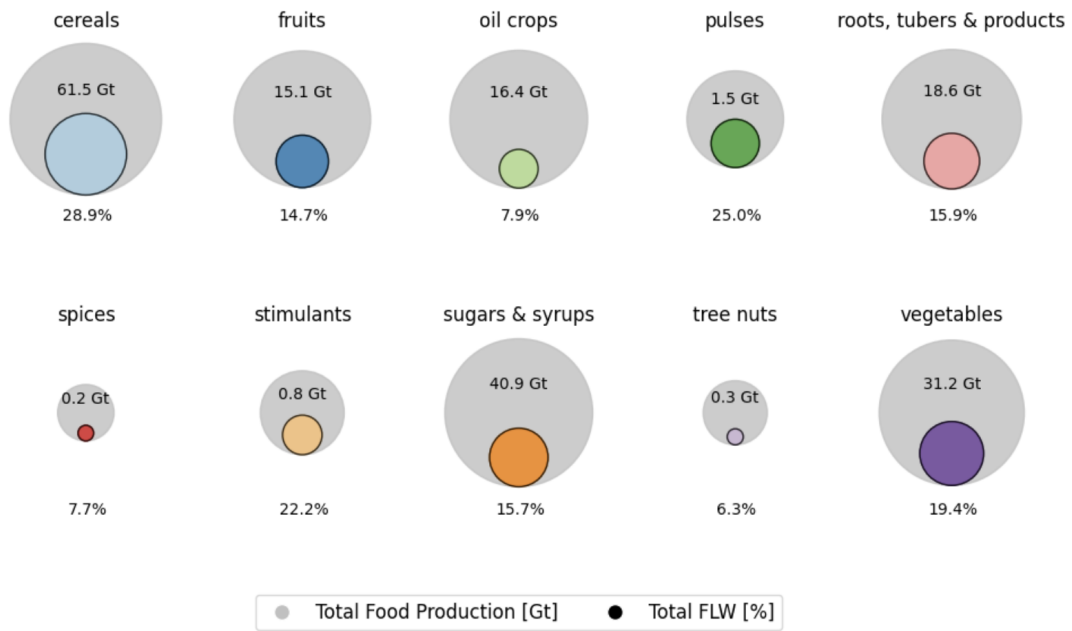


Figure 9: Total food production (Gt) over the years 2001-2020 and FLW (%) for each commodity group.

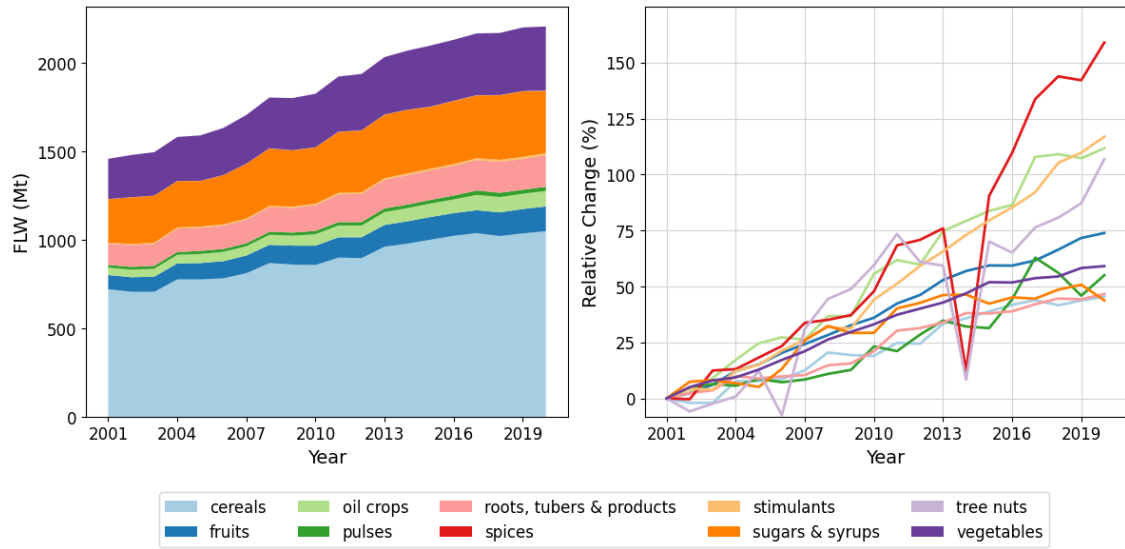


Figure 10: *FLW in weight (Mt) across commodity groups over time (left) and relative change (%) from the starting point of 2001 (right).*

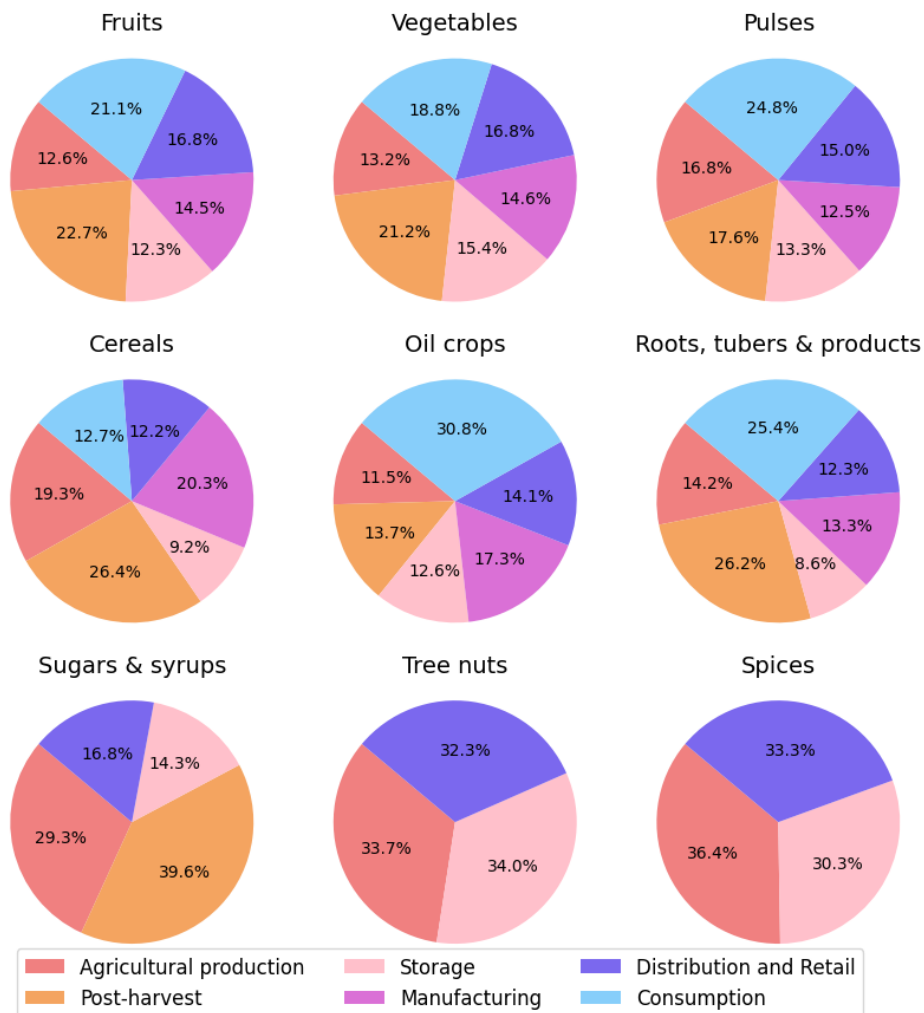


Figure 11: Pie charts showing FLW weight shares (%) across supply stages for each commodity group and all years. Note that some commodity groups lack specific stages due to insufficient data and that "stimulants" is not included since this commodity group only has data for "Whole supply chain". For a box plot showing the distribution of data, see appendix C.

The results show that Asia, i.e. our regions "East Asia" and "Rest of Asia", account for more than half (57.2%) of all FLW across all the years and commodity groups (figure 6). The remaining regions account for the other 42.8%, out of which "Oceania" has the smallest contribution, accounting for

only 1% (figure 6). Furthermore, figure 7 illustrates that the biggest region contributing to FLW apart from Asia is "South America".

It is also evident that the FLW has increased considerably in the regions "East Asia", "Rest of Asia" and "South America" over the studied years (figure 7). However, it is worth noting that even though the region "Africa" seems to have lower FLW than the three highest regions, it has the largest increase of about 90% over these 20 years (figure 7). Furthermore, Asia, as well as "South America" produce the most food, as evident in figure 6. Another aspect, illustrated in figure 8, is that of the up- and downstream distribution within the regions. The stages "Distribution and Retail" and "Consumption" comprise the downstream supply chain, while the remaining stages comprise the upstream supply chain. It is worth noting that the majority of the regions has a lot of FLW in the upstream supply chain while "North America", for example, has more FLW in the downstream supply chain than the other regions. We may also see that the "Manufacturing" stage is very large for "Rest of Asia" (figure 8).

For commodity groups, "cereals" alone account for almost half (47.7%) of all FLW across all the years and regions, followed by "sugars & syrups" and "vegetables" with 17.2% and 16.2% respectively (figure 9). These groups also hold large loss percentages. Moreover, it is worth noting that both "pulses" and "roots, tubers & products" have large FLW percentages while not necessarily holding very large productions (figure 9). The groups "spices", "tree nuts" and "stimulants" all have very small production in comparison to the other commodity groups (figure 9). The distribution amongst the commodity groups is also illustrated by figure 10. Regarding this figure, we can also see that "cereals", "sugars & syrups" and "vegetables" are not the commodity groups which have increased the most during the studied years, albeit the increase has still been around 50% (figure 10). The commodity group "spices" is the one with the largest increase in percentages with more than 150% (figure 10). However, this commodity group has a very small production, and thus not much FLW in weight compared to the other commodity groups (figure 9). This means that a big increase in percent does not necessarily give a big increase in tonnes.

Figure 11 visualises where in the food supply chain these losses occur. For example, the group "cereals" is primarily lost in the upstream supply chain while the FLW for "oil crops" occurs at larger scale in the downstream supply chain (figure 11). Regarding all the commodity groups, it is evident that a majority of the FLW occurs in the upstream supply chain.

3.2 Deforestation

We computed an annual average for deforestation and land use, meaning cultivation of arable land, that could be preventable through the reduction of FLW. These averages amount to 2.32 million hectares and 319 million hectares, respectively. The deforestation area corresponds to approximately the size of Djibouti, whereas the land use area is a bit larger than the size of India [27]. Note that these areas are annual averages and that the land usage for the studied crops is much larger than the corresponding deforestation. The numbers above were attained by summarising all values for preventable deforestation and land use separately over the 20 years and dividing these sums by 20 to attain an average per year.

Our study estimates that 93% of the deforestation due to the production of the examined crops during this period could have been prevented with a reduction of FLW. This number was attained by dividing the sum over the studied years of the total preventable deforestation of the studied crops, by the total deforestation due to production of these crops (without any connection to FLW). Similarly, through FLW reduction of the crops in this study, we could have avoided up to 38% of all deforestation for general agriculture (not only the studied crops) and forestry. This percentage is derived by dividing the total avoidable deforestation by minimising FLW for our examined crops by the total deforestation for all entries registered in the DeDuCE model, over the period from 2001 to 2020.

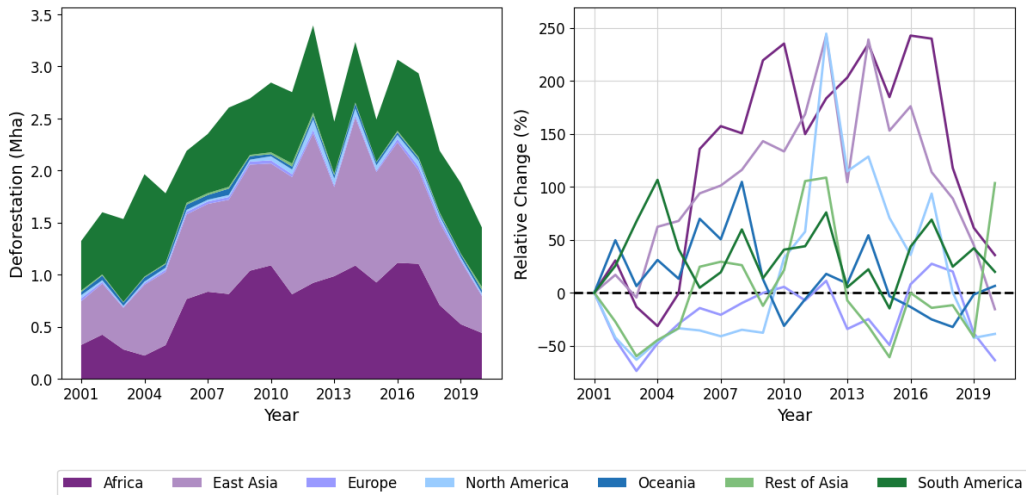


Figure 12: *Avoidable deforestation (Mha) by minimising FLW over time (left) and relative change (%) from the starting point of 2001 (right) for each region.*

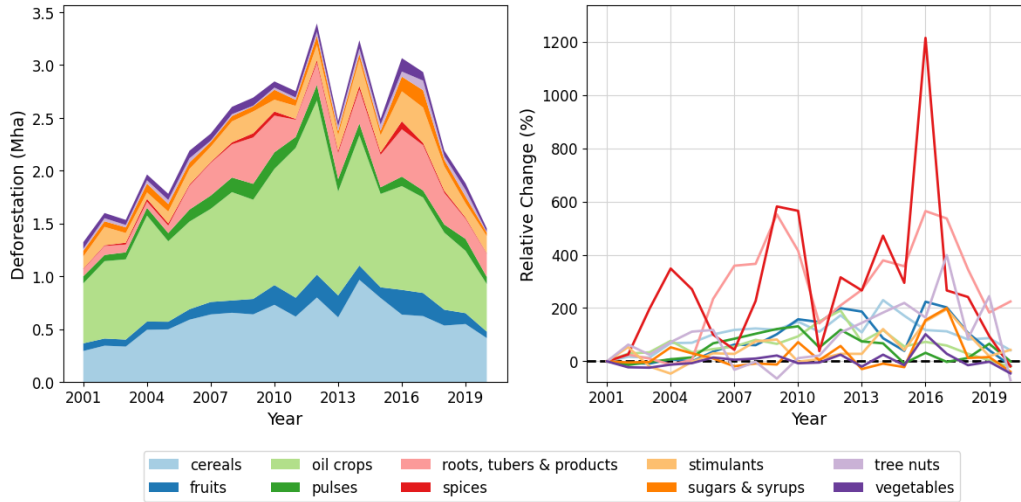


Figure 13: Avoidable deforestation (Mha) by minimising FLW over time (left) and relative change (%) from the starting point of 2001 (right) for each commodity group.

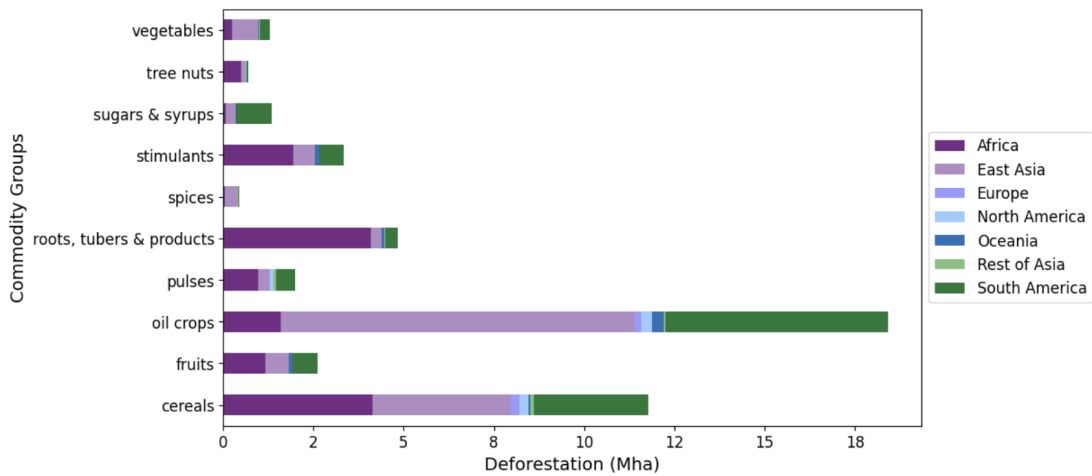


Figure 14: A horizontal bar plot illustrating the aggregated avoidable deforestation by minimising FLW (Mha) for each commodity group. Each bar also displays the distribution of the respective regions.

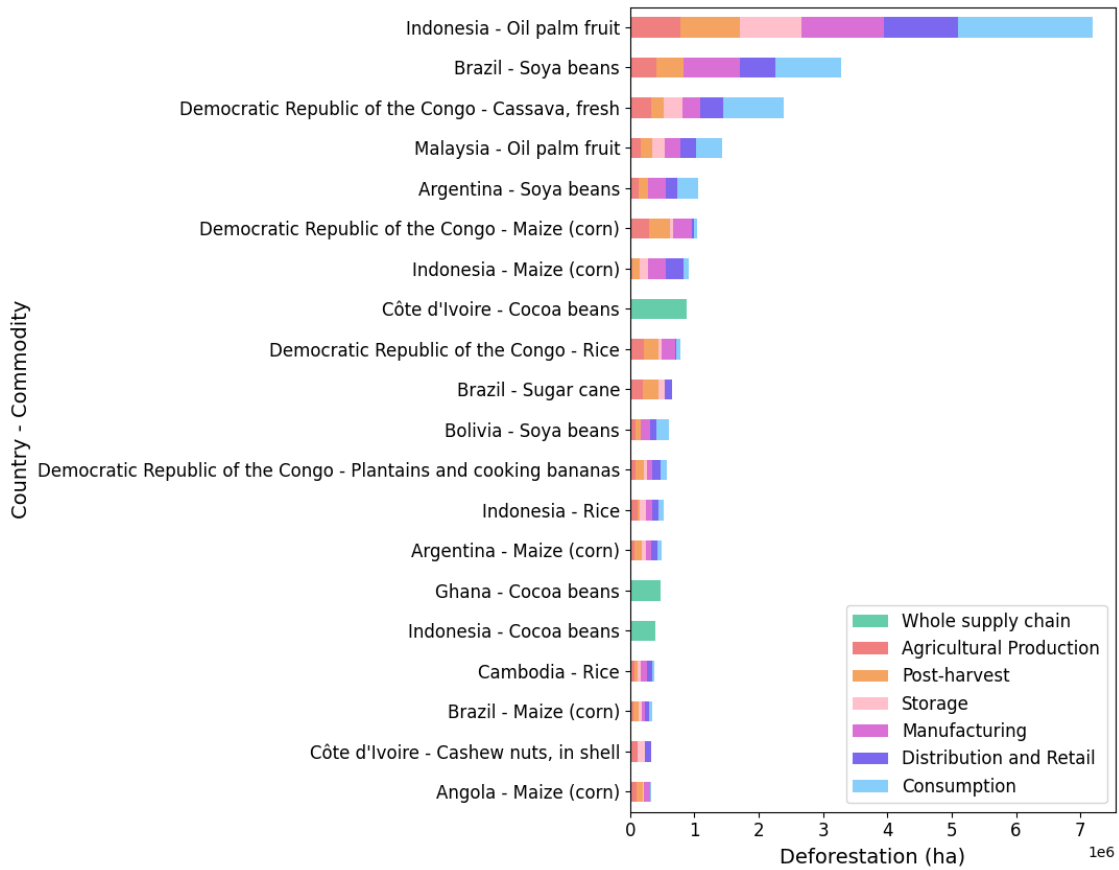


Figure 15: A horizontal bar plot illustrating the aggregated avoidable deforestation by minimising FLW (Mha) for the top 20 Country-Commodity pairs. Each bar also displays the distribution of the respective supply stages. Note that the deforestation in each supply stage is only a percentage of the food lost or wasted in this stage. For example, there is no deforestation happening in the "Consumption" stage, but the food lost or wasted there can be attributed to a share of deforestation.

The results for deforestation show that the regions with the largest potential reduction in deforestation through decreased FLW are "East Asia", "Africa" and "South America" as illustrated in figure 12. The relative changes for "East Asia" and "Africa" over the studied years reached above 200% at their peaks, whereas "South America" and the majority of the other regions had smaller changes. Note that "North America" had a peak at close to 250% around 2012 while having negative changes at other times (figure 12). Observing the same figure, it is also clear that there is a declining trend of

preventable deforestation.

Our results further show that the largest amount of deforestation preventable through reduction of FLW are in the commodity groups "oil crops" and "cereals", followed by "roots, tubers & products" at a much lower number, as shown in figure 13. In spite of "oil crops" and "cereals" having the largest contribution to the preventable deforestation, they do not have particularly large relative changes over the studied years. The highest relative changes are attained in the groups "spices", once at more than 1200%, and "roots, tubers & products" (figure 13). Where "roots, tubers & products" have the third largest contribution to avoidable deforestation by minimising FLW, thus meaning that their big relative change in percentage equals a great increase measured in hectares. The group "spices", on the other hand, does not have a big contribution in general meaning that the increase in hectares is not as large in comparison to "roots, tubers & products" (figure 13).

The results summarised above are further illustrated in figure 14. It is noticeable that "cereals" and "oil crops" are the two biggest commodity groups where both "East Asia" and "South America" are large contributors. Concerning "Africa", the two grandest commodity groups are instead "cereals" and "roots, tubers & products", followed by "stimulants".

This is further depicted by figure 15 where all the top 20 commodities are from countries within "East Asia", "Africa" and "South America". Furthermore, the commodity groups "oil crops", "cereals" and "roots, tubers & products" comprise 14 out of the 20 pairs depicted in this figure. These three groups include a grand majority of the staple crops. The top five pairs comprise four commodities from the group "oil crops", and one from "roots, tubers & products". The grandest country-commodity pair contributing to deforestation preventable through the reduction of FLW is "Oil palm fruit" in Indonesia. This pair is over twice the size of the second largest contributor, "Soya beans" in Brazil. Furthermore, it is worth noting that the stages depicted in figure 15 are relatively equally distributed. However, we may see a larger part occurring in the "Consumption" stage for the top five country-commodity pairs, than in the others.

3.3 Water Loss

Based on our data, we have concluded that the annual water loss which could be prevented through reduction of FLW for the examined crops is approximately 1 467 teralitres per year (figure 16). To attain this number, we summed the values seen in figure 16 and divided this sum by the number

of studied years. Note that the water data only spans 15 years (2001 to 2016). Moreover, we calculated that this annual average translates to circa 21% of the total water used for producing the studied crops. This number was achieved by dividing the annual avoidable water usage by reduction of FLW for the examined crops, by the annual average water usage (without connection to FLW) for these crops.

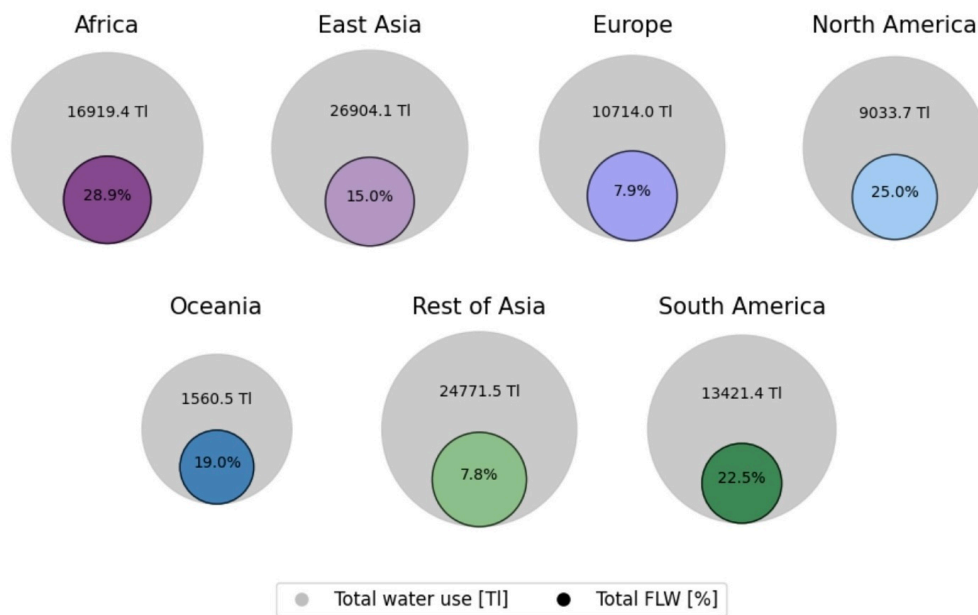


Figure 16: The total water usage (TI) over the years 2001-2016 and water loss (%) for each region.

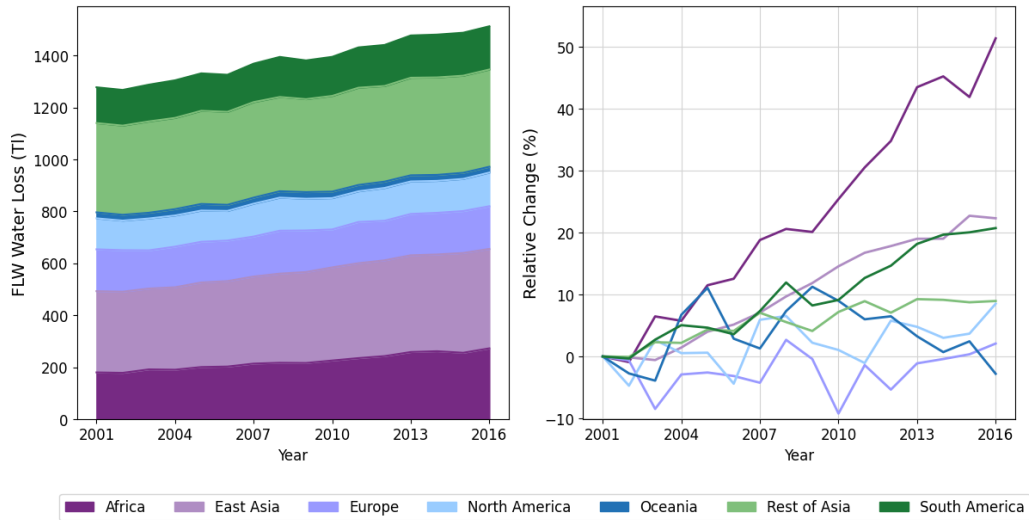


Figure 17: An area plot presenting the water loss (TI) over time (left) and relative change (%) plot from the starting point of 2001 (right) for each region.

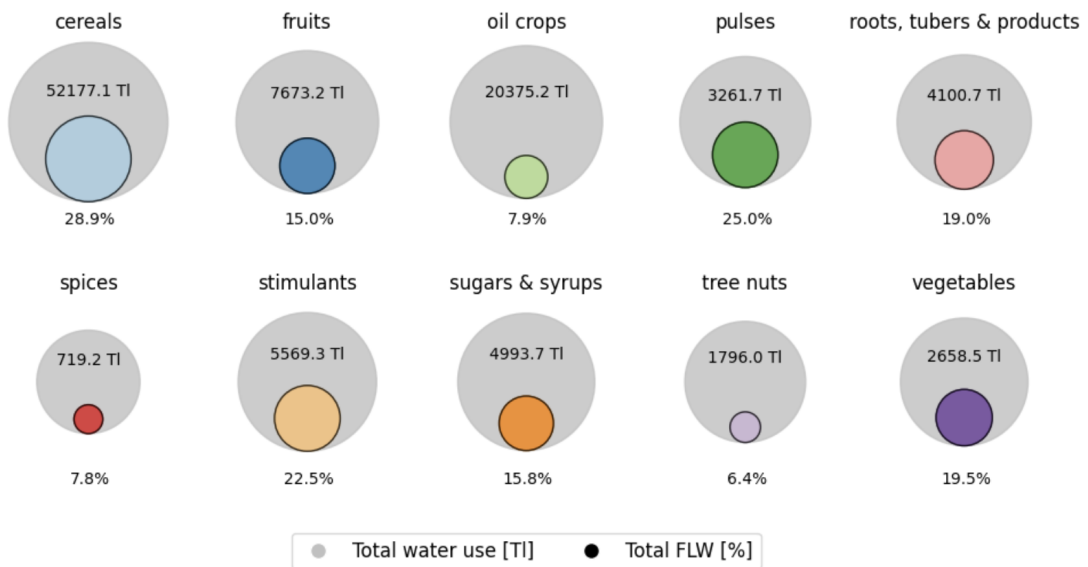


Figure 18: The total water usage (TI) over the years 2001-2016 and the water loss (%) for each commodity group.

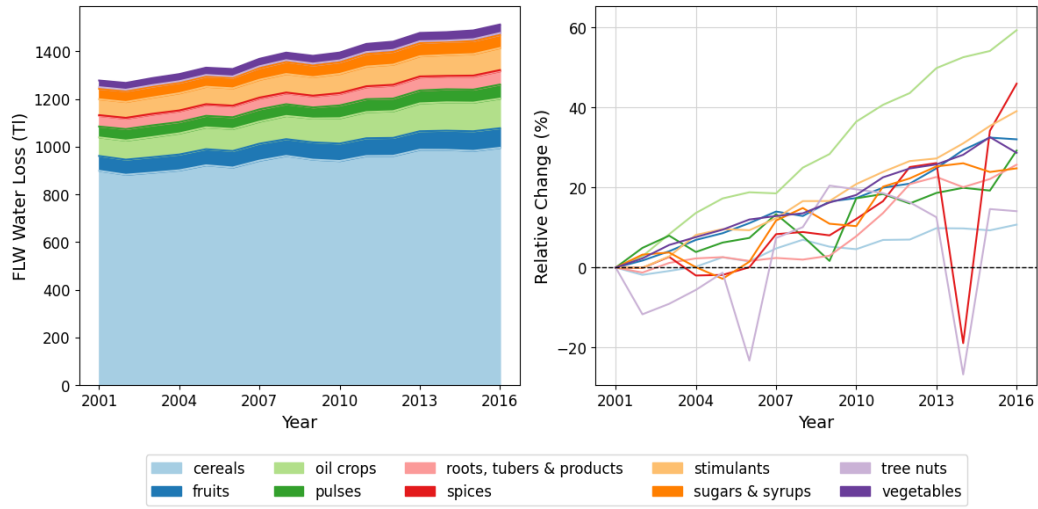


Figure 19: An area plot presenting the water loss (TL) over time (left) and relative change (%) plot from the starting point of 2001 (right) for each commodity group.

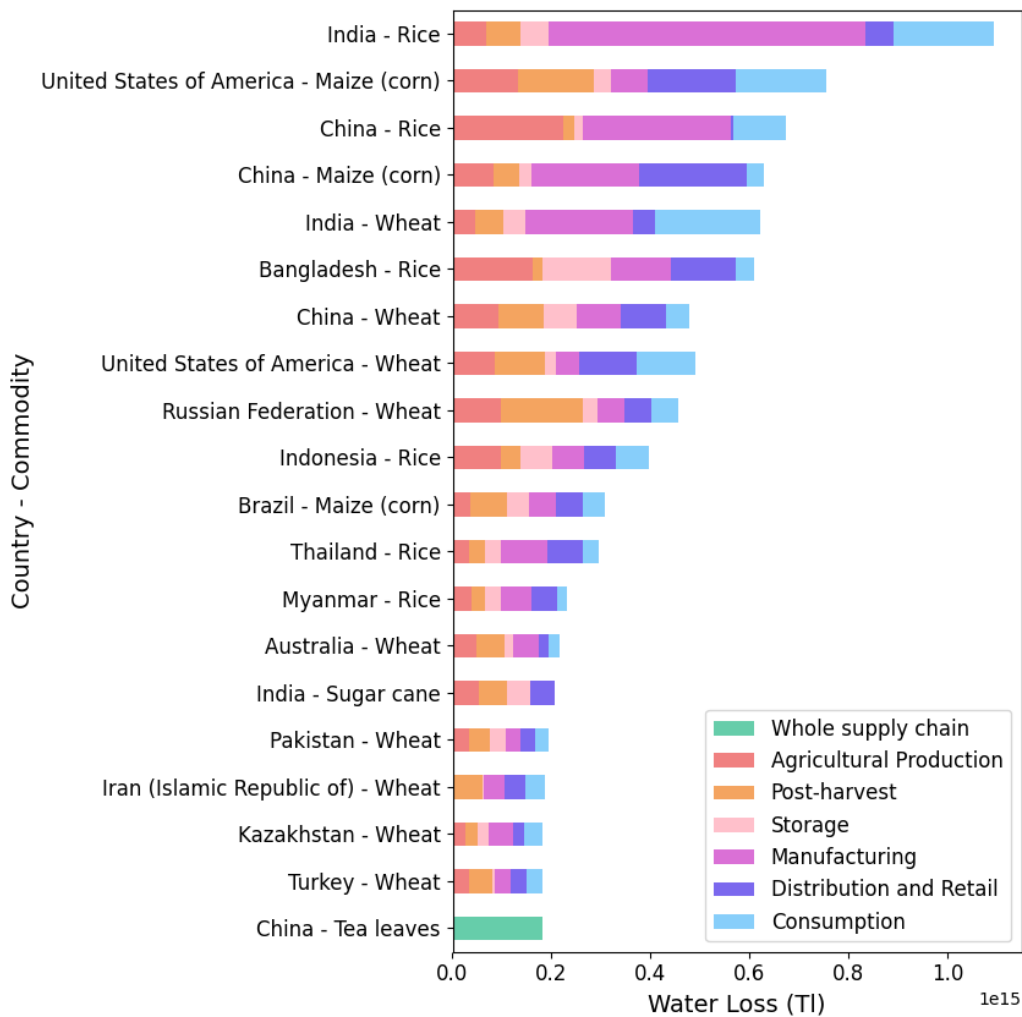


Figure 20: A horizontal bar plot illustrating the aggregated water usage to FLW (TL) for the top 20 Country-Commodity pairs. Each bar also displays the distribution of the supply stages. It is important to recognise that the water loss in each stage represents only the percentage of the food lost or wasted in that particular stage. While there is no direct water loss occurring in the "Manufacturing" stage (in the data used), the food lost or wasted in this stage can still be associated with a share of water loss occurring in the cultivation.

The results for water loss show that Asia, i.e. our regions "East Asia" and "Rest of Asia", account for more than half (51.2%) of all preventable water

loss through reduction of FLW (figure 16). The rest of the regions account for 48.8%, out of which "Africa" accounts for 16% and "Oceania", which has the smallest percentage, accounts for only 1.7% (figure 16). Moreover, figure 17 also illustrates that the grandest regions connected to water loss are foremost Asia and "Africa". The same figure also illustrates the significant increase in water loss for "Africa". We can also see that "East Asia" and "South America" have a larger increase than the other regions, apart from "Africa", increasing steady throughout the period (figure 17). If we connect this to the numbers and shares shown in figure 16 we can further understand this in regards to total water use and preventable water loss through reduction of FLW. It is clear that "East Asia", "Rest of Asia" and "Africa" all have a large total water usage, however, they differ quite a lot when regarding the respective shares. "Africa" has the largest share at 28.9%, whereas Asia has much lower shares. Note that "North America" and "South America" have large shares, thus making them regions with greater water loss in comparison to total usage (figure 16). "Oceania" also has a large total share, while simultaneously having the significantly smallest total water usage (figure 16).

Regarding the commodity groups, figure 18 shows that "cereals" has the notably largest total water usage and also contributes to 68% of the total preventable water loss through reduction of FLW. After "cereals", the largest contributors are "pulses" and "stimulants". However, these groups do not carry a lot of total water usage in comparison to others (figure 18). The commodity group "oil crops", on the other hand, has the second largest total water usage in teralitres, while simultaneously having a quite small FLW share. The distribution between the commodity groups is further illustrated in figure 19. It is also apparent that "oil crops" has the largest relative increase of water loss over the studied years, where "cereals" has the lowest relative increase, apart from "spices" and "tree nuts" which have fluctuated to a great extent (figure 19).

Finally, figure 20 shows that commodities from "cereals" dominate the top 20, carrying all spots but two. Note that commodities within "cereals" presented in this figure are all staple crops. Similarly, all but five countries in the top 20 pairs belong to Asia, thus further strengthening the results showing the relation between the largest contributor regions and commodity groups. When regarding figure 20, it is also clear that a lot of the water usage preventable through the reduction of FLW may be connected to the food supply stage "Manufacturing", but also the upstream supply chain in general.

4 Discussion

In this section, we will discuss the potential of reducing FLW and connected opportunities for reducing the burden on natural resources. We will commence with a discussion of possible FLW reductions by regions and commodity groups, along with the complexities of a reduction in reality. After this, we will discuss the connection between deforestation and water, while simultaneously discussing opportunities for reducing the stress on the Earth system through a lessening of the burden on these natural resources.

4.1 Potential for Reducing Food Loss and Waste

In this thesis, the focus is on the environmental impacts of deforestation and water loss, but FLW additionally leads to greenhouse gas emissions, economic resources being used unnecessarily, and endangerment of global food security[2]. However, when investigating possibilities to reduce FLW, it is important to consider the matter of food security. To achieve food security, the food system needs to be able to handle unpredictable events such as bad harvests due to weather, pest infestation or other climate shocks [5]. This means that some amount of food will need to be wasted to ensure food security. However, our intention is not to undermine the significance or feasibility of large reductions in FLW; rather, we acknowledge that aiming for zero FLW might not be justifiable.

Another aspect of FLW reduction which further complicates matters is societal aspects. For one, the cost and benefit distribution for the private agents, such as exporters and retailers, and for the end consumer will differ. Depending on where the measure is implemented in the supply chain, the price change will affect different agents somewhat depending on whether they are upstream or downstream relative to the intervention [5]. Measures might be expensive for one agent while simultaneously being profitable for another. An intervention can also have varying efficiency in urban versus rural areas, as well as different income groups [28]. These effects need to be studied further to implement measures well.

Our FLW results displayed several interesting findings concerning specific points where FLW is particularly large. It was clear that "East Asia" had the largest amount of FLW (figure 6), spiking interest in how this region could be a key factor in reducing FLW globally. Since "East Asia" has the largest production, it is reasonable for this region to have a large amount of FLW in tonnes. However, the loss percentage is also significantly higher than in the other regions. "East Asia" has relatively uniform losses in all stages.

Therefore, we want to highlight that in order to find appropriate solutions to reduce FLW, other factors need to be taken into consideration. Such a factor could be systemic effects of implementations in different stages. When considering systemic effects, we want to minimise the negative consequences of the implementation while simultaneously gaining the most benefits from the investment.

The trends in relative change of FLW show an increase in most regions, especially notable in "Africa" and "South America" (figure 7). This indicates that these regions might become problematic regarding FLW shortly. The reason for this increase could be the growing food production and the growing trade of these agricultural commodities to fulfil the food demand of a increasing and more affluent population. However, the loss percentage remains relatively constant. The increasing amount of FLW is nonetheless still a problem, since it puts higher pressure on the environment and Earth's resources.

4.2 Opportunities for Reducing Burden on Natural Resources by Minimising FLW

The connection between food production and natural resources is not only strong but also complex. When discussing what a reduction in FLW could mean for alleviate stress on natural resources it is important to understand that this stress only will be reduced if a decrease in FLW leads to a decrease in food production. Alternatively, maintaining current production levels and redistributing surplus could mitigate hunger, thus relieving the stress on some environmental impacts. In the following discussion, the feasibility of reducing this burden on natural resources by reducing FLW is based on the assumption that production will also be decreased.

Our results indicate that a significant percentage of deforestation is being unnecessarily executed because of FLW. Specifically, a decrease of 93% of deforestation due to the production of the studied crops could be possible if all FLW was reduced. Essentially, this means that there is almost no need for deforestation to produce these crops at all. Furthermore, water scarcity is an ever-growing issue, thus making the need for reduced stress crucial to achieve the sustainable development goals phrased by the UN [29]. Considering the result depicting a water loss of 21% out of the total water usage for primary crops, we see that a reduction of FLW could have a significantly positive impact on the Earth system through a reduction of deforestation and water losses.

Apart from FLW being indirectly connected to deforestation and water losses, there exist interesting connections between deforestation and water as is. The deforestation causes changes in weather patterns, which includes where precipitation occurs. Deforestation also has a great effect on the amount of precipitation occurring since, on average, half of the terrestrial precipitation (precipitation occurring over land) comes from green water sources such as vegetation and soil, with rainforests being a big contributor. An example of the connection between deforestation and weather patterns is the deforestation happening in the Congo Basin, containing the Congo rainforest. The deforestation here causes less precipitation in neighbouring countries and even over to the Amazon rainforest across the Atlantic Ocean. Furthermore, the land deforested is then used for agriculture as this was the direct or indirect intent of the deforestation. The cultivation of these deforested lands demands irrigation, which in turn means that blue water reservoirs such as rivers, lakes and underground aquifers are utilised. These sources contain the little fresh water that is accessible and is finite or sensitive to being drained. Thus, when using the water in these sources for irrigation of the arable lands attained by deforestation, while simultaneously experiencing less precipitation, these sources are not refilled at the same rate as they are drained. This causes issues for humans with water scarcity and lack of drinkable water, as well as an increase in food loss. Without irrigation, these arable lands will lose their fertility and crops will be lost as a consequence of the abating nutriment, thus aggregating the already existing issues of a growing global population and its growing food demand. [30]

When regarding our results, a substantial portion of deforestation occurs in the regions "South America", "East Asia" and "Africa". Within these regions, almost all of the world's rainforests exist, including the Amazon, the Congo rainforest, and the Southeast Asian rainforest. These rainforests help regulate the water and carbon cycle, as well as have a rich biodiversity, guarding the balance of the global climate [31]. Therefore, reducing FLW could have a significant positive effect on biodiversity. In this thesis, we focus on deforestation in terms of area. When deciding where interventions are most urgent, factors such as the forests biodiversity and ability to bind carbon dioxide and regulate the water cycle are also of great importance. Despite rainforests being very important for the Earth system, they are still the most exploited forests. In fact, 95% of all forests being deforested are tropical ones [32]. Reconnecting to our results, "East Asia", for instance, has a high FLW as well as being a region where a lot of deforestation occurs, indicating a large potential of reduction in FLW and deforestation simultaneously. Furthermore, the regions with the most avoidable deforestation,

”South America”, ”East Asia” and ”Africa”, are also regions where water scarcity is an issue [33]. Apart from the connection between deforestation and the water cycle, these are three regions with a lot of water usage as presented in our results.

Something worth noticing in the results is the decline in the latter four years of the deforestation avoidable through reduction of FLW. It is important to clarify that neither the total food production nor the FLW itself are causing this decline since they are both still increasing, as seen in our results. An example of this is that one tonne of ”oil palm fruit” from Indonesia had a lower contribution to deforestation in 2019 than in 2017. There might exist several causes for the drop in deforestation. For example, it is likely that the production of crops might have an indirect effect on deforestation due to the expansion of crop production over pastures, thus creating the need for deforestation to expand the pastures [34]. This effect would not be visible in our results due to our system boundaries excluding commodities other than crops, and the method of DeDuCE attributing deforestation (since it primarily captures direct driver of deforestation). Another reason for the decrease in deforestation might be that the previous high deforestation rate cleared a large amount of land that could be reused in later years. It is also possible that the implementation of policies and regulations on deforestation reduction has had a part in the increase in the later years.

Our results show that ”oil crops” is the commodity group with the most avoidable deforestation by minimising FLW, followed by ”cereals”. It is interesting to note that both the total production and total FLW of ”oil crops” are relatively low in comparison to other commodity groups. However, considering that ”oil crops” have such a large preventable deforestation, it is a commodity group worth studying since even a small reduction of FLW could have a large effect on the reduction of deforestation. When looking at the total water usage, ”oil crops” is also the commodity group with the second most usage, albeit a small water loss share. However, considering the steep increase in water loss, it is necessary to study this commodity group further in regards to its connection to avoidable water loss.

”Cereals” is the commodity group with the second most deforestation preventable through the reduction of FLW. Incorporating the values for FLW it makes sense that this is the case since the amount of ”cereals” lost or wasted is high. ”Cereals” is moreover the commodity group with the highest total water usage and water loss. It is also visible in the top 20 country-commodity pairs for deforestation preventable through reduction of FLW, that ”cereals” including e.g. rice and maize are high contributors to deforestation. This

can also be connected to the top 20 country-commodity pairs for water usage preventable through the reduction of FLW, where "cereals" dominate as well. One of the recent regulations, the EU Regulation on Deforestation-free Products (EUDR), is an attempt to reduce deforestation and aims to hinder the import and export of products contributing to deforestation in and out of the EU. This regulation comes into force in 2025 [35] and does not incorporate "cereals". This is quite pertinent as the EU imports one-third of the rice they consume [36]. Although rice and maize are staple crops and important for food security, our results show that reducing FLW of these commodities can be of importance to reduce the global deforestation.

Furthermore, when regarding the top 20 country-commodity pairs, we gain further information on where the most deforestation and water usage preventable through the reduction of FLW occur, not only by countries and commodities but by stages in the food supply chain. This gives us good starting points for further research to reduce FLW, aiding the reduction of deforestation and water usage.

4.3 Solutions to Reduce FLW at Different Supply Stages

From our results it is evident that a significant portion of FLW occurs upstream for the majority of regions, particularly noticeable in "Rest of Asia" at the "Manufacturing" stage. This implies that interventions at these stages could yield significant changes where technical solutions and investments could potentially target the problems with FLW. However, it is essential to consider that this effort can be financially burdensome for individual producers or manufacturers [5]. This means that the costs of investing and implementing technical solutions might be higher than the income from the food saved by these investments [37]. This gives no incentive for the different supply chain partners to make these changes, and to handle this there is a need to find a way to make these investments cost-effective, which might be done on a more global scale. Apart from the absence of mechanisation, good handling and storage facilities, the lack of information is also an issue. For instance, it is not sufficient to only make technologies affordable for smaller farmers, providing accessible information and training about these technologies is also crucial to reduce food loss [37].

In "North America", on the other hand, focusing on reducing FLW in the downstream supply chain can be more effective since a larger part of FLW, in comparison to the other regions, occurs in these stages. This requires alternative initiatives such as policies and campaigns aimed at increasing awareness about FLW [2]. For instance, in the USA the United States En-

Environmental Protection Agency (EPA) set a reduction goal in 2015 to halve their FLW by 2030. To succeed with this goal they have collaborations with the United States Department of Agriculture (USDA) and the Food and Drug Administration (FDA), as well as individual organisations, businesses and communities [38]. Similarly, the EU has set targets that each member state ought to achieve by 2030. These targets are: (1) to reduce food loss by 10% in manufacturing and processing; and (2) to reduce food waste by 30% per capita, at retail and consumption levels. How the countries are to achieve these goals is up to the individual nations [39].

This illustrates that different countries will need different solutions to reduce FLW efficiently. Low-income countries often have losses due to a lack of financial resources limiting harvesting and processing technologies. Lacking access to markets can also cause food to spoil before it can be sold. Higher-income countries, on the other hand, generally have more FLW in the downstream supply chain [19]. There is an existing pattern amongst consumers where higher income and more knowledge of health trends can lead to more food waste in the home. That, as well as lower food prices which reduce incentives to utilise all the bought food [40]. Therefore, there exists no global solution with a universal implementation ability. However, since the food system is a global system, international collaboration is still important to tackle FLW. Deepening our understanding of FLW at individual supply stages across various geographical and commodity settings is crucial for effectively reducing FLW.

Regarding commodity groups studied in this thesis, the result showed that "cereals" is the biggest issue when discussing pure FLW. Since "cereals" contains many staple commodities, it is important to keep a high production of these to ensure food security. However, since the share being lost or wasted is the largest of the commodity groups, there is potential to reduce a lot of FLW in this group. For "cereals", a grand majority of the FLW occurs in the upstream stages, where "Post-harvest" is the largest contributor. Besides, infrastructure development and proper planning are crucial to mitigate the impacts of climate change, such as droughts, pest and diseases to minimise FLW losses in the upstream supply chain. The downstream stages for "cereals" have relatively low FLW, which could be due to many of these crops having long shelf lives. Conversely, "oil crops" has a higher FLW in the downstream stages, with 44.9% of the FLW happening in "Distribution and Retail" and "Consumption". In the downstream supply chain, where individual contributions to food waste are higher, policies and campaigns are more important in the reduction of FLW. Policies can provide regulatory frameworks and incentives, while campaigns raise awareness and educate in-

dividuals about the importance of reducing food waste, thus addressing the challenges associated with FLW [2].

When considering the stage in the value chain where measures need to be taken, it is important to contemplate the impact they will have on the value chain as a whole. Reducing food loss in "Agricultural Production" without decreasing production will lead to more food into the system. This might have a cascading effect downstream causing increased FLW in "Distribution and Retail" and "Consumption". Therefore it might seem reasonable to focus on implementations of solutions at the consumer level, however if there is a substantial loss in a upstream supply stage it might still be more efficient to reduce food loss at this stage. [10]

4.4 Data Limitations and Uncertainties

This bachelor thesis has had its limitations, as expected from section 1.4. Due to using three different databases a homogenisation was necessary to make the data comprehensive. There is a lack of information about how loss is accounted for in the FLW dataset since the data is based on separate studies using various research methods. Especially ambiguous is how losses are accounted for regarding primary crops being processed into other products. Losses occurring in the "Consumption" stage of a primary crop might therefore mean the consumption of a processed product. The information shortage is also evident regarding definitions of supply stages, and consequently, we have had to make some assumptions.

In the FLW dataset we found many points with zero or 'nan' values, and several countries and commodities completely absent from the data. Therefore we needed to gap-fill, and there are many variations of how to do this. For missing values, we chose to extrapolate averages for commodity groups over all 20 years, which might lead to missing out on potential trends over some years. The gap-filling method follows steps described in 2.2.3, utilising averages for country and commodity when available, and thereafter trying more generic averages until the last step: commodity group and world average. This means that some gap-filled values have higher uncertainty than others. Another limitation is that when summarising the FLW values from all supply stages, many values were unreasonably high and we therefore chose to limit all values to a maximum and minimum for each commodity group (upper and lower whiskers in figure 5). These two methods lead to many data points having the same loss percentage. This is especially problematic in the commodity group "stimulants" where the FLW dataset originally only had one data point, resulting in all extrapolated points in this group receiving

the same percentage as the original, of 22.5%.

To get a better understanding of how these methods affected the results, a sensitivity analysis could be performed. Variables such as upper and lower restriction limits of the loss percentage could be altered to analyse the effect on the outcome. The method of gap-filling could also be varied to see what difference it would make. By doing this, a range could be created of possible outcomes which would show the uncertainty of our results clearer.

The average annual FLW from our calculations is 1.87 billion tonnes, accounting only for primary crops. This can be compared to existing literature, estimating a total annual FLW (including all food, not only primary crops) of 1.3 billion tonnes [6]. From this difference, we can assume that through our methods and assumptions, there is a possibility of an overestimation. Although, the FLW percentage calculated is consistent around 20% for all years, which is not an overestimation compared to existing literature, acknowledging about a third of food to be lost or wasted annually [6]. For the water usage, we estimated that 21% is preventable through a reduction of FLW, while the existing literature estimates 24% [16], which is also quite similar. However, FLW is difficult to measure and no study can give a completely certain answer of how much food is being lost or wasted.

For a more comprehensive understanding of FLW trends over the years 2001-2020 there would be a need for better data sampling as well as cohesive and standardised definitions of the food supply stages and activities. This would help with combining data from different sources and reduce the need for excessive extrapolation.

4.5 Further Research

To continue this field of study we would suggest digging deeper into the trade flows of FLW to not only find out how much of domestic production that is being lost or wasted but also where in the world it occurs. Investigating trade flows of food could open up new possible solutions for reducing FLW. Trade flows in combination with nutritional analysis could also be an interesting contribution if one were to examine possibilities to prevent hunger.

While crop-commodity-induced deforestation is a significant contributor, we can also not forget that deforestation is a problem beyond crop agriculture. Several other factors lead to deforestation. A few examples are material commodities (such as rubber), forest plantation, grazing animals, wildfires and urbanisation [32]. To further study the connection between FLW and deforestation and water resources, it would be of interest to include more

commodities than done in this thesis. A broader span of commodities would hopefully capture other mechanisms that could have been overseen in our thesis. Since there is also an ambiguity concerning the supply chains of primary crops and processed foods, it would be interesting to get a further understanding of how these supply chains differ or complement each other.

5 Conclusion

In wrapping up this thesis, our findings show that a reduction in FLW has the potential to significantly reduce the burden on land and water resources. Some critical points have also been pin pointed where reduction is of particularly high importance. This thesis has delved into a quite unexplored area of the connection between FLW and deforestation, as well as FLW and water usage, and thereby fills an existing knowledge gap. These connections can further support the research on FLW, as well as highlight leverage points for the importance of FLW reduction in all supply stages.

In order to reduce FLW and, thus, its impacts on the Earth systems it is crucial to implement integrated approaches considering the environmental, economic and social aspects. This demands a cooperation between stakeholders on different levels of the food supply chain in order to develop and efficiently realise these strategies. As discussed, it is of great importance to develop targeted interventions with individual focuses on specific parts of the food supply stage. These targeted interventions need to be specified by local production methods, consumption patterns and infrastructure to address the regional differences in FLW. Furthermore, policies and regulations, both nationally and globally will be of great importance to reduce FLW and create an environment where sustainable interventions will thrive.

Apart from these technical solutions, policies and regulations, consumer awareness will be a key measure in this adjustment. By educating consumers of the consequences of FLW while simultaneously encouraging behaviours such as meal planning and correct care for produce may reduce the waste at a consumer level. Moreover, an interdisciplinary collaboration between scientists will be crucial in order to stimulate knowledge and innovation for fast and big systemic changes to create the sustainable food supply chain of the future.

These recommendations aim to direct future interventions and initiatives to reduce FLW while simultaneously emphasising the complexity of FLW as is. Through elucidating the need for tailored measures, considering all factors necessary, we see possibilities to develop new solutions and technologies in order to tackle these complex challenges connected to the conservation of land and water resources through FLW reduction.

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A Commodity groups

Commodity Group	Commodities Covered in Original Dataset	Commodities Added in Extrapolation
Cereals	Barley, Fonio, Maize (corn), Millet, Mixed grain, Oats, Quinoa, Rice, Rye, Sorghum, Wheat	Buckwheat, Canary seed, Cereals n.e.c., Triticale
Pulses	Bambara beans, dry, Beans, dry, Broad beans and horse beans, dry, Chick peas, dry, Cow peas, dry, Lentils, dry, Other pulses n.e.c., Peas, dry, Pigeon peas, dry	Lupins, Vetches
Fruit	Apples, Apricots, Avocados, Bananas, Blueberries, Cherries, Cranberries, Dates, Figs, Grapes, Kiwi fruit, Lemons and limes, Mangoes, guavas and mangoosteens, Oranges, Other citrus fruit, n.e.c., Other fruits, n.e.c., Other pome fruits, Other stone fruits, Papayas, Peaches and nectarines, Pears, Persimmons, Pineapples, Plantains and cooking bananas, Plums and sloes, Pomelos and grapefruits, Raspberries, Strawberries, Tangerines, mandarins, clementines	Cashewapple, Currants, Gooseberries, Other berries and fruits of the genus vaccinium n.e.c., Other tropical fruits, n.e.c., Quinces, Sour cherries

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Table 4 – continued from previous page

Commodity group	Commodities Covered in Original Dataset	Commodities Added in Extrapolation
Vegetables	Artichokes, Asparagus, Broad beans and horse beans, green, Cabbages, Cantaloupes and other melons, Carrots and turnips, Cauliflowers and broccoli, Cucumbers and gherkins, Eggplants (aubergines), Green corn (maize), Green garlic, Leeks and other alliaceous vegetables, Lettuce and chicory, Mushrooms and truffles, Okra, Onions and shallots, green, Other beans, green, Other vegetables, fresh n.e.c., Peas, green, Pumpkins, squash and gourds, Spinach, Tomatoes, Watermelons	Chicory roots, Chillies and peppers, green (Capsicum spp. and Pimenta spp.), Locust beans (carobs), Onions and shallots, dry (excluding dehydrated), String beans
Oil crops	Coconuts, in shell, Groundnuts, excluding shelled, Mustard seed, Olives, Rape or colza seed, Safflower seed, Sesame seed, Soya beans, Sunflower seed	Castor oil seeds, Hempseed, Jojoba seeds, Kapok fruit, Karite nuts (sheanuts), Linseed, Melonseed, Oil palm fruit, Other oil seeds, n.e.c., Poppy seed, Tallowtree seeds, Tung nuts
Roots, tubers, products	Cassava, fresh, Edible roots and tubers with high starch or inulin content, n.e.c., fresh, Potatoes, Sweet potatoes, Yams	Taro, Yautia
Continued on next page		

Table 4 – continued from previous page

Commodity group	Commodities Covered in Original Dataset	Commodities Added in Extrapolation
Spices	Anise, badian, coriander, cumin, caraway, fennel and juniper berries, raw, Other stimulant, spice and aromatic crops, n.e.c.	Chillies and peppers, dry (Capsicum spp., Pimenta spp.), raw, Cinnamon and cinnamon-tree flowers, raw, Cloves (whole stems), raw, Ginger, raw, Nutmeg, mace, cardamoms, raw, Pepper (Piper spp.), raw, Vanilla, raw
Stimulants	Cocoa beans	Coffee, green, Maté leaves, Peppermint, spearmint, Tea leaves
Sugar and syrups	Sugar beet, Sugar cane	Other sugar crops n.e.c.
Tree nuts	Almonds, in shell, Areca nuts, Cashew nuts, in shell, Hazelnuts, in shell, Pistachios, in shell, Walnuts, in shell	Chestnuts, in shell, Kola nuts, Other nuts (excluding wild edible nuts and groundnuts), in shell, n.e.c.

B Regions

NB: Below are the countries included in the FLW dataset, meaning that some countries disappear when merged with the DeDuCE and Water-To-Food datasets as they may not have data for all the countries included in the FLW one. Furthermore, duplicates of countries which may exist twice due to different spellings of the names have later been removed, leaving only one name.

Region Name	Countries Covered in Original Dataset	Countries Added in Extrapolation
Africa	Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Chad, Côte d'Ivoire, Democratic Republic of the Congo, Egypt, Eritrea, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Togo, Tunisia, Uganda, United Republic of Tanzania, Zambia, Zimbabwe	Cabo Verde, Central African Republic, Comoros, Equatorial Guinea, Libya, Mauritius, Sao Tome and Principe, Seychelles, Tanzania
East Asia	Cambodia, China, Democratic People's Republic of Korea, Indonesia, Lao People's Democratic Republic, Malaysia, Philippines, Republic of Korea, Thailand, Timor-Leste, Viet Nam	Brunei, Japan, Laos, Mongolia, Myanmar, North Korea, Singapore, South Korea, Vietnam
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Table 5 – continued from previous page

Region Name	Countries Covered in Original Dataset	Countries Added in Extrapolation
Europe	Denmark, Finland, France, Italy, Norway, Serbia, Sweden, Switzerland, Ukraine, United Kingdom of Great Britain and Northern Ireland	Albania, Austria, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Czechia, Estonia, Germany, Greece, Hungary, Ireland, Latvia, Lithuania, Luxembourg, Malta, Moldova, Netherlands, North Macedonia, Poland, Portugal, Romania, Russia, Slovakia, Slovenia, Spain, United Kingdom
North America	Canada, United States of America	<i>No added countries</i>
Oceania	Australia, Fiji, New Zealand	Micronesia, New Caledonia, Papua New Guinea, Solomon Islands, Vanuatu
Rest of Asia	Armenia, Azerbaijan, Bahrain, Bangladesh, India, Iran (Islamic Republic of), Jordan, Kazakhstan, Lebanon, Nepal, Oman, Pakistan, Palestine, Saudi Arabia, Sri Lanka, Syrian Arab Republic, Turkey	Afghanistan, Bhutan, Cyprus, Georgia, Iran, Iraq, Israel, Kyrgyzstan, Maldives, Syria, Tajikistan, Turkmenistan, Uzbekistan, Yemen
South America	Argentina, Bolivia (Plurinational State of), Brazil, Chile, Colombia, Costa Rica, Cuba, Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Saint Lucia, Trinidad and Tobago, Venezuela (Bolivarian Republic of)	Antigua and Barbuda, Bahamas, Barbados, Belize, Bolivia, Dominica, Dominican Republic, Grenada, Jamaica, Puerto Rico, Saint Vincent and the Grenadines, Suriname, Uruguay, Venezuela

C Plots Showing Uncertainty in Data Collection

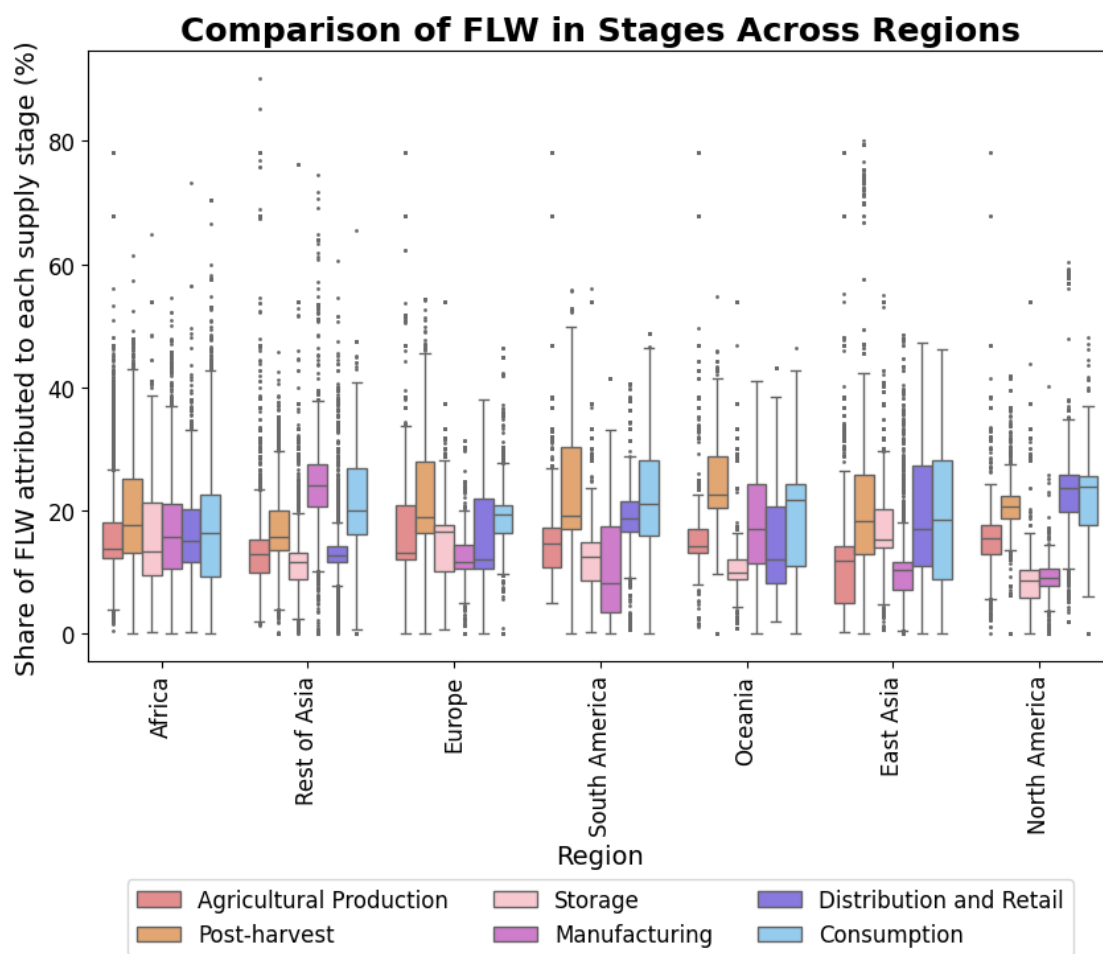


Figure 21: Box plot showing per cent of FLW attributed to respective supply stage for each region. The boxes show the upper and lower quartiles and the vertical line represents the median. The dots show outliers, determined by the interquartile range method. The data presented in this plot is the FLW data after gap-filling, across all years.

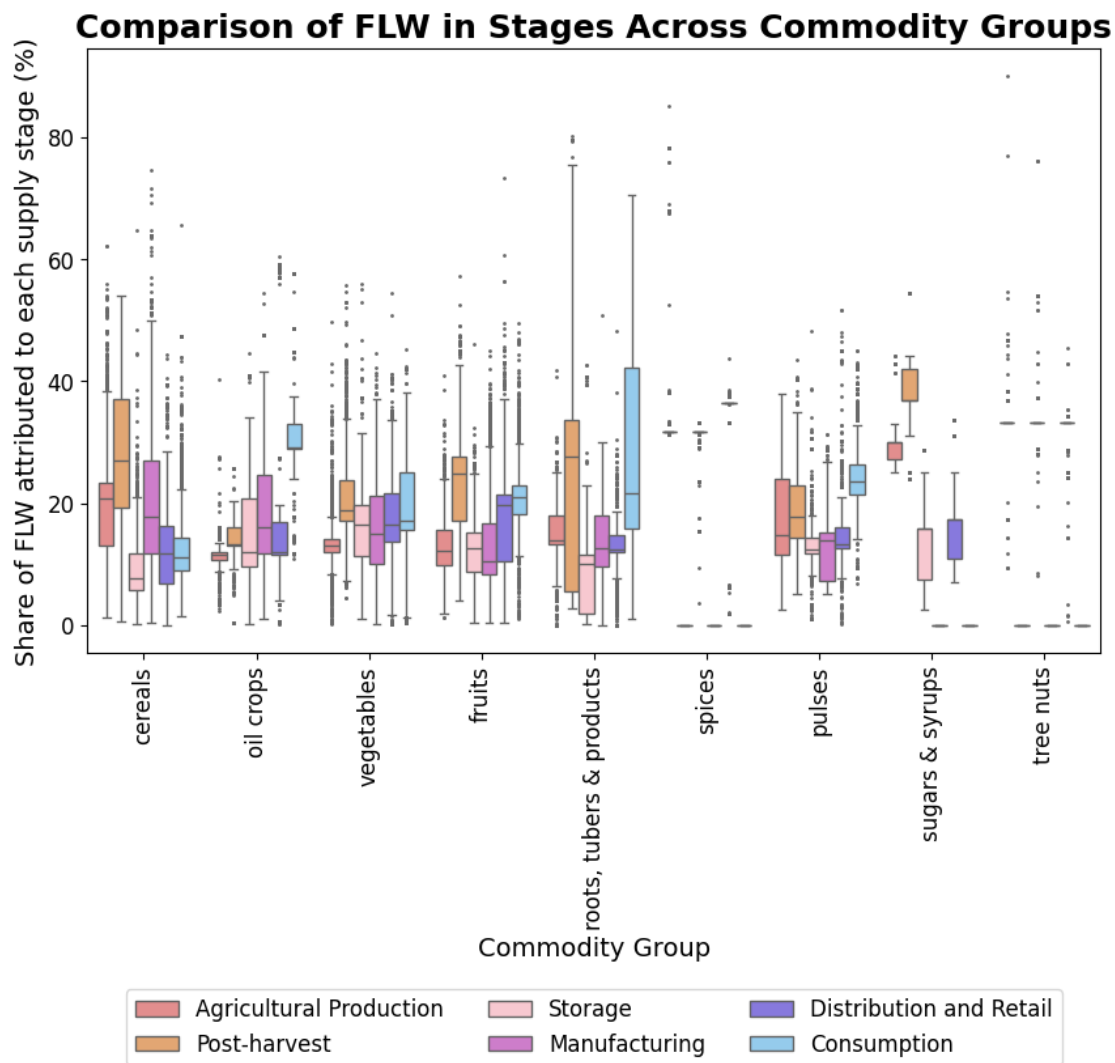


Figure 22: Box plot showing per cent of FLW attributed to respective supply stage for each commodity group across all the years. The boxes show the upper and lower quartiles and the horizontal line represents the median. The dots illustrate outliers, determined by the interquartile range method. Observe that the boxes on zero per cent in the plot are due to a lack of data in the represented stages. Additionally, the commodity group "stimulants" is not included since this commodity group only has data for "Whole supply chain".

DEPARTMENT OF SPACE EARTH AND ENVIRONMENT
CHALMERS UNIVERSITY OF TECHNOLOGY
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