UC SANTA BARBARA
Bren School of Environmental
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GLOBAL FOOD PRODUCTION HOTSPOT & MITIGATION ANALYSIS

UN environment programme

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Signature Page

This Group Project is submitted in partial satisfaction of the requirements for the degree of Master of Environmental Science and Management (MESM) for the Bren School of Environmental Science & Management. The Group Project Final Report is authored and completed by the project team under the direction of faculty advisor, Dr. Roland Geyer.

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Glossary

AU - Australia

AEZ - Agro Ecological Zoning

BR - Brazil

CED - Cumulative Energy Demand

CN - China

CP - Crude Protein

DE - Denmark

EG - Egypt

ES - Spain

FAO - Food and Agriculture Organization

FEP - Freshwater Eutrophication Potentials

FR - France

GHG - Greenhouse Gasses

GLO - Global

GWP - Global Warming Potential

ID - Indonesia

IE - Ireland

IEA - International Energy Agency

IN - India

IPCC - Intergovernmental Panel on Climate Change

LCA - Life Cycle Assessment

LCT - Life Cycle Thinking

LUC - Land Use Change

MX - Mexico

MY - Malaysia

PK - Pakistan

ROW - Rest of World

RU - Russia

SDGs - Sustainability and Development Goals

TH - Thailand

UAV - Unmanned Aerial Vehicle

UNEP - United Nations Environment Programme

US - United States of America

WMS - Waste Management System

Project Objectives and Significance

The primary goal of this project is to aid the United Nations Environment Programme (UNEP) in evaluating global food production. The UN Sustainable Development Goals (SDGs), which aim to tackle climate change and preserve oceans and forests by 2030, are helping to drive these efforts for sustainable agricultural processes. In particular, the Sustainable Development Goal 2, “Zero Hunger”, revolves around achieving food security, while improving nutrition and promoting sustainable agricultural practices. Sustainability Target 2.4 states, “by 2030 ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters, and that progressively improve land and soil quality,” (UNEP). The necessity to address agricultural processes is further illustrated by the fact that 25% to 30% of our global Greenhouse gas emissions (GHG) come from our food systems. This increases to one-third when agricultural products are included (IPCC, 2019). Global population growth, changing diets, and an increase in income per capita has necessitated an increase in food production to meet demand (Ndue & Pàl, 2022). “Building on the United Nations Food and Agriculture Organization’s (FAO) food demand projections, we estimate that the world needs to close a 70 percent “food gap” between the crop calories available in 2006 and expected calorie demand in 2050” (Ranganathan, 2016). In order to meet this demand in an ever-changing climate with less predictable yields, climate resiliency and sustainability strategies must be implemented in existing food production systems. Yield increases alone will not be enough to close this gap and would exert even more pressure on clearing natural ecosystems. Life Cycle Thinking (LCT) is one of these climate resiliency and sustainability strategies that has the ability to methodologically assemble parts of an entire product system to successfully analyze environmental impacts. Our group project will utilize existing Life Cycle Analyses (LCAs), a subset of LCT, to identify hotspots of environmental improvement within food production to help close this gap and address the food demand that puts our natural surroundings in peril. Within the environmental realm of agricultural impact studies, there are many high-level global food footprints and commodity specific LCAs that are commissioned. However, mid-level contribution analyses of food types that connect these two are much rarer. Our contribution helps to connect the high-level analyses on global food production with the granularity of product-specific LCAs and point to areas that have the highest impact within the food production process, farm to gate. These different methodological approaches are complementary, and benefit from being combined, as they help widen an expanding evidence base. The higher-level global studies help illuminate impacts of products, while the commodity specific LCAs aid in providing granularity and quantify these impacts, helping with prioritization efforts within system processes. Global production quantities combined with environmental intensities facilitated our efforts of ranking food items with the highest impact and then the contribution analyses of those items facilitated identifying hotspots.

Background

Literature Review

Our literature review consisted of two parts: landmark studies on global-level environmental intensities of food items and individual LCAs. The core of our knowledge was constructed by top-level research papers which include intensity figures from Clark et al. 2019, Clune et al. 2017, and Poore and Nemecek 2018. The current state of knowledge has advanced greatly from the work of these papers ranging from focus on raw and primary food items to entire food products. Using our constructed ranking of global food items (explained below) from the 2022 FAO production quantities combined with environmental intensities of global warming potential (GWP), students split up the work of researching individual LCAs for food items identified as highly impactful. Advantageously, these highly specific LCAs also include recommendation sections that provide direction for mitigation efforts. Literature sources that were used to supplement data followed the ReCiPe Midpoint (H) method of impact assessment to be congruent with our methods described below.

Poore and Nemecek's, "Reducing Food's Environmental Impacts Through Producers and Consumers" references research and studies dating back to 2010 but was included in our literature review as it analyzes 38,000 farms in 119 countries and spans 40 products. This research paper was also important in determining the top five impact categories used in this report: 1. Land Use 2. Water Use 3. Greenhouse Gasses (GHG) 4. Marine Eutrophication and 5. Freshwater Eutrophication.

A knowledge gap was identified in mesa-level analyses that use individual LCAs to inform global studies that are inherently broad. While it was not possible to locate and synthesize all LCAs during this project timeline, key findings helped inform the relevance and importance of LCA studies and methods to allow us to compare impacts and mitigation strategies within food production processes.

Special attention is needed at every step of the LCA process. For example, LCAs must show transparency on what data is being included and the methods of allocation according to ISO 14044 compliant standards. Hence, the importance of selecting only LCAs using the parameters of farm-to-gate. For example, energy demand includes what powers farm equipment and machinery, but not the fuel intake of farmworkers conducting manual labor within the process.

Key findings of our literature review include insights into each food product system can be found in Table 1 below.

Table 1

Key literature sources utilized for this research report

Reference	Article	Conclusion
Abín, Rocio, et al., 2018. Spain.	Environmental Assessment of Intensive Egg Production: A Spanish Case Study.	LCA of egg production showing emissions of global warming potential, land transformation and alternative feed formulas for mitigation.
de Andrade Junior, et al., 2019. Brazil.	Exploring future scenarios of ethanol demand in Brazil and their land-use implications.	Analyzes the land-use effects of policies and macroeconomic drivers for ethanol production in Brazil.

Carvalho et al., 2022. Brazil.	Environmental Life Cycle Assessment of Cow Milk in a Conventional Semi-Intensive Brazilian Production System.	Enteric methane, nitrogen emissions and inputs for feeding animals were the main contributors to impacts. Allocation methods did not substantially differ impact categories and literature-based mitigation strategies were offered.
Clark, M. et al., 2019. US.	Multiple Health and Environmental Impacts of Foods.	Environmental impacts of 15 different food products and recommendations to shift to a healthier diet as mitigation.
Clune, S. et al., 2017. UK and Australia.	Systematic Review of Greenhouse Gas Emissions for Different Fresh Food Categories.	Meta-analysis and literature review of 369 LCA studies for 168 food types and global warming potential values used to supplement data gaps.
Giusti et al., 2023. Brazil.	Environmental impact management of grain and sweet maize through life cycle assessment in São Paulo, Brazil.	LCA comparing impacts of grain maize and sweet maize suggesting improvements by minimizing or substituting fertilizers.
Halpern, B. et al., 2022. US.	The Environmental Footprint of Global Food Production.	Assessment of 26 food crops, 19 livestock categories and fish emissions from farm to gate production.
Horillo, A. et al., 2020. Spain.	Organic Farming as a Strategy to Reduce Carbon Footprint in Dehesa Agroecosystems: A Case Study Comparing Different Livestock Products.	LCA comparing organic and conventional production systems for livestock highlighting mitigation strategies addressing feed and manure management.
Hussain, S. et al., 2020. Switzerland.	Rice Production Under Climate Change: Adaptations and Mitigating Strategies	Rice is grown in flooded conditions in most parts of the world releasing large amounts of methane.

King, L. C., & van den Bergh, J., 2022. EU.	Sugar taxation for climate and sustainability goals.	Modeling reduction in emissions from sugar cane as a crop and implications of conversion to ethanol production.
Ndue, K. and Pál, G., 2022. Hungary.	Life Cycle Assessment Perspective for Sectoral Adaptation to Climate Change: Environmental Impact Assessment of Pig Production.	LCA of pig production addressing feed and manure management as mitigation strategies to inform future sustainability policies.
Poore, J. and Nemecek, T., 2018. UK.	Reducing Food's Environmental Impacts Through Producers and Consumers.	Data consolidation on different impacts of 38,000 farms and 40 different agricultural products comparing food production systems.
Wang, L. et al., 2014. UK.	Economic and GHG emissions analyses for sugarcane ethanol in Brazil: Looking forward.	Combines economic and GHG emission analyses to suggest it is more favorable to use sugarcane for electricity rather than ethanol.
Yan et al., 2010. Europe.	An Evaluation of Life Cycle Assessment of European Milk Production.	13 LCA studies of European milk production were analyzed, identifying strengths and weaknesses of LCA for evaluation of agricultural systems.
Yao and Guo et al., 2024. England.	A Global Meta-Analysis of Yield-scaled N2O Emissions and its Mitigation Efforts for Maize, Wheat, and Rice.	A global study including analysis of emissions related to fertilizer including 6,000 observations of data for the three agricultural products.

Methods

Project Description

This project was divided into three phases: 1a. Rank top food items by GHG impact to pinpoint the food items to further analyze, 1b. Rank these chosen food items by four other environmental impact categories, 2. Contribution analysis by country and process to identify hotspots within top food items, and 3. Research mitigation strategies for each commodity's production process.

Phase one was focused on methodically choosing a handful of food items as the point of focus for contribution and mitigation analyses. These priority commodities were chosen by analyzing the majority of primary crops and livestock that are produced globally, aligning them with their greenhouse gas intensities, and ranking them based on their total impact. Total impact was derived by multiplying each commodity's 2022 production quantities with their greenhouse gas intensity. See Table 2, 3, and 4. Greenhouse gas intensity refers to the amount of greenhouse gasses emitted per ton of product. The values were purposefully multiplied, as opposed to just isolating the consideration of strictly high GHG intensity food items or strictly high production food items. This was an important methodological component, as production quantities and GHG intensities are not correlated. Commodities with larger production totals were generally observed to have lower GHG intensities.

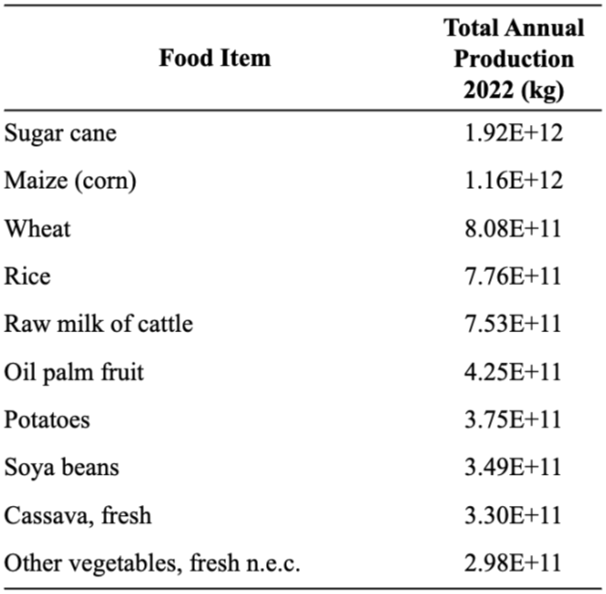
The production values for the year 2022 were obtained from the Food and Agriculture Organization database, FAOSTAT. The FAO database contains a range of data related to food and agriculture, but our project mainly extracted production values for all countries and regions, including global totals, from this database. The project scope included only primary crops and livestock. Processed items were not considered in this analysis. The 2022 production database from FAOSTAT consists of 210 global food items and their annual production numbers. The database does not include any fish, as there is a separate FAO FISHSTAT database that exists. The latest available data in this database is from 2021 and includes a sum of aquaculture (brackish water, freshwater, and marine) and capture production. 14 of the most produced fish globally were extracted from this database and added to the analysis. Two duplicate FAOSTAT food items were removed, totaling 222 total food items with annual production quantity data.

Greenhouse gas intensity was the chosen environmental metric for this portion of the analysis as it is the primary driver of climate change, of which food production is a major contributor. This helped create a streamlined approach coupled with robust and consistent data to utilize. The GHG intensity values were taken from Clune et al. 2017 that conducted a meta-analysis of the LCA studies for the following categories: fresh vegetables (root vegetables, brassica, leaves and stems); fresh fruits (pepo, hesperidium, true berries, pomes, aggregates fruits and drupes); staples (grains, legumes, nuts, seeds and rice); dairy (almond/coconut milk, soy milk, dairy milk, butter and cheese); non-ruminant livestock (chicken, fish, pork); and ruminant livestock (lamb and beef). This paper was chosen as its provided intensity values are consistent with the project scope of items pulled from FAO's production database. Any missing GHG intensities for countries with large production quantities not available in Clune et al. 2017 were filled using emissions intensities from FAOSTAT or the Agri-footprint 6.3 database. GHG intensity numbers are shown in CO2 equivalent (CO2-eq).

Agri-footprint 6.3 is a Life Cycle Inventory (LCI) database that our team purchased from Blonk Consultants to provide data for phase two. Phase two of this project involved gathering specific process and impact information for each chosen food item to provide insights for hotspot and mitigation analyses. This data was gathered on a country level basis to create a global food process for each commodity. Countries included for each commodity were based off of availability from the Agri-footprint database. The database was accessed using openLCA software.

Table 2

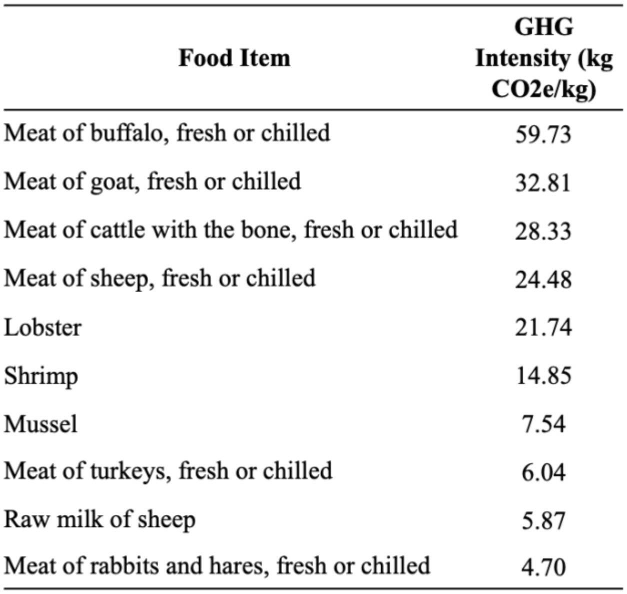
Top globally produced food items, 2022



Food Item	Total Annual Production 2022 (kg)
Sugar cane	1.92E+12
Maize (corn)	1.16E+12
Wheat	8.08E+11
Rice	7.76E+11
Raw milk of cattle	7.53E+11
Oil palm fruit	4.25E+11
Potatoes	3.75E+11
Soya beans	3.49E+11
Cassava, fresh	3.30E+11
Other vegetables, fresh n.e.c.	2.98E+11

Table 3

Top GHG intensive food items

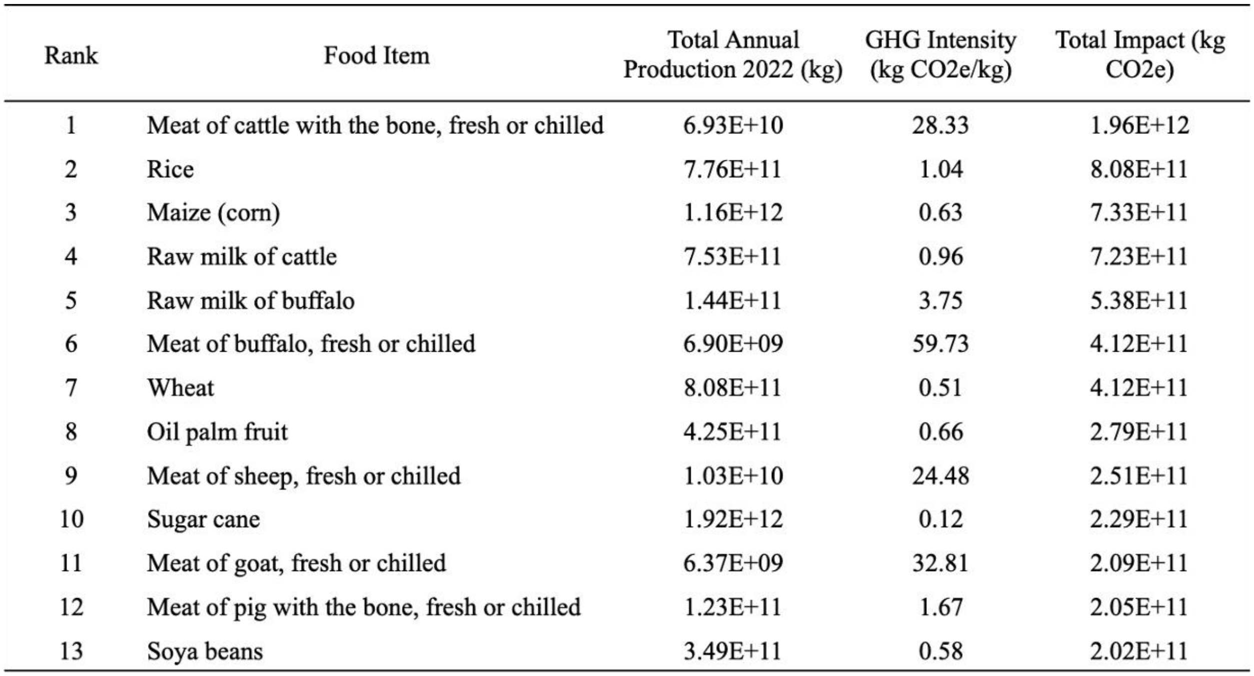


Food Item	GHG Intensity (kg CO2e/kg)
Meat of buffalo, fresh or chilled	59.73
Meat of goat, fresh or chilled	32.81
Meat of cattle with the bone, fresh or chilled	28.33
Meat of sheep, fresh or chilled	24.48
Lobster	21.74
Shrimp	14.85
Mussel	7.54
Meat of turkeys, fresh or chilled	6.04
Raw milk of sheep	5.87
Meat of rabbits and hares, fresh or chilled	4.70

It is important to note that not one of the top 10 globally produced food items in 2022 overlap with the top GHG intensive food items.

Table 4

Top foods ranked by total GHG impact



Rank	Food Item	Total Annual Production 2022 (kg)	GHG Intensity (kg CO2e/kg)	Total Impact (kg CO2e)
1	Meat of cattle with the bone, fresh or chilled	6.93E+10	28.33	1.96E+12
2	Rice	7.76E+11	1.04	8.08E+11
3	Maize (corn)	1.16E+12	0.63	7.33E+11
4	Raw milk of cattle	7.53E+11	0.96	7.23E+11
5	Raw milk of buffalo	1.44E+11	3.75	5.38E+11
6	Meat of buffalo, fresh or chilled	6.90E+09	59.73	4.12E+11
7	Wheat	8.08E+11	0.51	4.12E+11
8	Oil palm fruit	4.25E+11	0.66	2.79E+11
9	Meat of sheep, fresh or chilled	1.03E+10	24.48	2.51E+11
10	Sugar cane	1.92E+12	0.12	2.29E+11
11	Meat of goat, fresh or chilled	6.37E+09	32.81	2.09E+11
12	Meat of pig with the bone, fresh or chilled	1.23E+11	1.67	2.05E+11
13	Soya beans	3.49E+11	0.58	2.02E+11

From the ranked food items, 10 were chosen for further study; Rice, Maize, Raw milk of cattle, Wheat, Oil palm fruit, Sugar cane, Meat of pig, Soybeans (soya beans), Eggs, and Sugar beet. For each commodity, the percentage of production values that were official figures of the country was noted.

Although hen eggs, in shell ranks 26th for total GHG impact (GHG intensity by total annual production), it was included in this study as an alternative animal protein source that is not meat. Additionally, although sugar beet ranks 43rd for total GHG impact, it was included in this study as an alternative to sugar cane. Meat of cattle was excluded from this study as the environmental impact of beef has been widely studied and mitigation analyses are readily available.

Lastly, phase three required extensive research of peer-reviewed literature and specific commodity LCAs to compile strategies for mitigation. For each commodity, the size and type of production was taken into consideration to determine appropriate methods of minimizing the overall impact within the hotspot identified. Best practices in sustainable cultivation were shared as well as innovative solutions where improvements can be made to reduce emissions. For this analysis, since our project relates to global food production, we have restricted our scope of analysis to a cradle to farm gate boundary. This is not a limitation, as the 2022 OECD Food, Agriculture, and Fisheries review shows that the majority of environmental impacts in food supply chains occur via land use or at the stage of agricultural production (Deconinck et al., 2022).

Data

The secondary sources of information consisted of peer-reviewed literature for individual LCAs. Researching various databases to use for our LCA purposes, though, yielded several options. Ecoinvent, a Swiss database that spans several different industries, was a potential data option (Wernet et al., 2016). World Food LCA Database by Quantis was another option that is geared towards a suite of services for businesses covering many sectors (Quantis, 2014). These sources were considered, but ultimately, as we compared them with the Agri-footprint database, Agri-footprint consistently stood out, and we chose Agri-footprint to support our analysis. Although these databases are similar in scope, the Agri-footprint database is highly respected within the agri-food industry and has well documented and robust data. Agri-footprint was developed by Blonk Consulting, a company based in the Netherlands, and has 5,000 country-specific products and processes specific to the agri-food sector (Blonk). The latest version 6.3 is available on the open-source software platform, openLCA, and was a cost-effective option for our research purposes. The Agri-footprint database was developed using a ReCiPe Midpoint H version 1.07, 2016 LCA method, which consists of characterization factors that are representative of global scale and included the mid-point impact categories within the scope of this project.

The impact categories analyzed in this study included (Huijbregts et al., 2017):

Climate Change - The midpoint characterization factor selected for climate change is the widely used GWP100, which quantifies the infrared radiative forcing increase as a result of GHGs, expressed in kg CO2-eq.

Land Use - The characterization factor for land use is based on the relative species loss of a specific land cover type proportionate to the relative species loss for annual crops. It is a measure integrating land occupation and transformation and is expressed in m2 annual crop-eq.

Water Consumption - The characterization factor at midpoint level is m3 of water consumed per m3 of water extracted. It applies a characterization of (-1) for water returns and (+1) for water withdrawals, resulting in water consumption at an inventory level.

Freshwater Eutrophication - The fate of phosphorus (P) forms the basis of the midpoint characterization factors for freshwater eutrophication. Freshwater eutrophication potentials (FEP) are expressed in kg P-eq.

Marine Eutrophication - Marine eutrophication occurs due to the runoff and leach of plant nutrients from soil, and to the discharge of those into riverine or marine systems, and the subsequent rise in nutrient levels, i.e. phosphorus and nitrogen (N). The characterization factor is expressed in units of kg N-eq indicating the marine eutrophication potential of dissolved inorganic nitrogen emissions to water bodies.

OpenLCA was utilized to conduct contribution analyses for the chosen commodities, as it is an open-source tool and supports the use and manipulation of the Agri-footprint database format, JSON (JavaScript Object Notification). The contribution analyses consisted of comparing the environmental intensity impacts of selected countries for each commodity to the global weighted average intensity. Furthermore, the contribution of the countries to the global result of the selected impact categories was analyzed. Lastly, process-specific contribution analyses were performed for five countries. In order to capture the variance in the contribution analyses, three of the five selected were top emitting countries, and two of the five countries were selected for their lower emissions.

Data Limitations

It is notably difficult to show an error margin in LCA and there is limited guidance available for data uncertainty management in LCA studies (Pelletier, 2017). Given that this research is conducted as end-users of a collection of databases and not creating an LCA, uncertainty and sensitivity analysis was not assessed. Sources and methodologies are reported for each data point directly within the Agri-footprint database and peer-reviewed LCAs.

The Agri-footprint database provided limited coverage for the commodities chosen. Achieving a high level of coverage is a goal in the industry of LCA but total coverage is very rare. Even commodities like steel, aluminum and plastic include low data collection percentages in final metric reports as low as 38% (Wu, 2019). This contributes to certain evidence gaps, as certain products, impacts, and geographies have not been sufficiently studied. Biodiversity and soil carbon have been less studied. Additionally, there are notable gaps for LCAs conducted in Central Asia and Africa (Deconinck et al., 2022). To ensure completeness in analyzing the contribution of the countries to the global impact, a proxy "rest of world" (ROW) was calculated based on the total impact of countries and assuming that the calculated global weighted average intensity is the intensity attributed to global production of the commodity. It was observed that greater coverage resulted in a smaller error for impact due to ROW proxy.

Results

Contribution Analyses - Sugar Cane and Sugar Beet

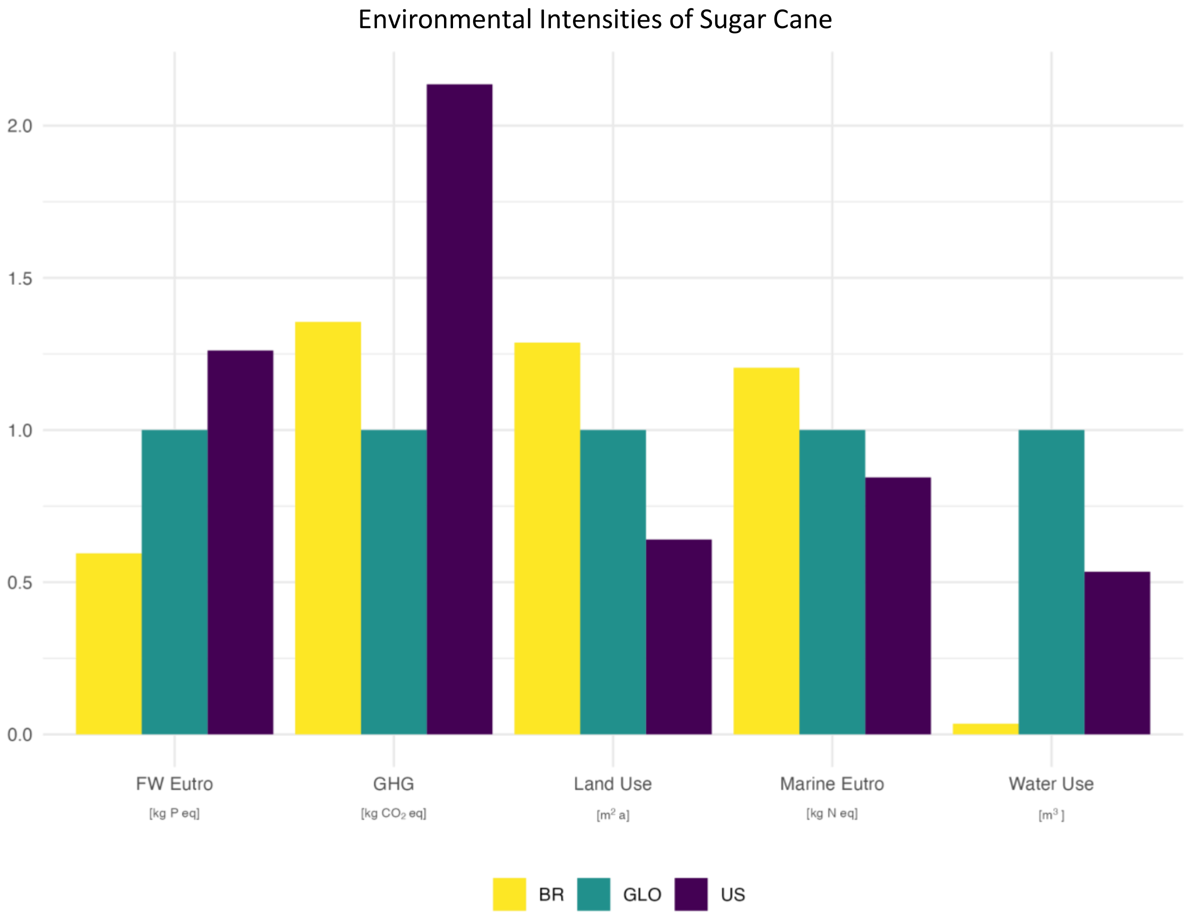

Environmental Intensities of Sugar Cane

Figure 1: The figure presented depicts impact intensities of Brazil (BR) and the United States normalized against the weighted global average of the sugar cane dataset. The global weighted average intensity is higher than that of BR for freshwater eutrophication and water use. The US is significantly more GHG intensive but less land intensive.

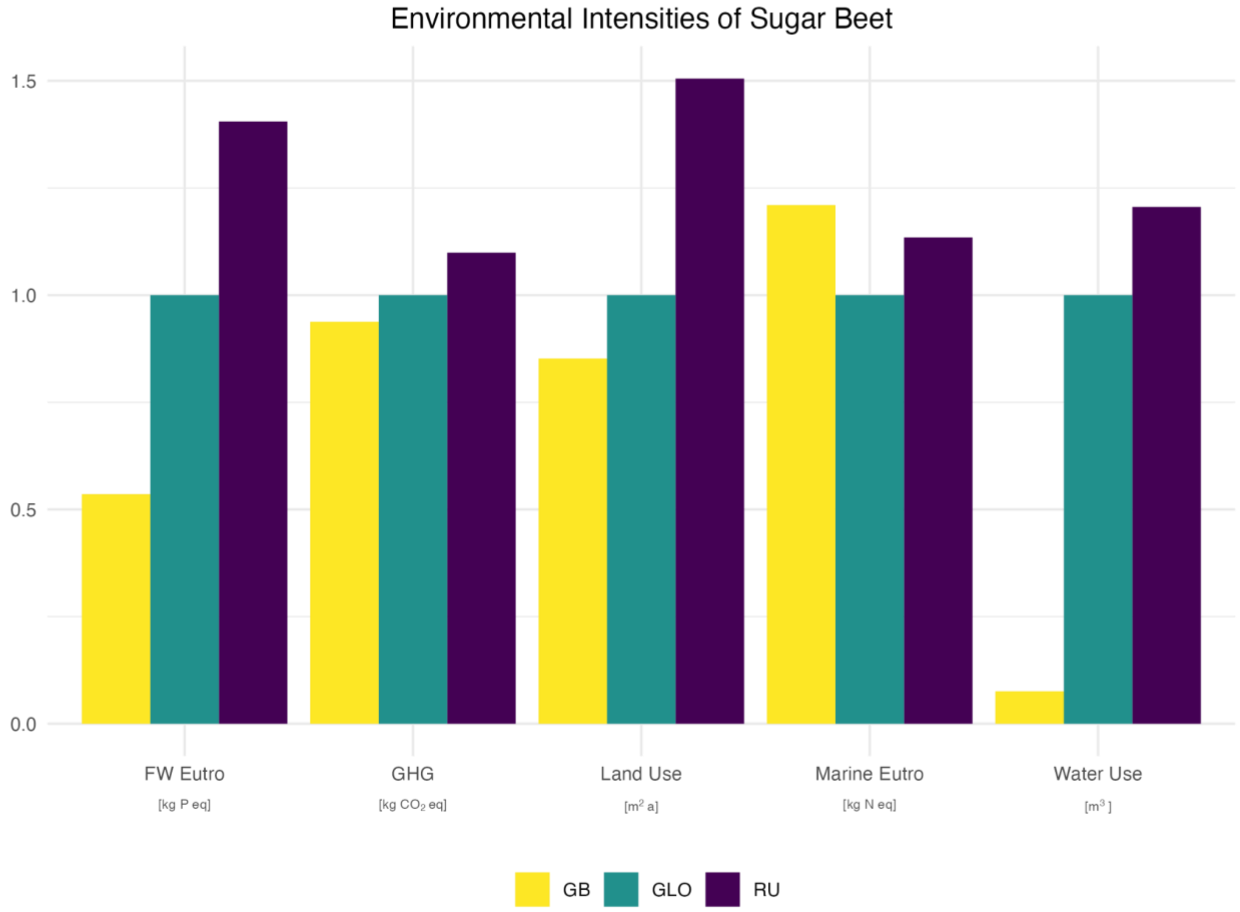


Figure 2: The figure presented depicts impact intensities of Great Britain (GB) and Russia normalized against the weighted global average of the sugar beet dataset. The global weighted average intensity is higher than that of GB for freshwater eutrophication, land use, and water use. Water use in Great Britain is significantly lower than the global average. Sugar beet production in Russia is slightly above the global average for all environmental impact indicators and significantly greater for freshwater eutrophication and land Use.

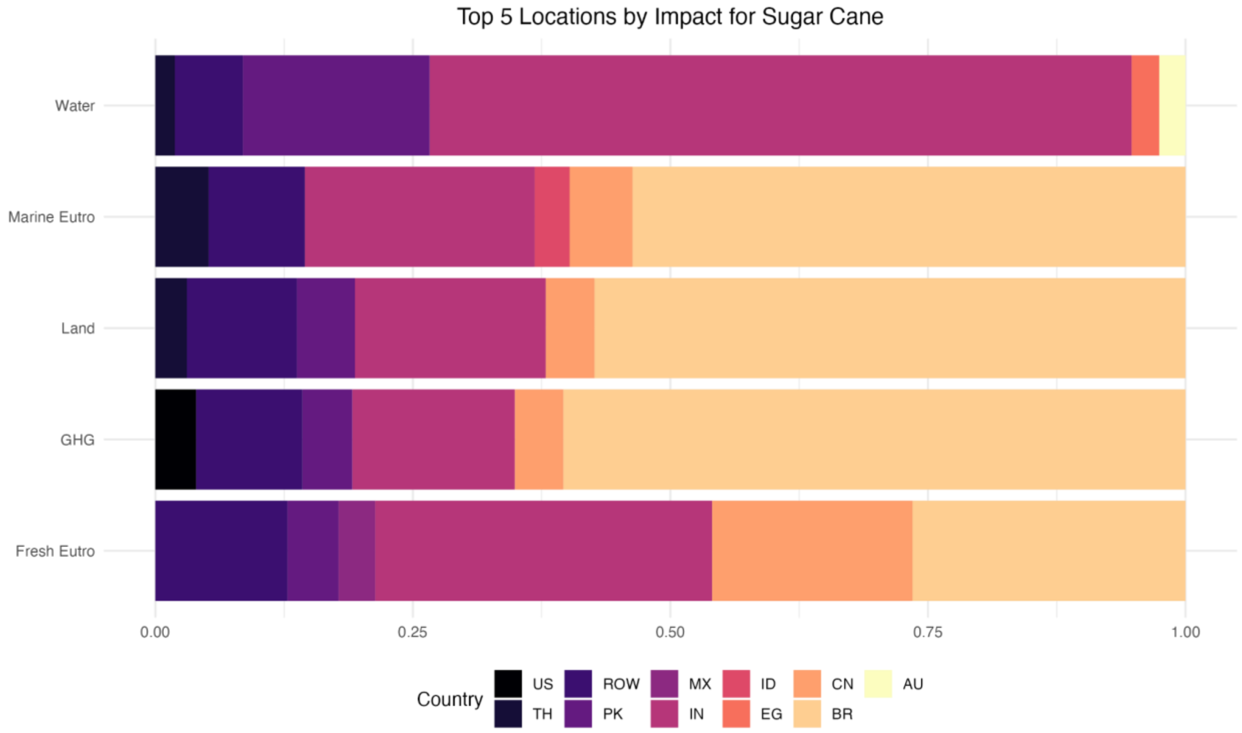


Figure 3: India experiences the largest water impact in sugar cane cultivation. Brazil, the world's largest producer, contributes significantly to marine eutrophication, land use, and greenhouse gas emissions. China, Brazil, and India face major impacts on freshwater eutrophication due to sugar cane cultivation. The United States has the highest impact in marine eutrophication, but overall impacts are relatively low across impact categories.

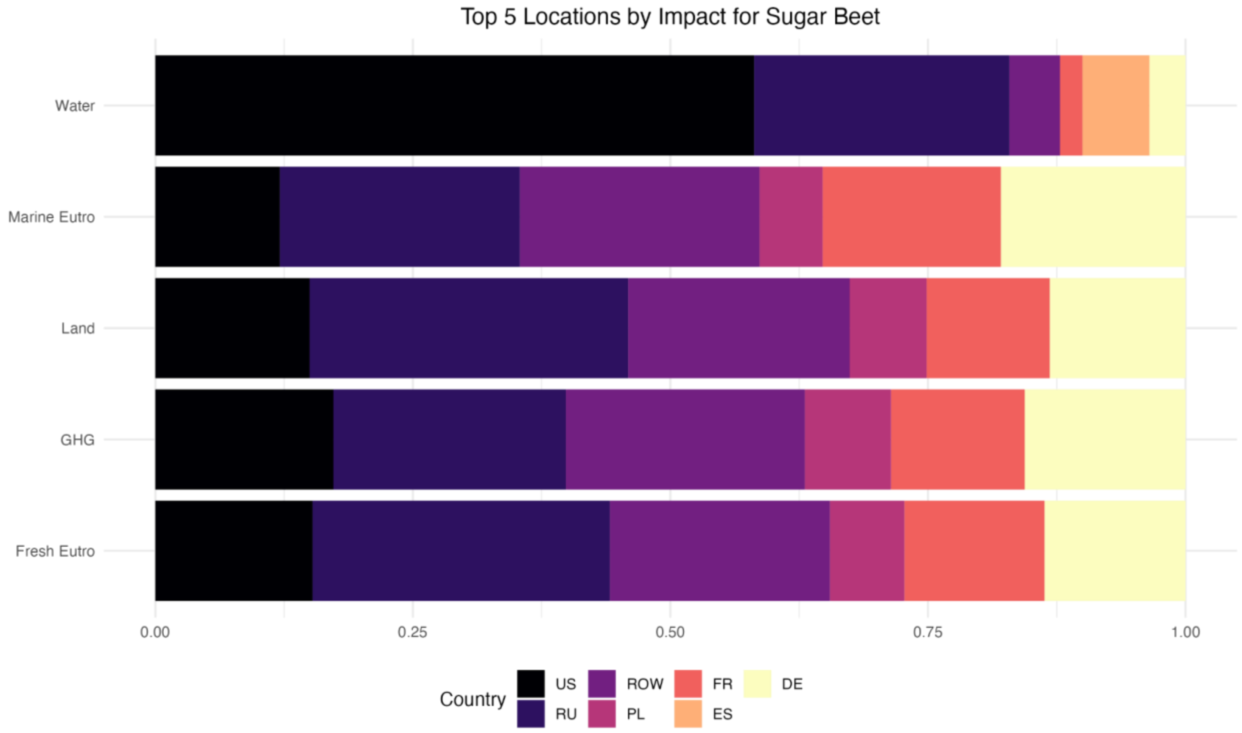


Figure 4: The United States exhibits the largest water impact in sugar beet cultivation due to the high impact intensity of water production. The ROW is a significant contributor across impact categories, representing approximately 26% of global production due to data availability. Russia, as the largest producer of sugar beets, significantly contributes across all impact categories. France and Poland both make substantial contributions across impact indicators, but their water usage intensity is relatively lower than in other countries and dramatically lower compared to the United States, attributed to a lower environmental intensity of water use, particularly less irrigation.

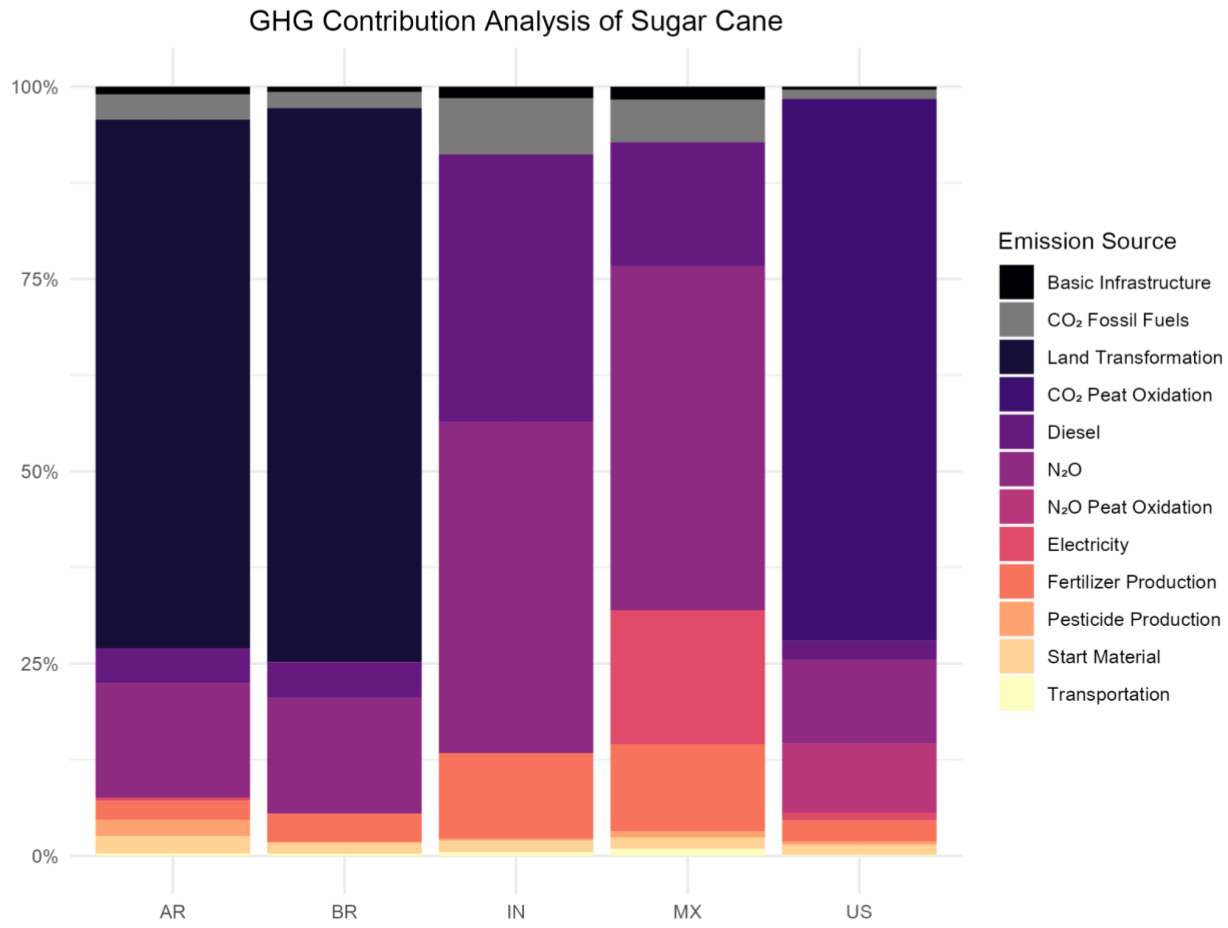


Figure 5: In the GHG contribution of sugar cane cultivation, Argentina and Brazil primarily generate emissions from land transformation, with smaller proportions stemming from N2O peat oxidation. The United States exhibits significant emissions from CO2 peat oxidation, alongside other notable contributions from N2O peat oxidation and N2O. In India and Mexico, GHG emissions are distributed more evenly, with significant contributions from CO2 peat oxidation and N2O peat oxidation. In Mexico, electricity and fertilizer also emerge as substantial emitters, while in India, fertilizers play a significant role, but electricity is not a major contributor. Across all countries, transportation makes a relatively small contribution to GHG emissions.

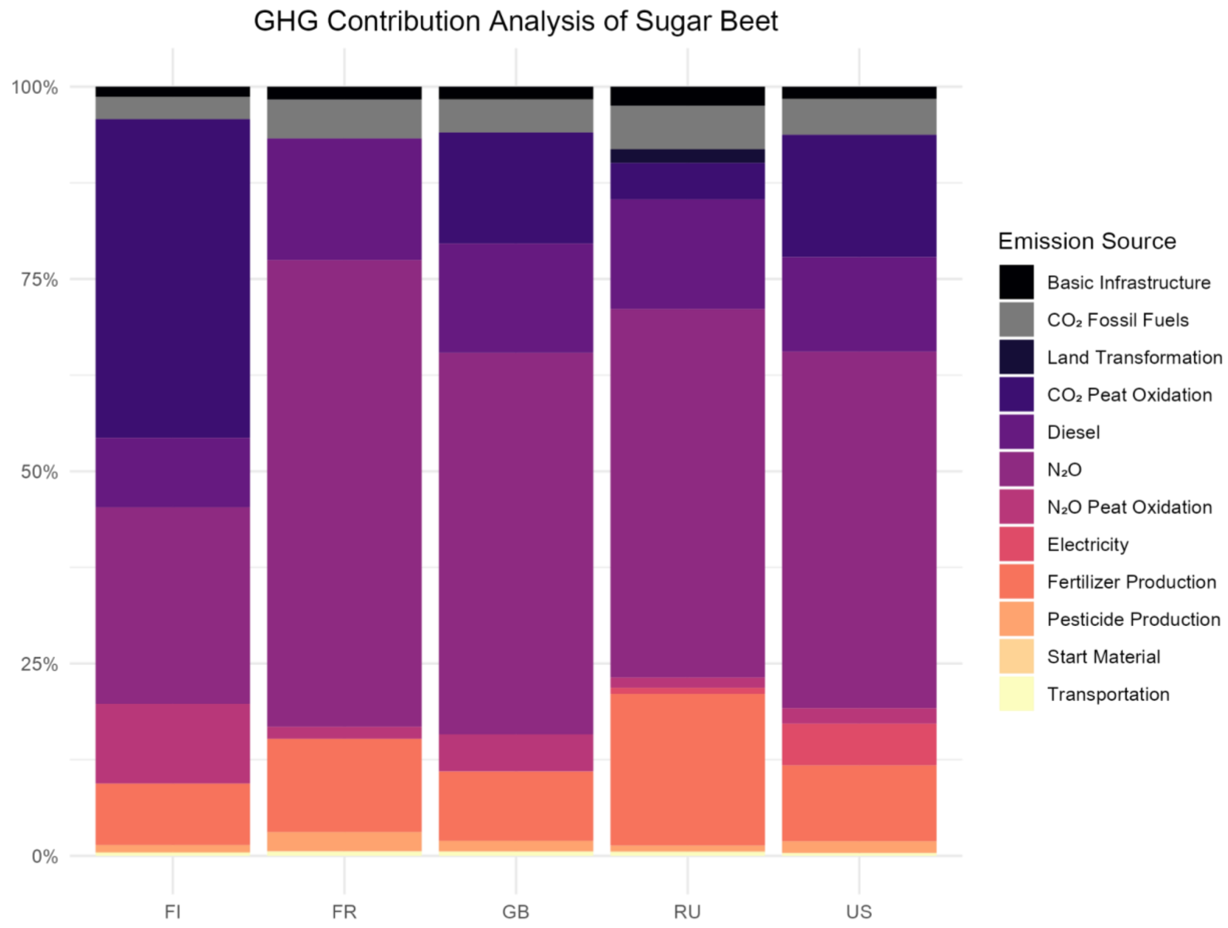


Figure 6: In the GHG contribution of sugar beet cultivation, impacts are relatively evenly distributed across impact categories, with N2O emissions being the most significant in four out of five countries. Another notable portion of emissions across all five countries is attributed to CO2 peat oxidation. Finland exhibits a more evenly distributed impact, with significant contributions from fertilizer, N2O, N2O peat oxidation, diesel, CO2 peat oxidation, and basic infrastructure. Fertilizer emerges as a significant contributor across countries, with Russia having the highest contribution in this category.

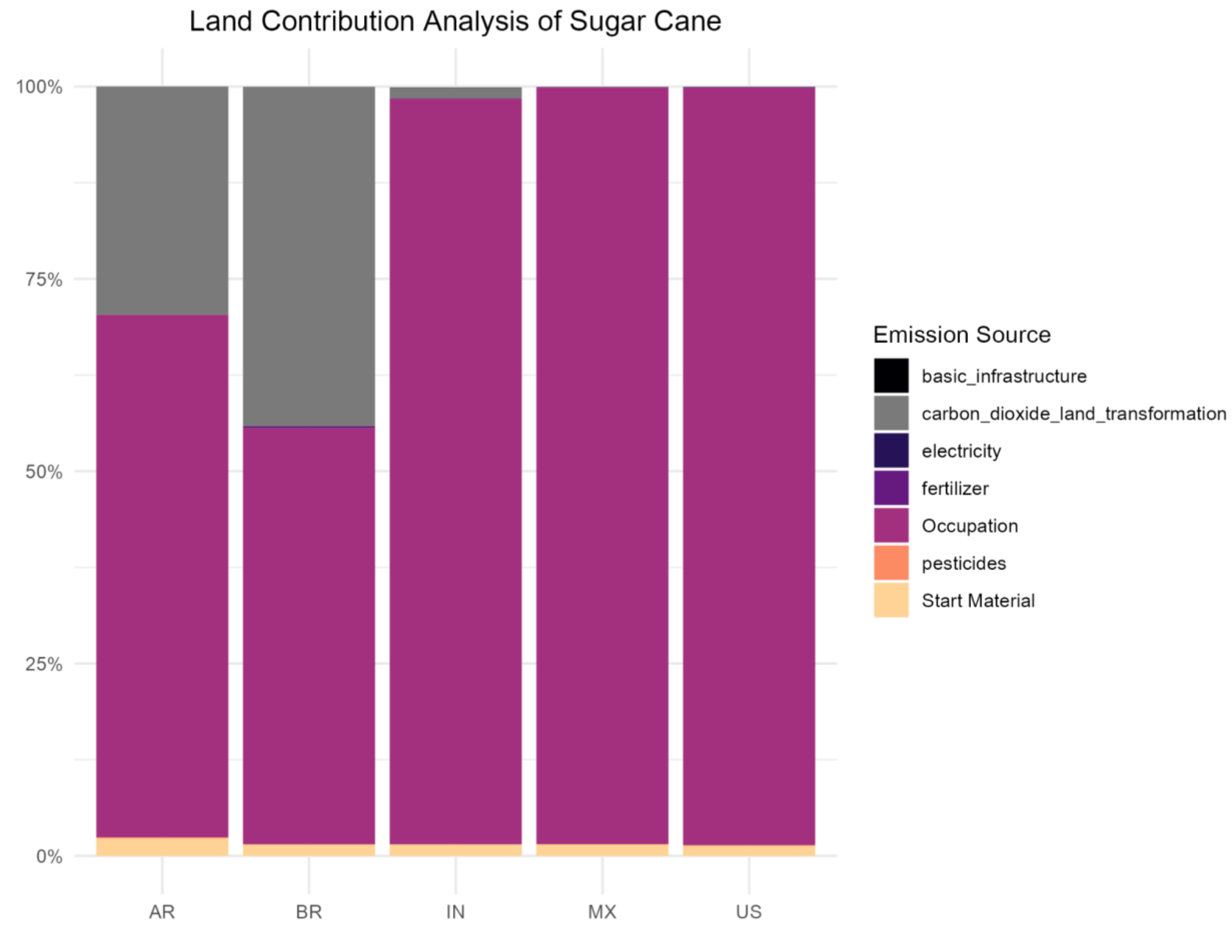


Figure 7: In sugar cane cultivation, the predominant factor driving land occupation is, by and large, occupation itself. In Argentina and Brazil, a notable land concern arises from land transformation, while in India, land transformation is relatively small. Conversely, in Mexico and the United States, land transformation is negligible, and the most significant category contributing to land occupation is, once again, occupation itself.

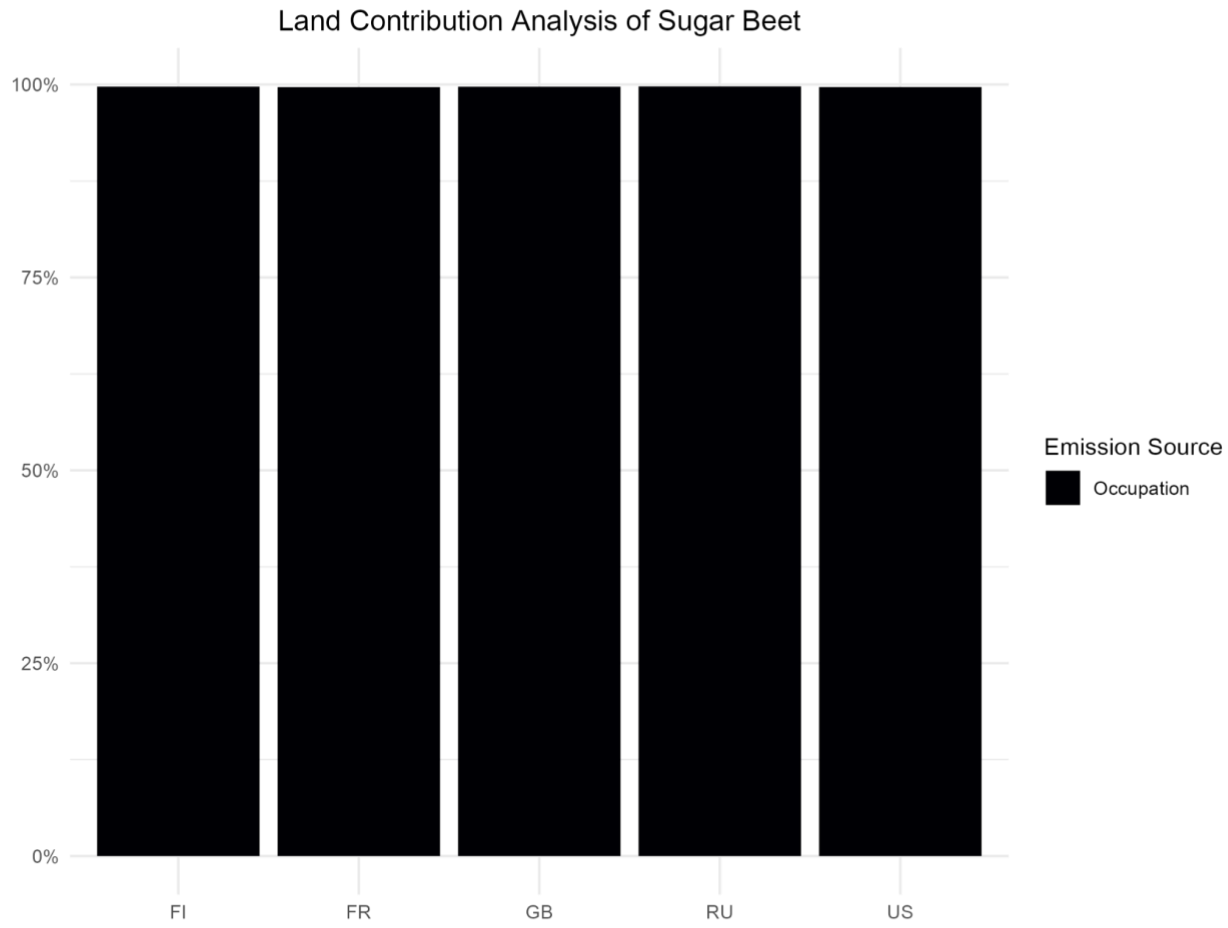


Figure 8: The primary factor contributing to land occupation in sugar beet cultivation for all countries is overwhelmingly land occupation itself.

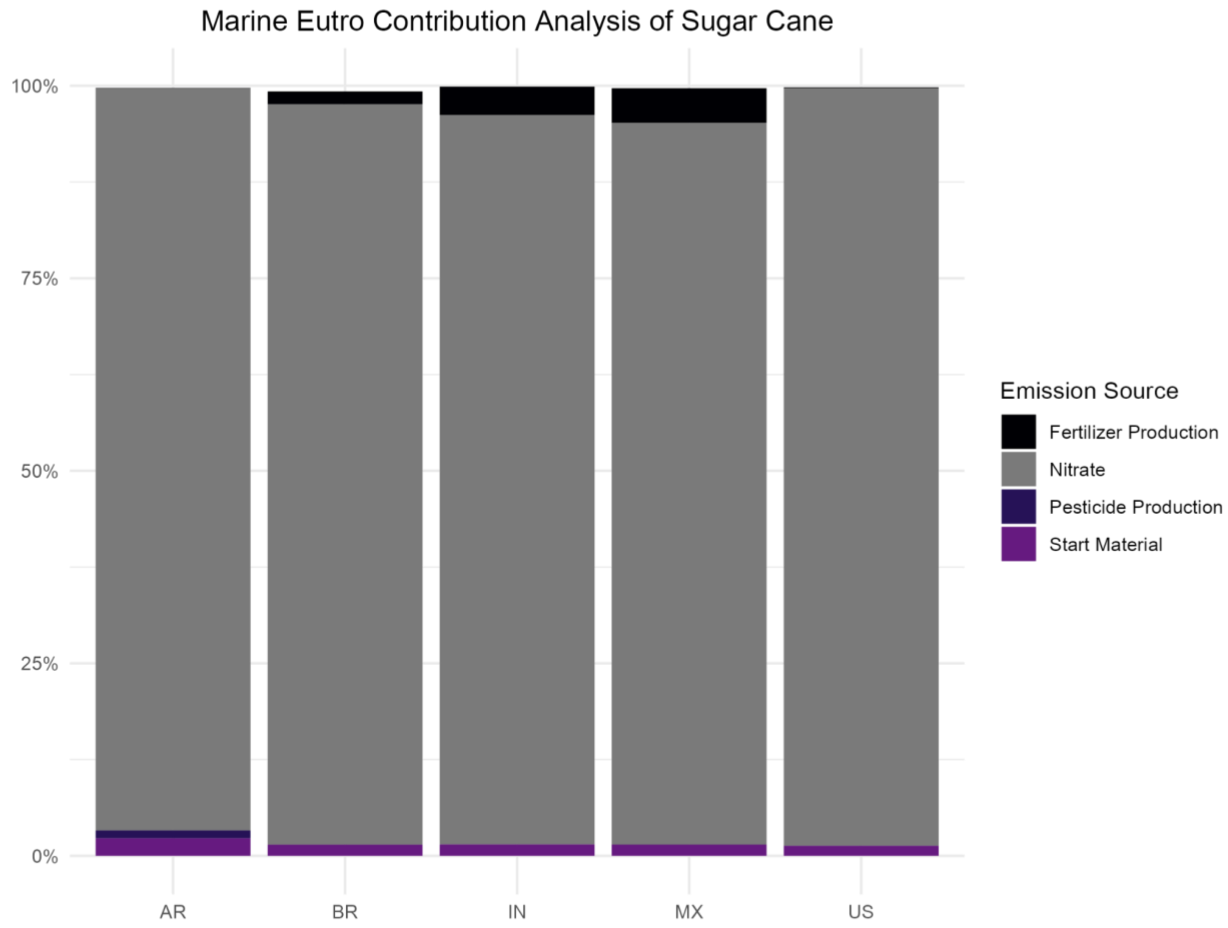


Figure 9: In sugar cane cultivation, the primary contributor to marine eutrophication is nitrate, representing nearly all of the impacts in this category. Start material contributes minimally across all five countries, while in India and Mexico, electricity also has a very slight impact. Additionally, in Brazil, electricity contributes a small fraction to marine eutrophication.

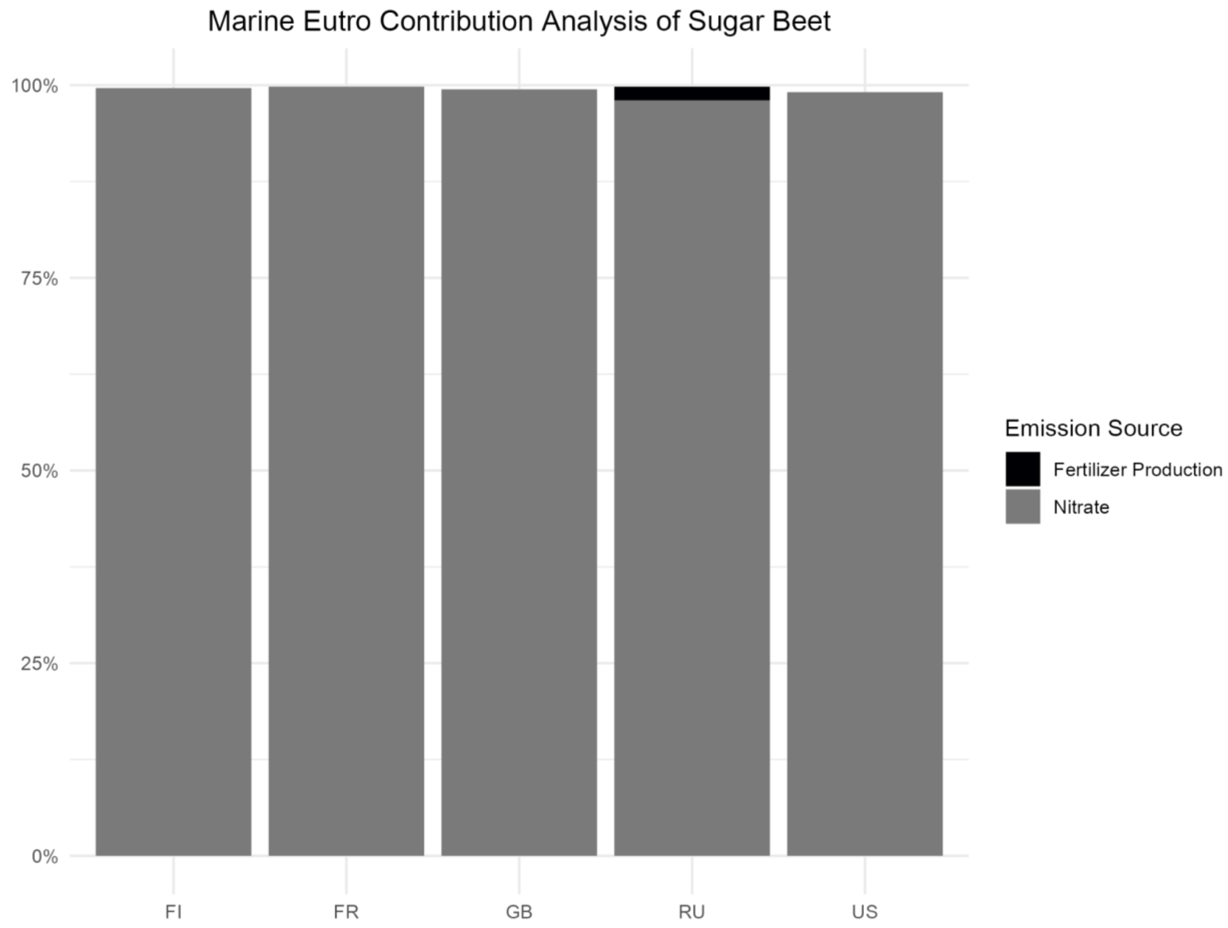


Figure 10: The predominant contributor to marine eutrophication in sugar beet cultivation is nitrate, accounting for nearly all of the impacts in this environmental category.

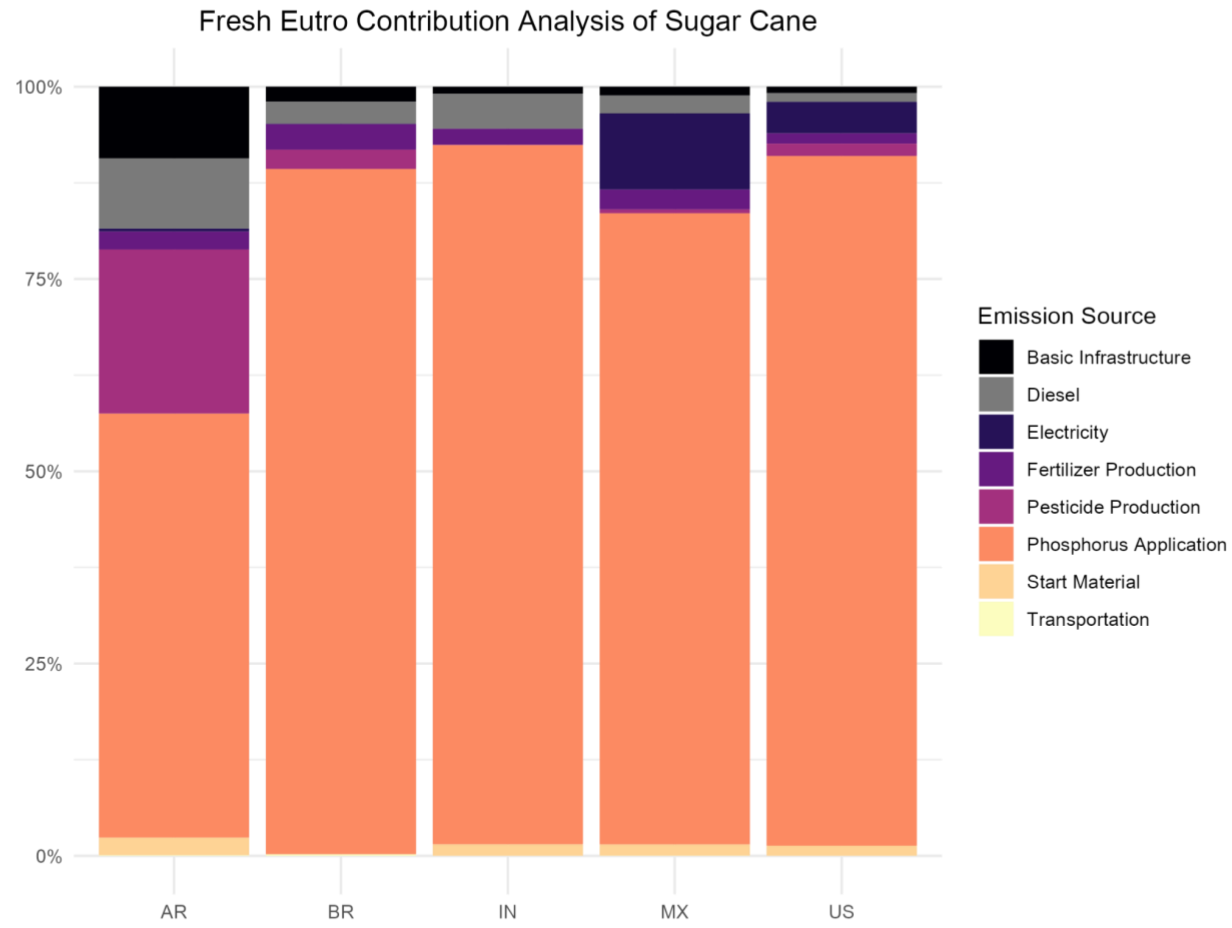


Figure 11: The largest impact on freshwater eutrophication in sugar cane cultivation stems from phosphorus. In Argentina, the impacts are notably diverse, with pesticides, transportation, diesel, electricity, and basic infrastructure collectively contributing to just under half of the freshwater eutrophication impacts. Among these factors, pesticides emerge as the most significant contributor. Across other countries, phosphorus remains the most significant contributor, while electricity plays a notable role in Mexico's freshwater eutrophication impacts.

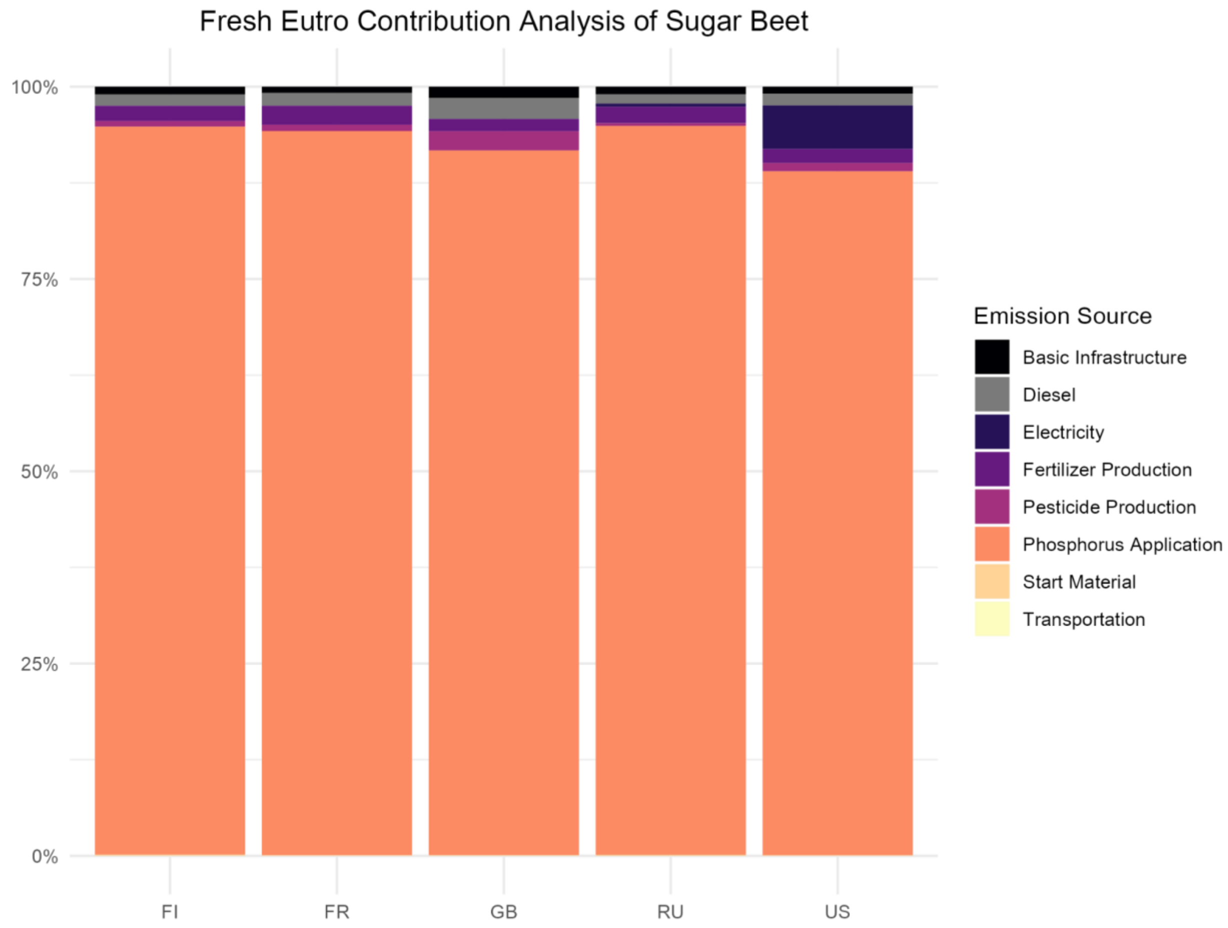


Figure 12: The largest impact on freshwater eutrophication in sugar beet cultivation is attributed to phosphorus. In the United States, there is a small impact due to electricity, but phosphorus remains the predominant factor contributing to eutrophication across all countries.

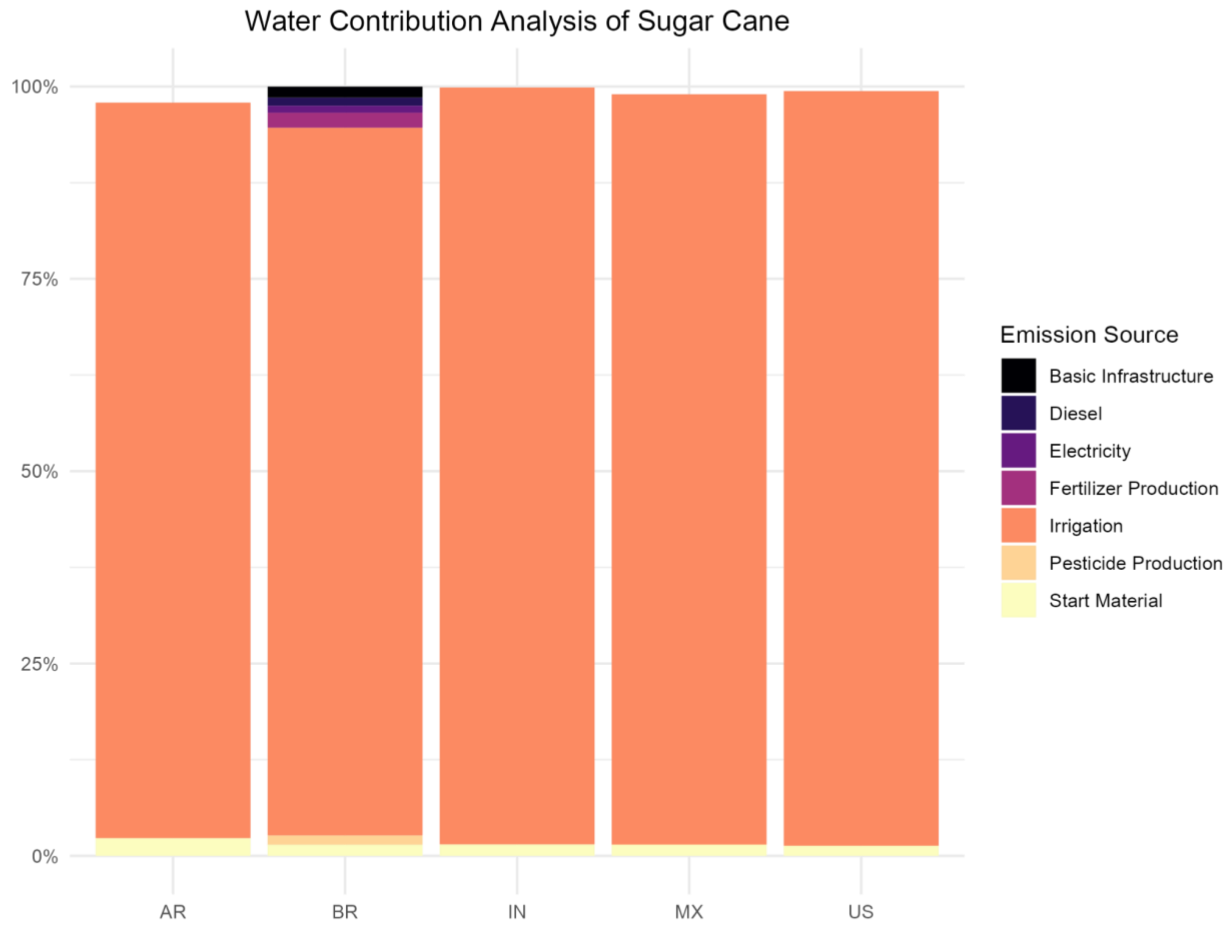


Figure 13: In sugar cane cultivation, irrigation emerges as the largest and most significant impact on water use across all five countries. Start material makes a minimal contribution, consistently small across all nations. In Brazil, there is a slight impact from basic infrastructure, diesel, and electricity at the farm level, adding additional factors to the water use considerations in sugar cane cultivation.

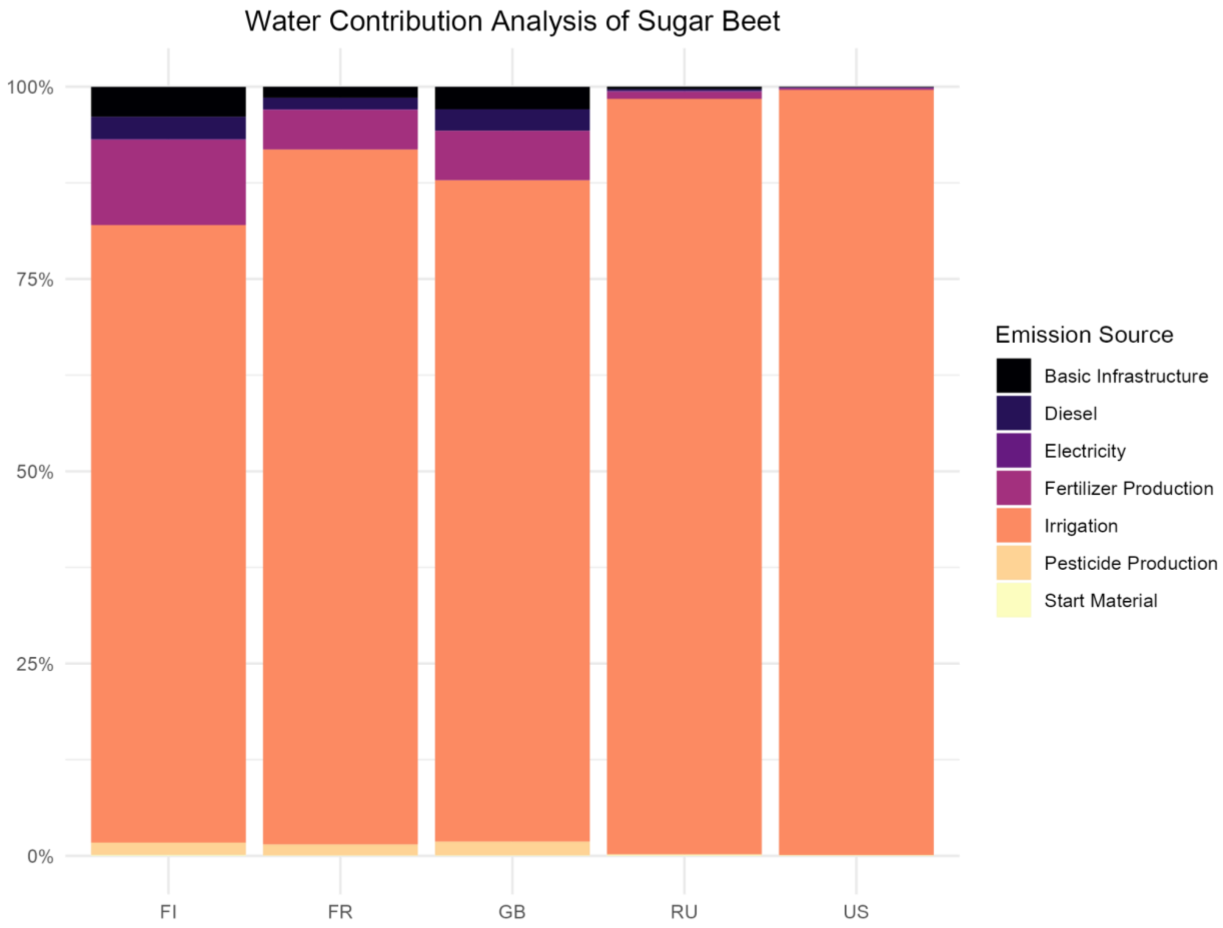


Figure 14: In sugar beet cultivation, the greatest contributor to water use across all five countries is irrigation. In Finland, France, and Great Britain, pesticides and fertilizer also contribute, with fertilizer being the more significant factor. However, in Russia and the United States, irrigation comprises nearly the entire contribution to water use in sugar beet cultivation.

Mitigation Analysis - Sugar Cane and Sugar Beet

Sugar, derived from sugar cane, is the least efficient food to consume from a human health perspective but the most efficient to utilize as a biofuel feedstock (King & van den Bergh, 2022; Wong et al., 2019). This is because refined sugars provide empty calories devoid of essential nutrients. From a biofuel perspective, sugarcane-derived sugar is considered efficient due to its high carbohydrate content. Sugar cane contains significant amounts of sucrose, a carbohydrate easily converted into ethanol through fermentation. Bioethanol from sugar cane can provide a renewable and low-emission energy source. Therefore, taxation aimed at reducing refined sugar intake in humans and promoting deliberate bioethanol production from existing sugar cane cropland can promote positive human health outcomes while decreasing reliance on fossil fuel energy sources and reducing GHG emissions (Cortez et al., 2016; Fargione et al., 2008). Utilizing existing sugar cane cropland for ethanol production would limit deforestation and indirect land use change (LUC), which is pivotal to promoting environmentally positive bioethanol (King & van den Bergh, 2022).

Human consumption of refined sugar (from cane or beet) is linked to multiple negative health outcomes, including heart disease, diabetes, and obesity (Graaf & Hofstra, 2020). Refined sugars are essentially “empty calories,” a calorically dense carbohydrate with negligible nutritional value (Schmidhuber et al., 2018; Wong et al., 2019). Given the connection between sugar consumption and poor health outcomes, prioritizing sugar as a human food source becomes questionable in a global food production system that meets the caloric needs of the population but lacks sufficient macro and micronutrients (Graaf & Hofstra, 2020). Transitioning sugar derived from sugar cane away from refined sugar and toward bioethanol production is an appealing mitigation strategy due to sugar cane's higher energy yield per acre and relatively low carbon payback period compared to other biofuel crops (King & van den Bergh, 2022; Sant'Anna, 2024). A 2024 environmental assessment of Brazilian ethanol production found that carbon payback times range from 5.6 to 21.5 years depending on sugar cane cropland conversion (Sant'Anna, 2024). However, the carbon payback times in any scenario are significantly smaller compared to US corn ethanol, which pays back in 167 years (Sant'Anna, 2024; Searchinger et al., 2008; Wang et al., 2014). This vast discrepancy is primarily because of lower carbon efficiency in corn ethanol production compared to sugar cane (Searchinger et al., 2008).

The most crucial factor in determining ethanol's carbon savings and payback time depends on LUC associated with growing sugar cane (Picoli & Machado, 2021; USDA, 2010). The overarching controversy regarding the use of ethanol biofuels comes from the trade-off between the carbon emission from land conversion and the avoided emissions over time by replacing fossil fuels with a renewable source (Alvarado et al., 2023; Group, 2023). In the case of sugar cane ethanol, there is little consensus across the literature for carbon payback times. The carbon payback time could vary from five to more than a hundred years, depending on assumptions regarding the type of land cover substituted by sugar cane (Gibbs et al., 2008; Fargione et al., 2008; Searchinger et al., 2008; Elshout et al., 2015). If the land converted to sugar cane fields comes from areas of natural cover with high carbon storage (tropical forests), the carbon payback time is high. However, if land with lower carbon retention is converted to sugarcane (existing cropland or pasture), the carbon payback time will be significantly lower (Sant'Anna, 2024). The smallest payback time would be to use existing sugar cane cropland

(King & van den Bergh, 2022; Renzaho et al., 2017). Depending on future ethanol demand, the land needed to produce Brazilian sugar cane for ethanol is expected to increase by 14 to 58% above 2018 land use (de Andrade et al., 2020). Reducing refined sugar demand for human consumption while bioethanol demand increases allow for greater ethanol production on existing sugar cane cropland.

Governments, corporations, and sustainable development organizations (like the UNEP) have promoted bioethanol production to promote several UN Sustainable Development Goals. Bioethanol production can reduce fossil oil dependency on energy and reduce toxic emissions (SDG 7) (USDA, 2010). Using agricultural residues and municipal solid wastes supports a circular economy (SDG 2 and 3) (Borges, 2023). Deliberate production and land use planning can facilitate land restoration and promote using marginal lands to grow energy crops, creating high-quality and stable rural jobs (SDG 8 and 13) (Borges, 2023; International Energy Agency, 2019). However, the Intergovernmental Panel on Climate Change (IPCC) recognizes a lack of consensus on the role of biofuels in climate change policies (Smith & Porter, 2018). The IPCC Fifth Assessment Report (IPCC, 2014) recommends support for biofuels be reviewed on a case-by-case basis (Jeswani et al., 2020).

A 2022 study found that global emissions could fall between 20.9 to 54.3 Mt CO2e per year if the European Union (EU) were to reduce its sugar consumption in line with health guidelines and the excess Brazilian sugar cane redirected to ethanol (King & van den Bergh, 2022). Sugar consumption per capita in the EU is estimated to be 102.14 g per day (Sánchez-Romero et al., 2020). The WHO recommends 25 g per person per day (Thow & Hawkes, 2014). The 77.14 g reduction per person per day to meet WHO recommendations would require a

12.54 Mt decrease in total annual EU sugar consumption, a 75.5% reduction on current levels (Alvarado et al., 2023; King & van den Bergh, 2022). If the EU keeps its sugar production stable and exports the excess 12.54 Mt instead of consuming it domestically, it would free up 1.06–1.31 (mean 1.18) million hectares of cropland to produce ethanol in Brazil (Cunningham et al., 2015; King & van den Bergh, 2022). The study found that this would be the most environmentally advantageous way to reduce emissions (other options being the EU produces ethanol from domestically farmed sugar beet or EU-afforested sugar beet domestic cropland) (de Andrade Junior et al., 2019; King & van den Bergh, 2022). The analysis posits that a European Union–Brazil agreement focusing on sugar production from sugar beet and Brazil producing ethanol from sugar cane would provide the greatest environmental benefits to society (King & van den Bergh, 2022; (Manochio et al., 2017). This analysis illustrates how global collaboration can improve human health and reduce emissions from the agricultural sector. This scenario could occur through market mechanisms alone, but ideally, a European Union–Brazil treaty would reinforce land planning and policy to produce a more certain positive effect (Outlaw et al., 2007; Pillay & van den Bergh, 2016).

Land use policies, like “agro ecological zoning” (AEZ) in Brazil that protect environmentally sensitive areas from sugarcane agricultural expansion are crucial to promoting life cycle thinking in biofuel policy (de Andrade Junior et al., 2019; Solomon, 2010). The expansion in ethanol production may endanger tropical forests, which could offset the carbon savings accrued over time by the replacement of fossil fuels (Timilsina & Shrestha, 2011). However, developing a biofuel program in Brazil that restricts deforestation and land use change in high carbon storage areas could promote multiple SDGs and champion sustainable agriculture, human health, and reduce fuel emissions in the transportation sector. These policies, like AEZ, promote land intensification and prohibit deforestation while helping Brazil meet future scenarios of demand for sugarcane-based ethanol (Jaiswal et al. 2017).

Mitigating the environmental impacts of growing sugar cane and sugar beet requires sustainable land management practices. One crucial behavioral change at the farm level is reducing chemical pesticides and fertilizers (Yousefi et al., 2014). A study analyzing sugar beet cultivation in Germany found that the CO2-eq emissions from N fertilization were 2.5 times higher than those caused by diesel burning (Trimpler et al., 2016). The study used data from 1181 farms and reported that emissions of N fertilization (including N2O field emissions) were the predominant part of CO2-eq emissions, and the origin of N fertilization (either mineral or organic) influences total GHG emissions (Trimpler et al., 2016). Organic fertilizer had lower emissions across the study results. A potential mitigation strategy for this fertilization issue is to use organic fertilizer and livestock husbandry to avoid emissions from mineral fertilizer production (Trimpler et al., 2016; Yousefi et al., 2014). In addition, reducing excessive mineral fertilizers and using precision agriculture techniques reduces the eutrophication potential of chemical runoff into waterways.

A 2014 study analyzing sugar beet production in Iran highlighted that reducing diesel fuel (by lessening plowing and land preparation) and chemical fertilizer consumption (mainly nitrogen) are the most effective methods to decrease energy usage and emission of greenhouse gasses in sugar beet production systems (Yousefi et al., 2014). A 2018 study on conventional and organic beet farming reported that no-tillage yielded the lowest carbon emission input. In addition to GHG emissions, reduced tillage helped minimize soil erosion and maintain soil health (Šarauskis et al., 2018). The study also found that by increasing the size of the farm from small (2 ha) to large (80 ha), the overall carbon emissions per beet decreased (Lowder et al., 2016). The most environmentally friendly sugar beet farming methods involved no-tillage on large farms. An effective emission weed control technique was the use of inter-row loosening, which decreased energy use and tillage at the farm level (Šarauskis et al., 2018).

A UK study of sugar beet production on peat, silt, and clay loam soils found that more water-retentive soils produced larger yields, increased energy efficiency, and minimized the GWP from chemical inputs (Tzilivakis et al., 2005). The crucial factor driving energy input per hectare was soil conditions, not organic conditions or conventional growing techniques. Growing beets in sand soil increased irrigation necessity and mineral fertilizer application. The GWP was smallest for beets grown on fertile peat and silt soils, while GWP was greatest for beets irrigated on sand and sandy loam soils (Tzilivakis et al., 2005). This finding highlights the need to grow sugar beets in suitable soil conditions to reduce the necessary irrigation and fertilizer use, which significantly contribute to GHG emissions, water use, and eutrophication potential.

Contribution Analysis - Maize

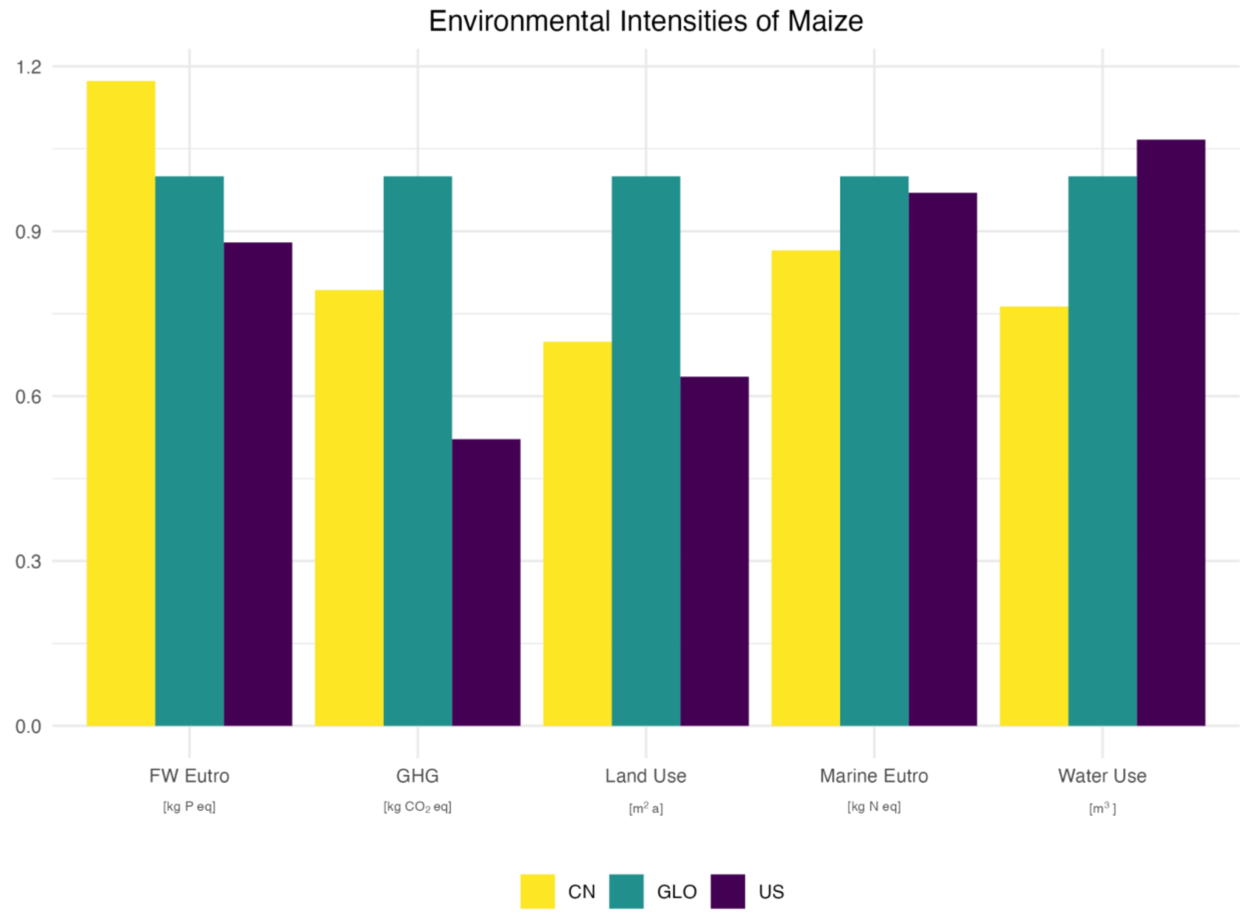


Figure 15: The figure presented depicts impact intensities of China and the United States normalized against the weighted global average of the maize dataset. The global weighted average intensity is higher than that of CN and the US for all impact categories apart from freshwater eutrophication and water use. The US is relatively less GHG intensive while being the most water intensive.

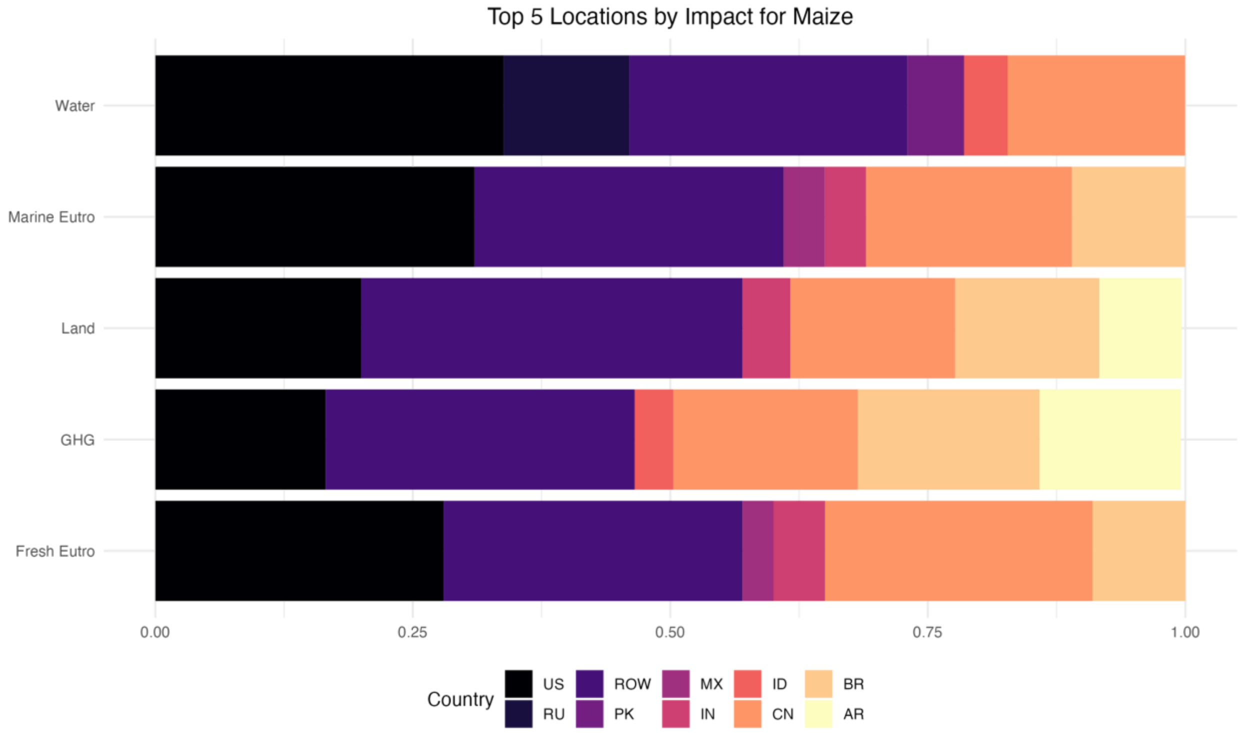


Figure 16: This figure illustrates the contribution of the top five countries to the global impact for each impact category. The United States, Brazil, and China are significant contributors across all impact categories; however, Brazil does not contribute significantly to water consumption.

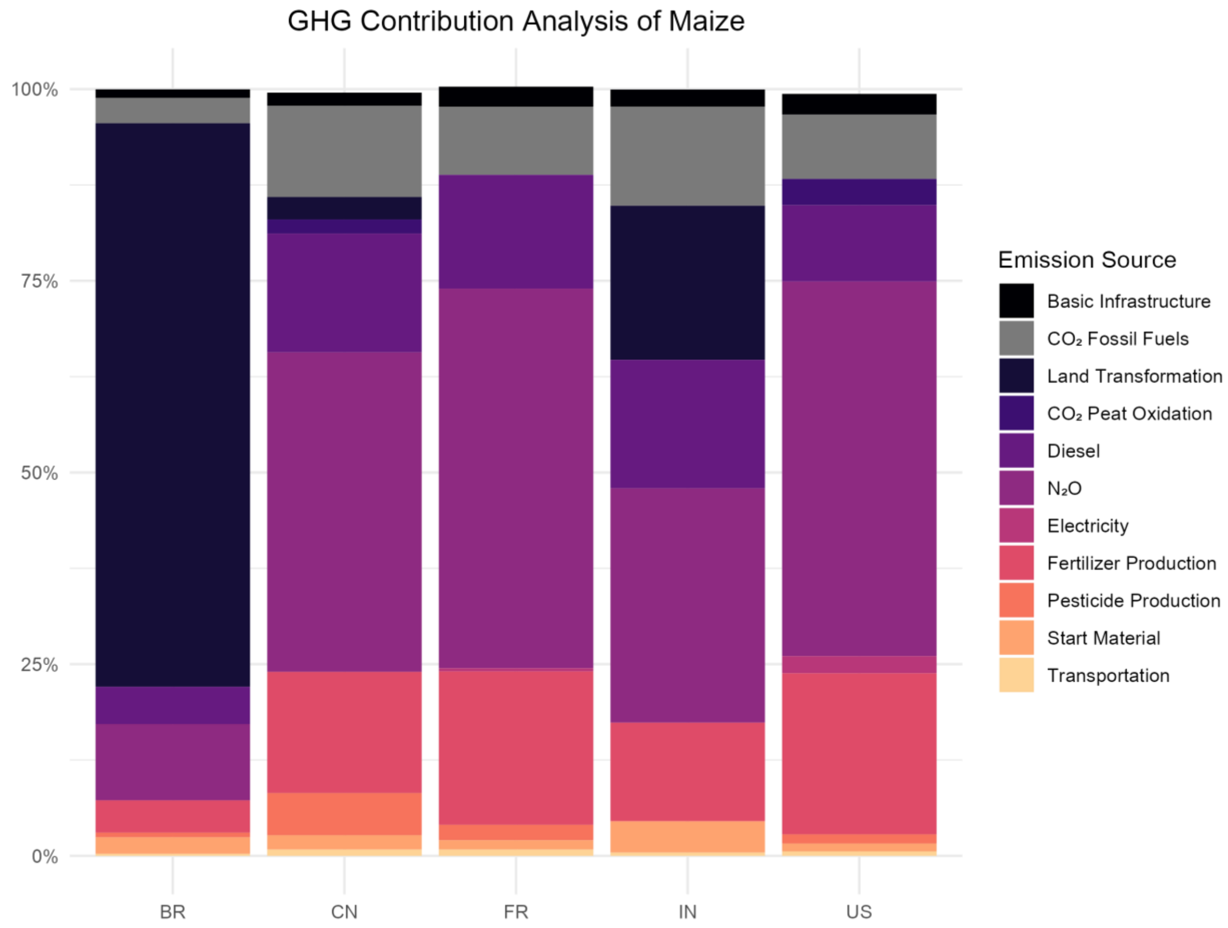


Figure 17: This figure illustrates the GHG hotspot analysis of maize in Brazil, China, France, India, and the United States. N2O emissions from fertilizer production and applications are a major source across all countries. For Brazil, CO2 emissions from land transformation are a significant contributor to maize production.

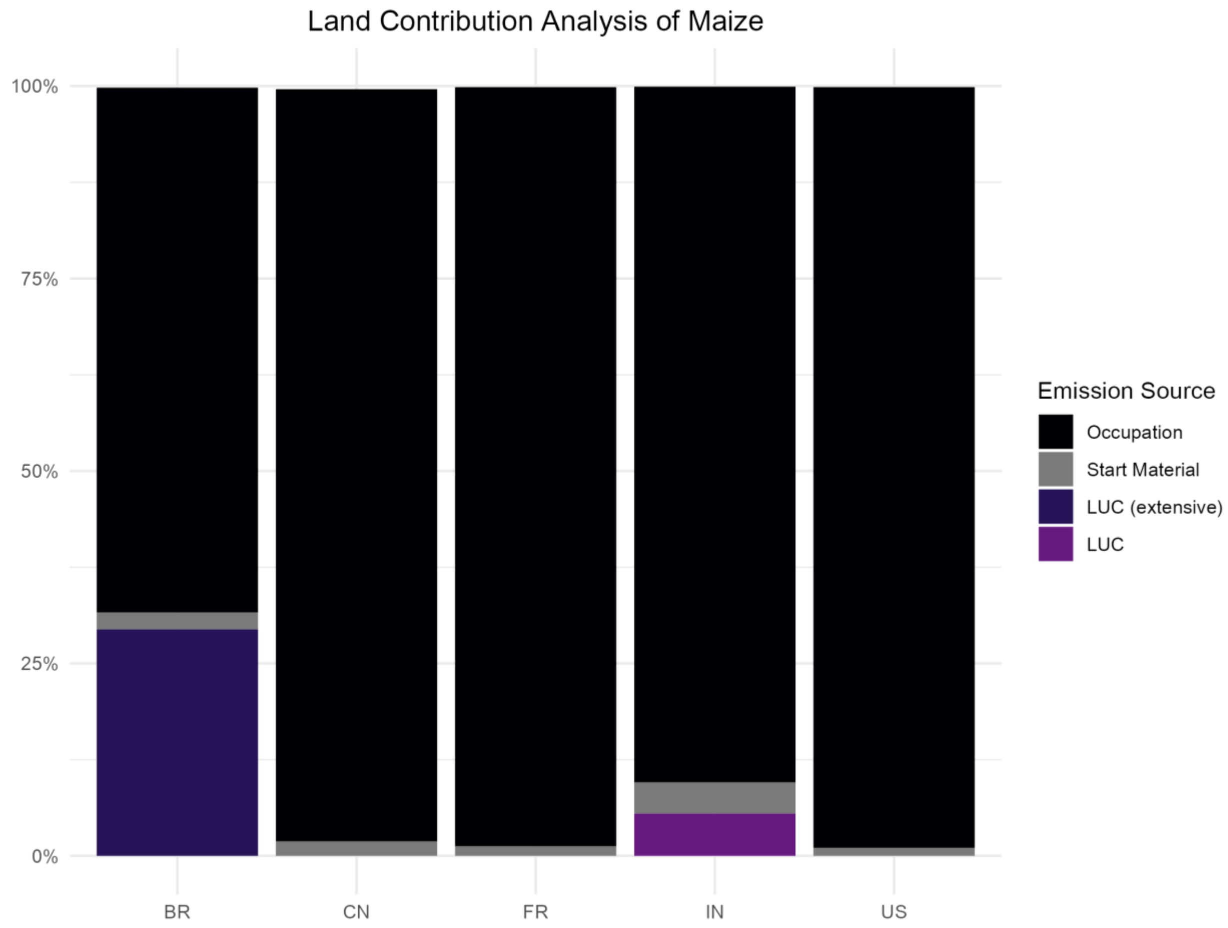


Figure 18: This figure illustrates the land use hotspot analysis of maize in Brazil, China, France, India, and the United States. Majority of land use is attributed to land occupation for all countries. Due to extensive land transformation from forests, LUC is a significant contributor for Brazil while LUC is a minor contributor for India due to land transformation from grassland.

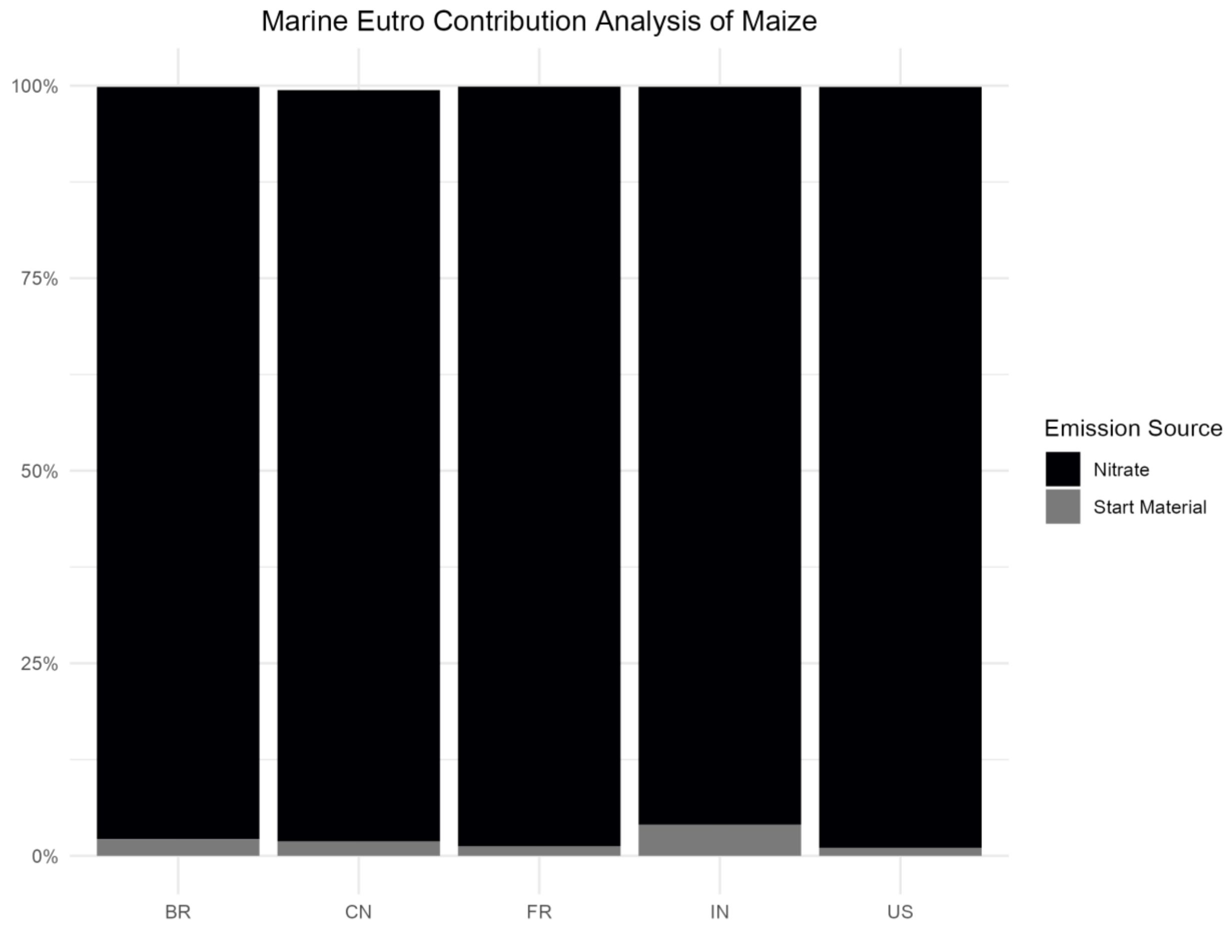


Figure 19: This figure illustrates the marine eutrophication hotspot analysis of maize in Brazil, China, France, India, and the United States. Nitrate emissions from the use of fertilizer contributes to 100% of marine eutrophication

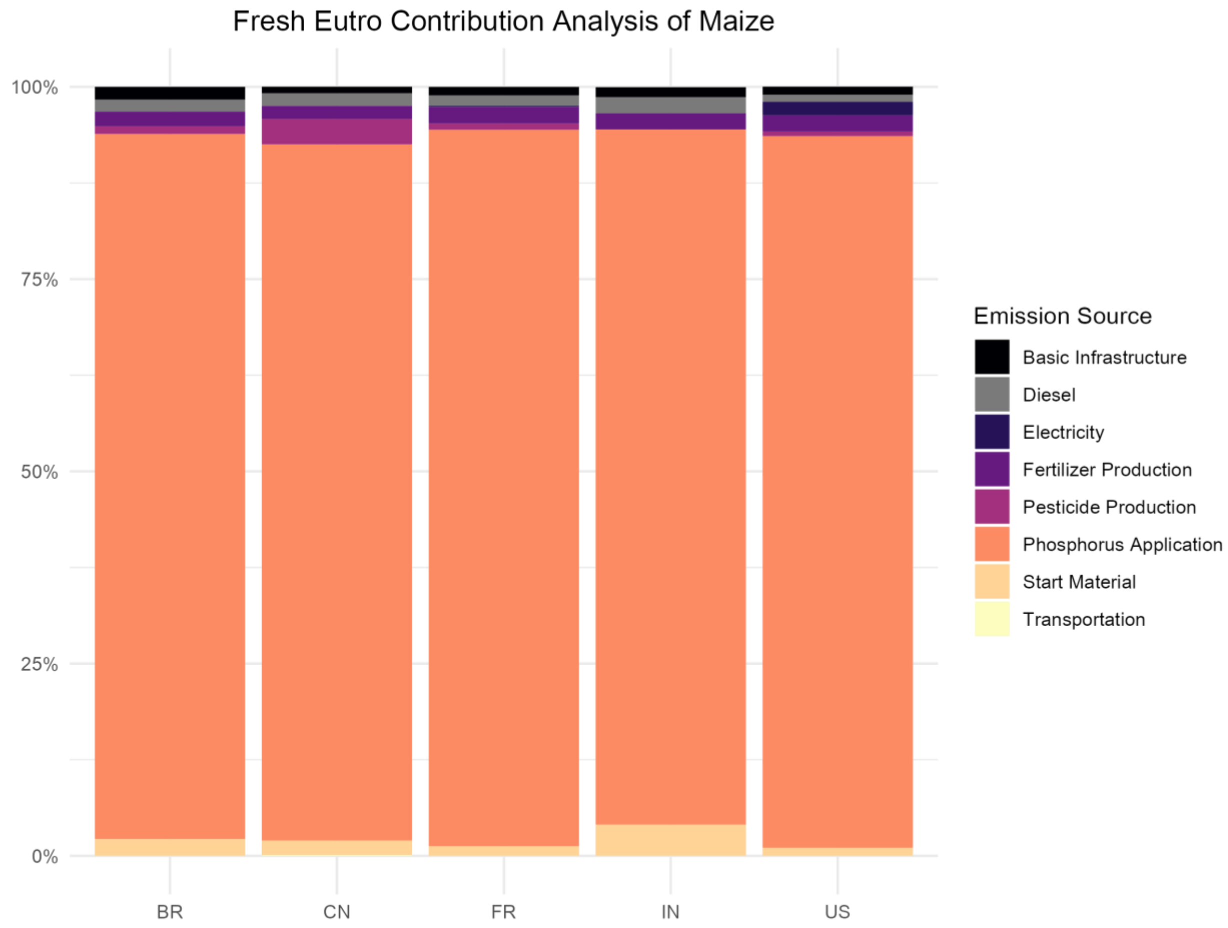


Figure 20: This figure illustrates the freshwater eutrophication hotspot analysis of maize in Brazil, China, France, India, and the United States. Phosphorus emissions from the use of fertilizer contribute to over 90% of freshwater eutrophication.

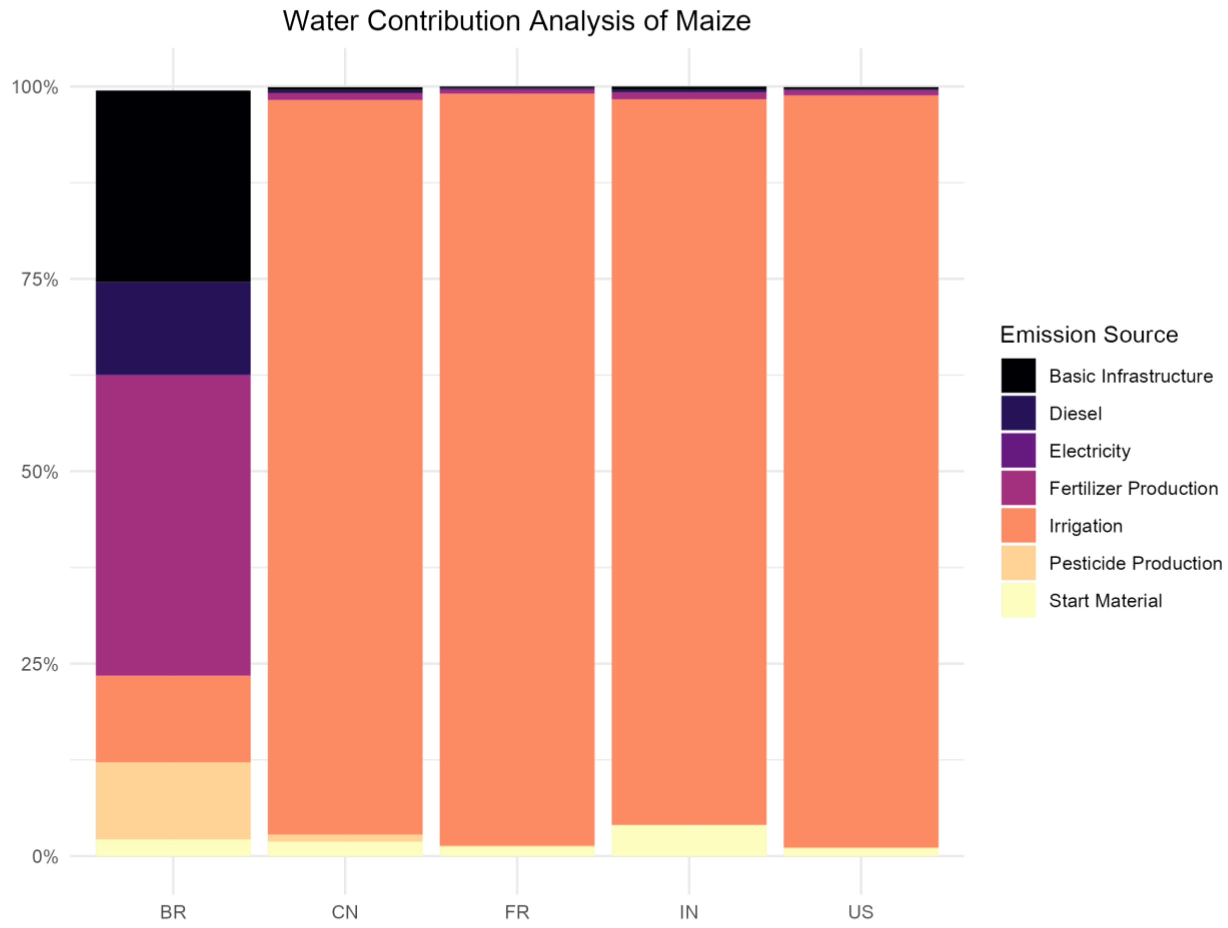


Figure 21: This figure illustrates the water consumption hotspot analysis of maize in Brazil, China, France, India, and the United States. Water consumption from irrigation is a major contributor for all countries apart from Brazil, where water used in fertilizer, pesticide and electricity production is a hotspot.

Mitigation Analysis - Maize

Globally, maize production accounts for a large area (197.23 Mha) (Erenstein et al., 2022). It accounts for 30% of the food supply in the Americas, 38% in Africa and 6.5% in Asia, and is a major contributor to local food security (Prasanna et al., 2020; Tripathi et al., 2021). The areas span across sub-Saharan Africa (SSA), Asia, North America and Latin America (FAO, 2020). Despite primarily being utilized as feed for animals, it also serves as a source of bioenergy (Erickson & Berger, 2013). The use of maize for biofuel production has garnered increasing attention albeit controversial due to its high GHG emissions. However, corn-based ethanol is considered a mitigation strategy for emissions from fossil fuel use (Jayasundara et al., 2014). However, a previous study illustrated that ethanol produced from corn grown in only two out of eight counties met the regulatory target set by the US EPA for qualifying as a renewable fuel (Fast et al., 2012). Thus, aligning with the mitigation strategy for Sugar, substituting ethanol production from maize with sugar could be an option that could be explored owing to the lower environmental impact of growing sugar compared to maize.

Owing to its versatile nature (Erenstein et al., 2022), mitigation strategies can be developed based on how maize is being used - feed or food. For maize being used as food for human consumption, sweet maize poses as an environmentally friendly alternative to conventional maize, as it demonstrated lower impacts across the studied impact categories including GHG emissions (Giusti et al., 2023). This can be attributed to its increased green mass due to the amount of water and presence of corncob in its composition, and the absence of mechanical harvesting and drying processes as it serves as food to humans (Giusti et al., 2023).

Other mitigation strategies are centered around farming practices and could potentially be utilized to grow maize grain in a more sustainable manner. This includes intercropping, which has been determined to be an effective way to improve system productivity (Yu et al., 2015). Intercropping exploits species complementarities to achieve sustainable intensification by increasing crop outputs per unit land with reduced anthropogenic inputs. There have been several studies highlighting the benefits of a cereal and legume intercrop, of which maize/soybean have been extensively covered (Gao et al., 2010, Xu et al., 2020, Zhao et al., 2024).

A global-scale meta-study examining the efficiency of land and fertilizer nitrogen use in maize-soybean intercropping revealed that, under similar yield conditions, maize-soybean intercropping can save an average of 32% of land resources and 44% of fertilizer nitrogen. While the practice improves land use efficiency worldwide, the extent of improvement varies significantly, ranging from 4% in South America to 48% in Europe (Xu et al, 2020). This practice could have a positive impact on land availability to meet the requirements of other resources due to the land sparing potential of the system. Moreover, several LCA studies highlighted the lower GHG of the intercrop system, due to reduced anthropogenic inputs like fertilizers, which could also lead to a potential reduction in the eutrophication impact as a result of lower fertilizer input.

Contribution Analysis - Rice

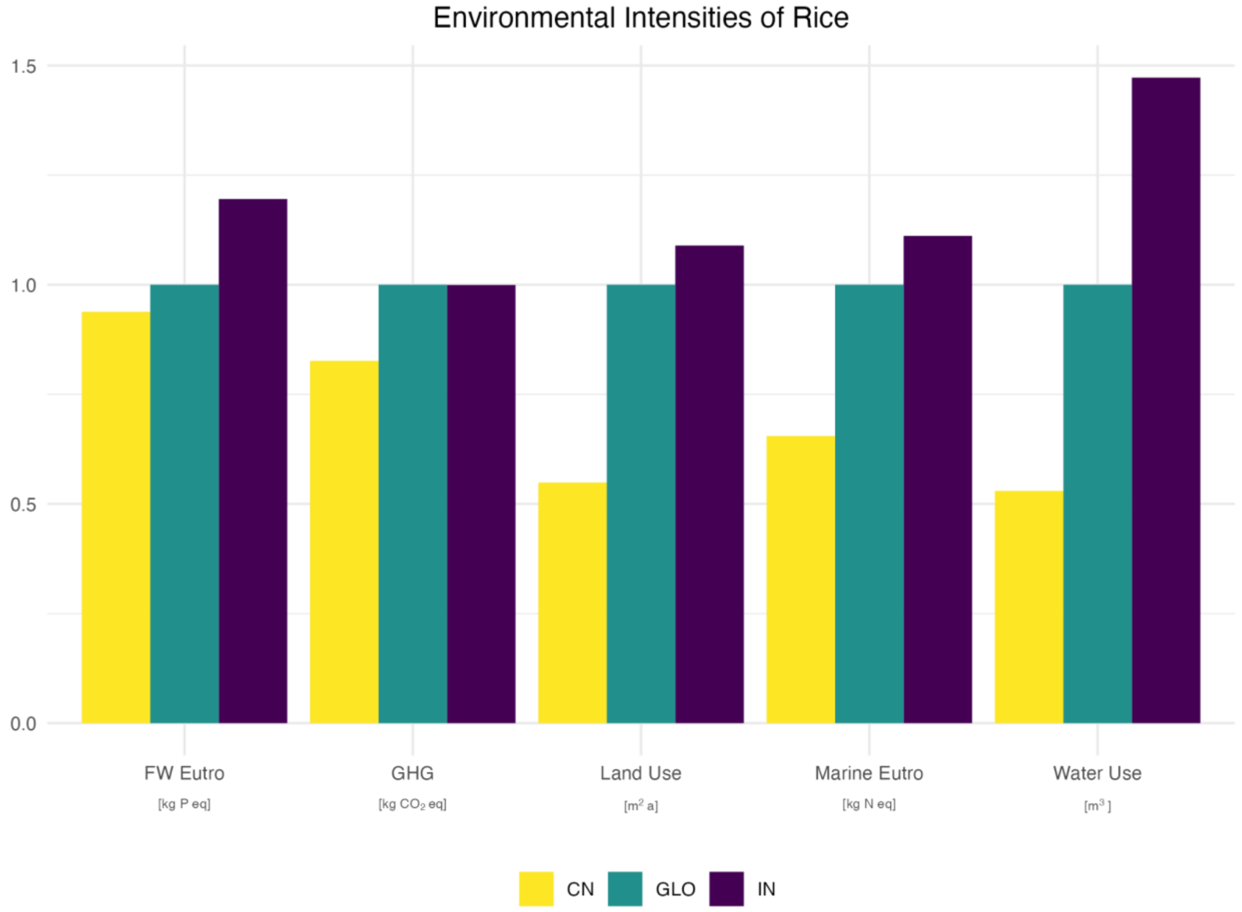


Figure 22: The figure presented depicts impact intensities of India and China normalized against the weighted global average of our dataset. Among all impact categories, China exhibits lowest impacts compared to global average. On the other hand, India has the highest intensity across all impact categories, particularly for water use. China has a remarkably low water consumption compared to the rest of the world.

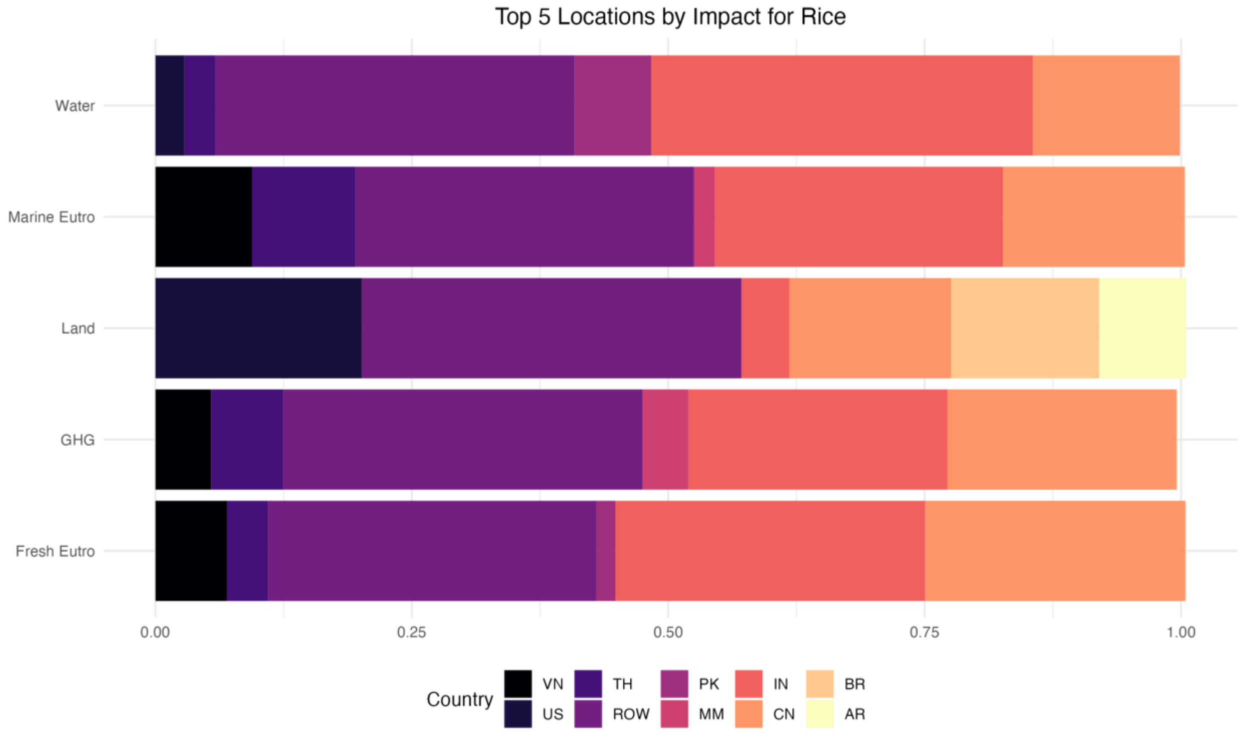


Figure 23: This figure illustrates the contribution of the top 5 countries to the global impact for each impact category. China and India are significant contributors in all categories while Brazil and the US are notable contributors for land use.

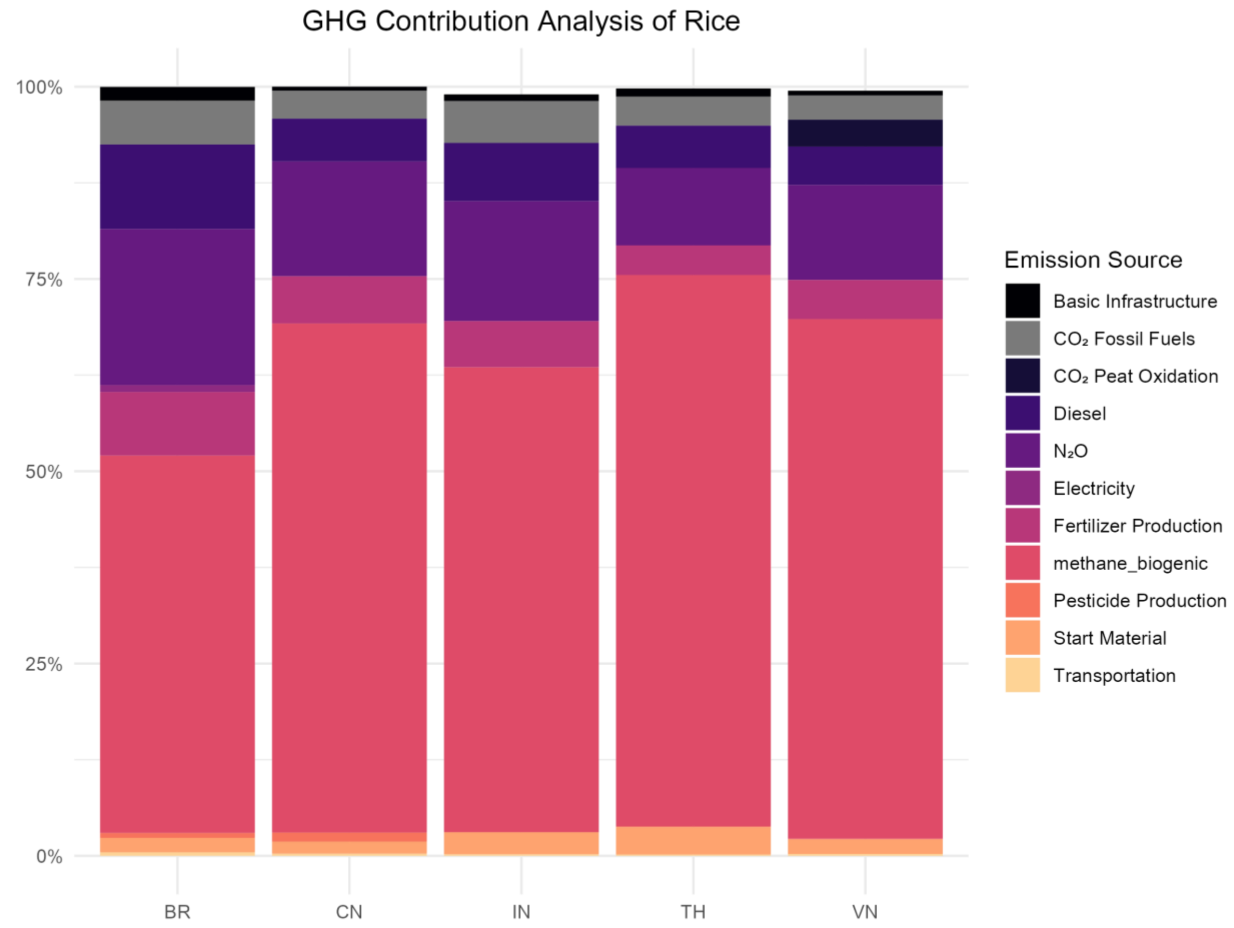


Figure 24: This figure illustrates the GHG hotspot analysis of rice in Brazil, China, India, Thailand and Vietnam. Methane (CH4) emissions from the soil due to flooded conditions are a primary hotspot for all countries. N2O emissions from fertilizer application and production is another hotspot.

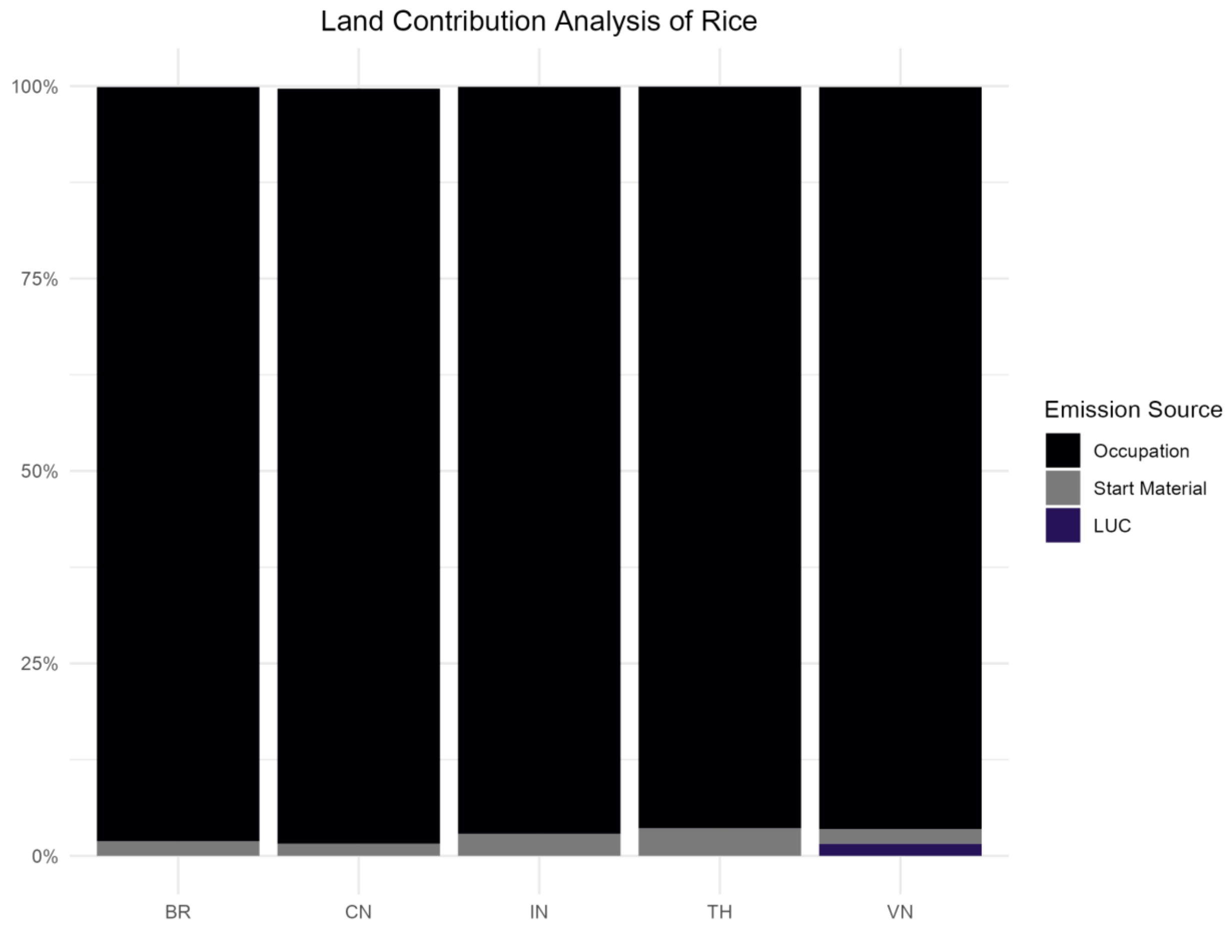


Figure 25: This figure illustrates the land use hotspot analysis of rice in Brazil, China, India, Thailand and Vietnam. Land use impacts due to land transformation or LUC occurs only in Vietnam and accounts for a small percentage of the total impact.

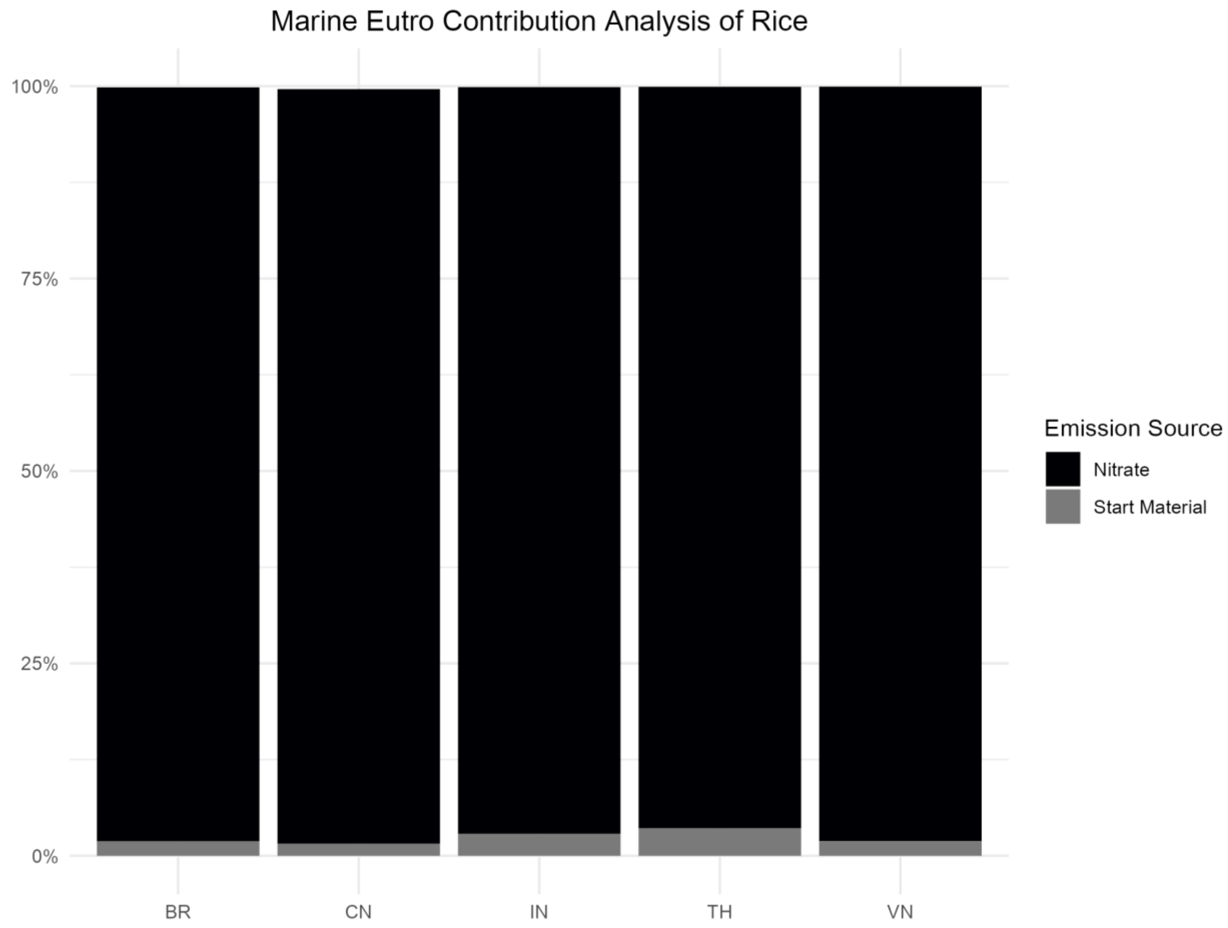


Figure 26: This figure illustrates the marine eutrophication hotspot analysis of rice in Brazil, China, India, Thailand and Vietnam. Nitrate emissions from the use of fertilizer contributes to almost 100% of marine eutrophication.

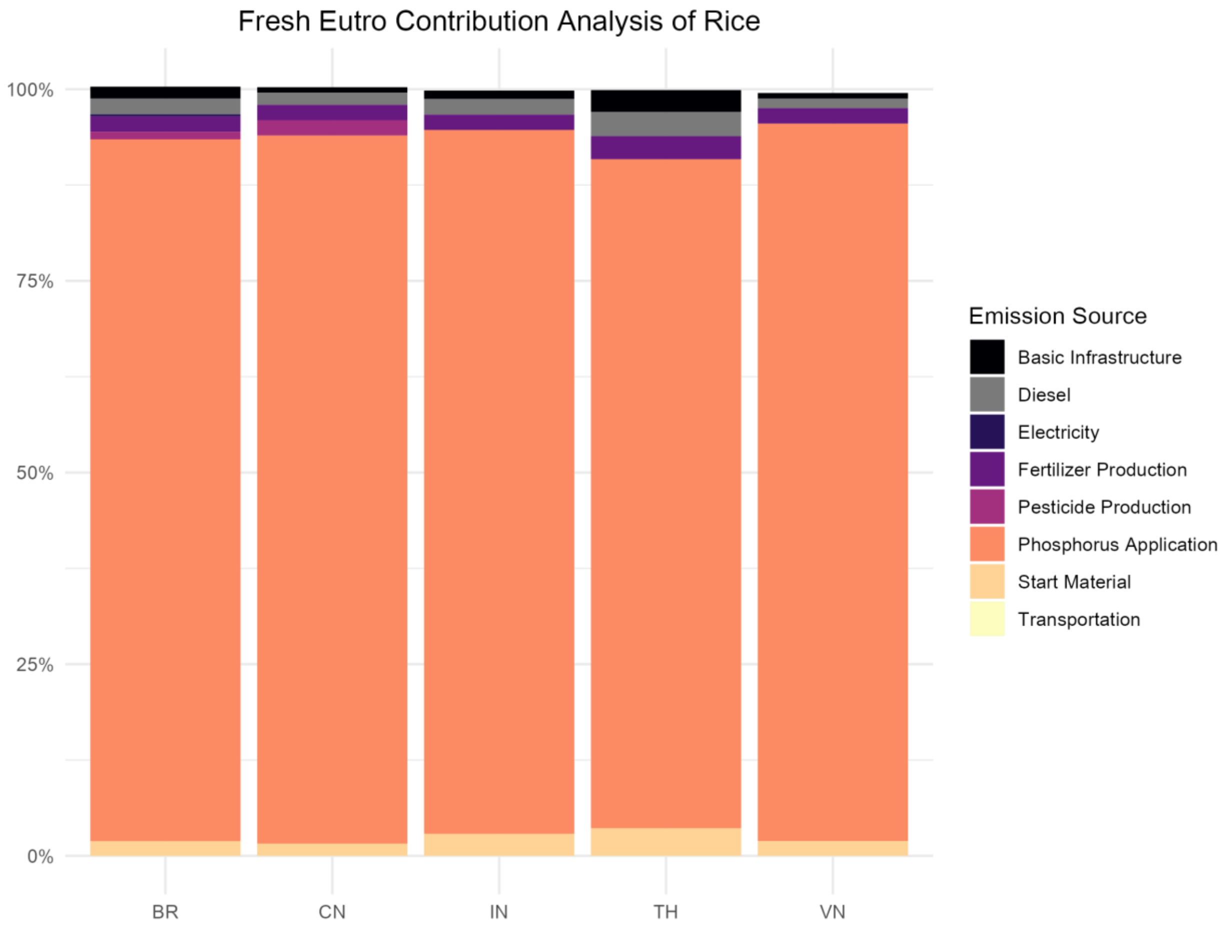


Figure 27: This figure illustrates the freshwater eutrophication hotspot analysis of rice in Brazil, China, India, Thailand and Vietnam. Phosphorus emissions from the use of fertilizer contributes to almost 100% of freshwater eutrophication.

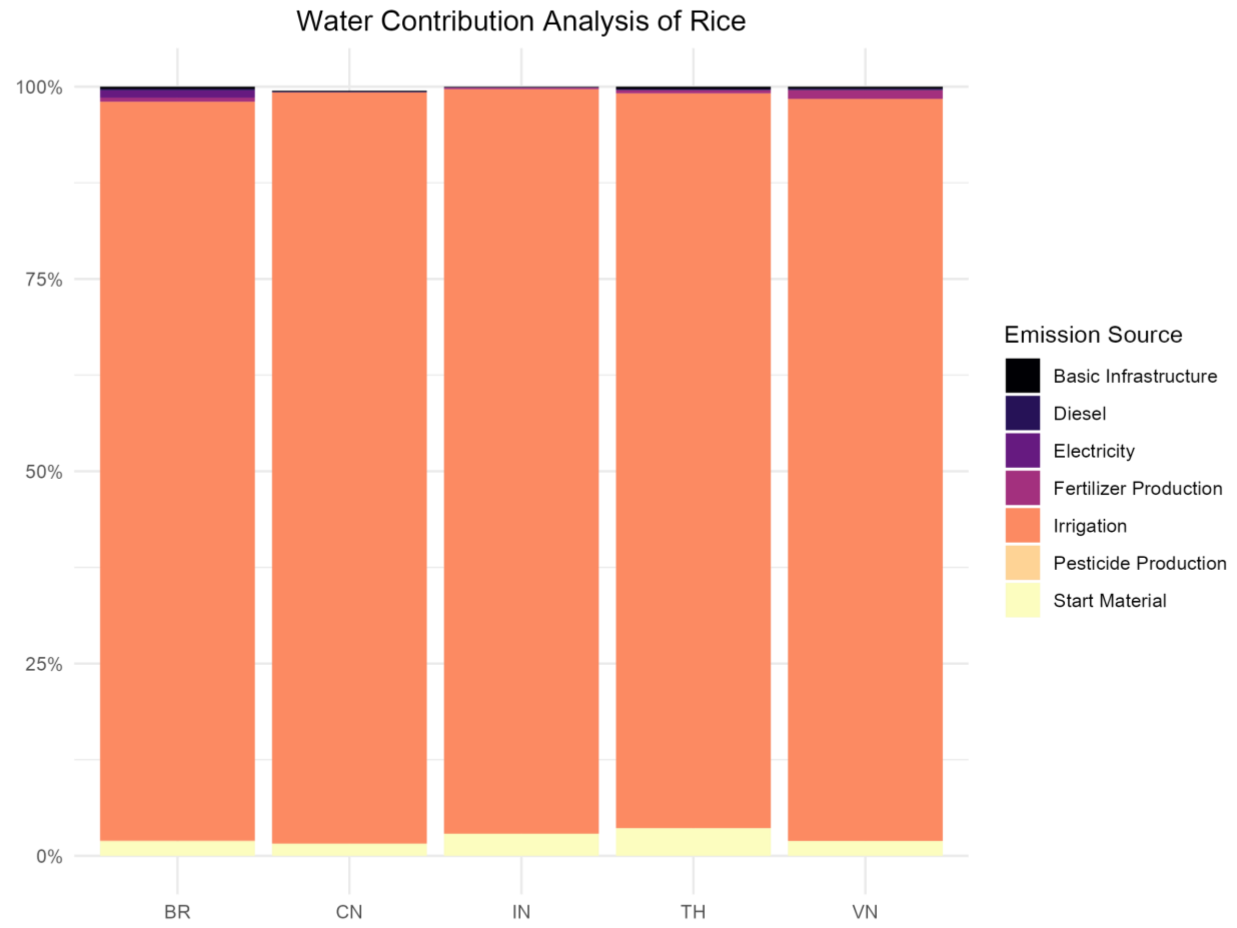


Figure 28: This figure illustrates the water consumption hotspot analysis of Rice in Brazil, China, India, Thailand and Vietnam. Rice production involves significant water consumption to generate flooded conditions of soil. Water consumption for irrigation is the primary hotspot for all countries.

Mitigation Analysis - Rice

Globally, rice cultivation covers 165 Mha of land, which is approximately 11% of the agricultural land (Hussain, S. et al., 2020). Rice is the primary staple crop after wheat and maize and is the source of 50% of calories for almost 50% of the world's population. Its demand is predicted to increase by 28% in 2050 (Zhu et al., 2018). Rice is produced all across the world, but Asia accounts for around 90% of global production. In Asia, most rice is produced by China, followed by India.

Rice production primarily occurs in irrigated areas where the fields are flooded. The emissions of GHGs from Rice cultivation can be mainly attributed to the burning of paddy straw, that releases CO2, N2O and CH4, and to the anaerobic flooded irrigations that lead to methane emissions. Moreover, if the paddy straw is not burnt and incorporated into the soil, it increases the amount of CH4 emissions in the next cultivation period (Bautista & Saito, 2015). Based on an LCA study that measured the operations and agricultural inputs of rice production on an IRRI (International Rice Research Institute) farm, when comparing rice straw management scenarios, there is evidence that incorporation of rice straw into the soil leads to the highest GHG emissions. This can be mitigated by partial or complete removal of rice straw (Van Hung et al., 2020).

LCA studies on rice production have highlighted that the emissions from the field during the cultivation stage represent most of the GHG emissions (Nunes et al., 2017, Bautista & Saito 2015, Blengini, G. A., & Busto, M. 2009). The anaerobic decomposition of organic matter is directly related to the water management practices and is also influenced by the use of fertilizers. Alternative water management strategies such as including aeration periods (Zoli et al., 2021) or alternate wetting and drying (Bautista & Saito, 2015) is demonstrated to be useful in mitigating methane emissions. Moreover, mid-season draining of fields has proven to decrease methane release by 80% without affecting grain yield. However, alternate wetting and drying simulates a rainfed area and would decrease the yield whereas mid-season draining of fields is not suitable for lowland rice fields with consistent water supply and availability (Hussain, S. et al., 2020).

Contribution Analysis - Oil Palm

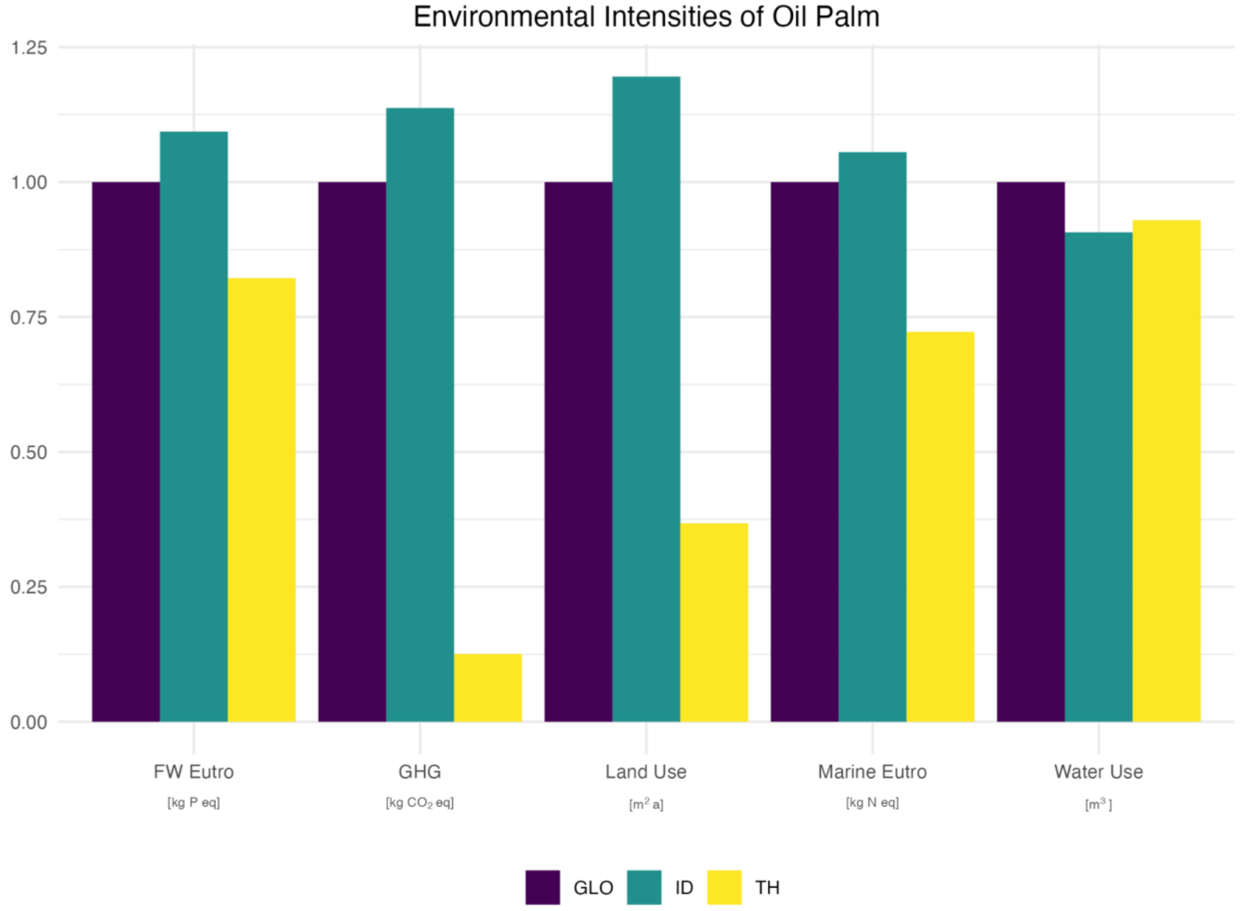


Figure 29: The figure presented depicts Indonesia and Thailand normalized against the weighted global average of our dataset. Among all impact categories, Thailand has the lowest intensity except for water use. On the other hand, Indonesia has the highest intensity across all impact categories except for water use. Thailand has a remarkably low GHG intensity compared to the rest of the world.

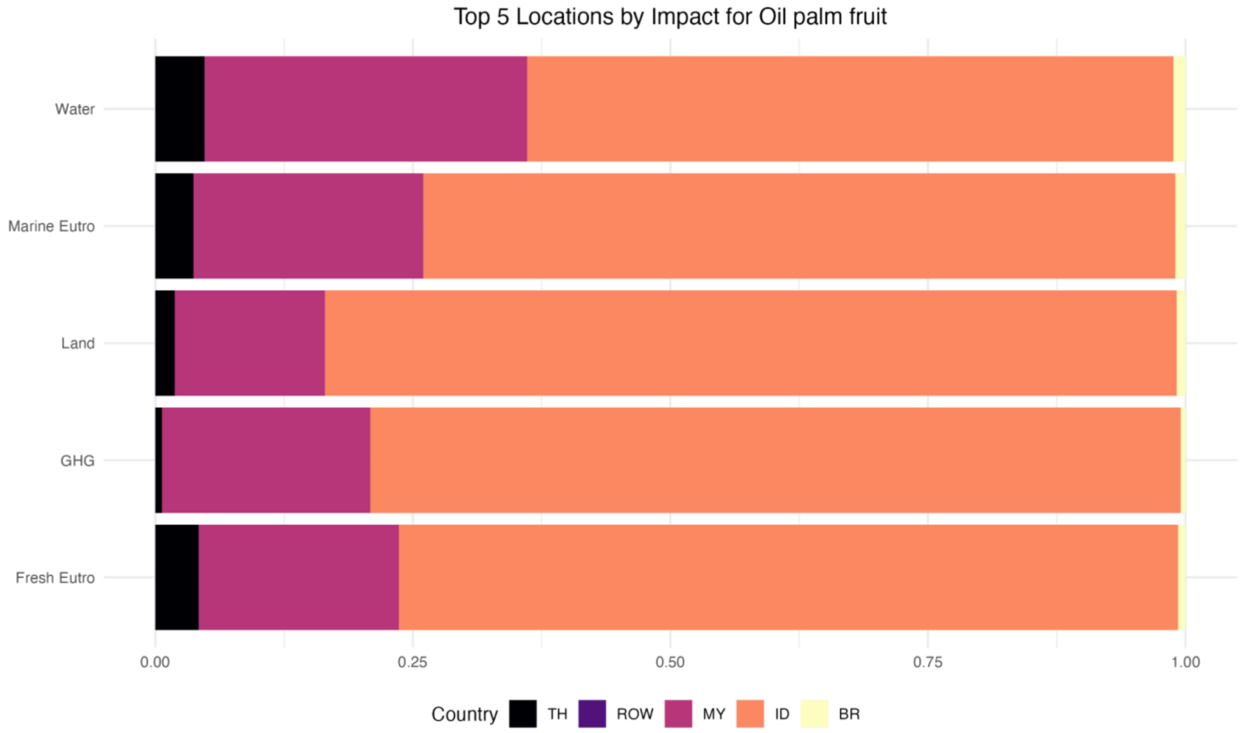


Figure 30: The figure illustrates the top five contributing countries to the global impact for each impact category. Across all categories, Indonesia has the highest impact, followed by Malaysia, Thailand, and Brazil.

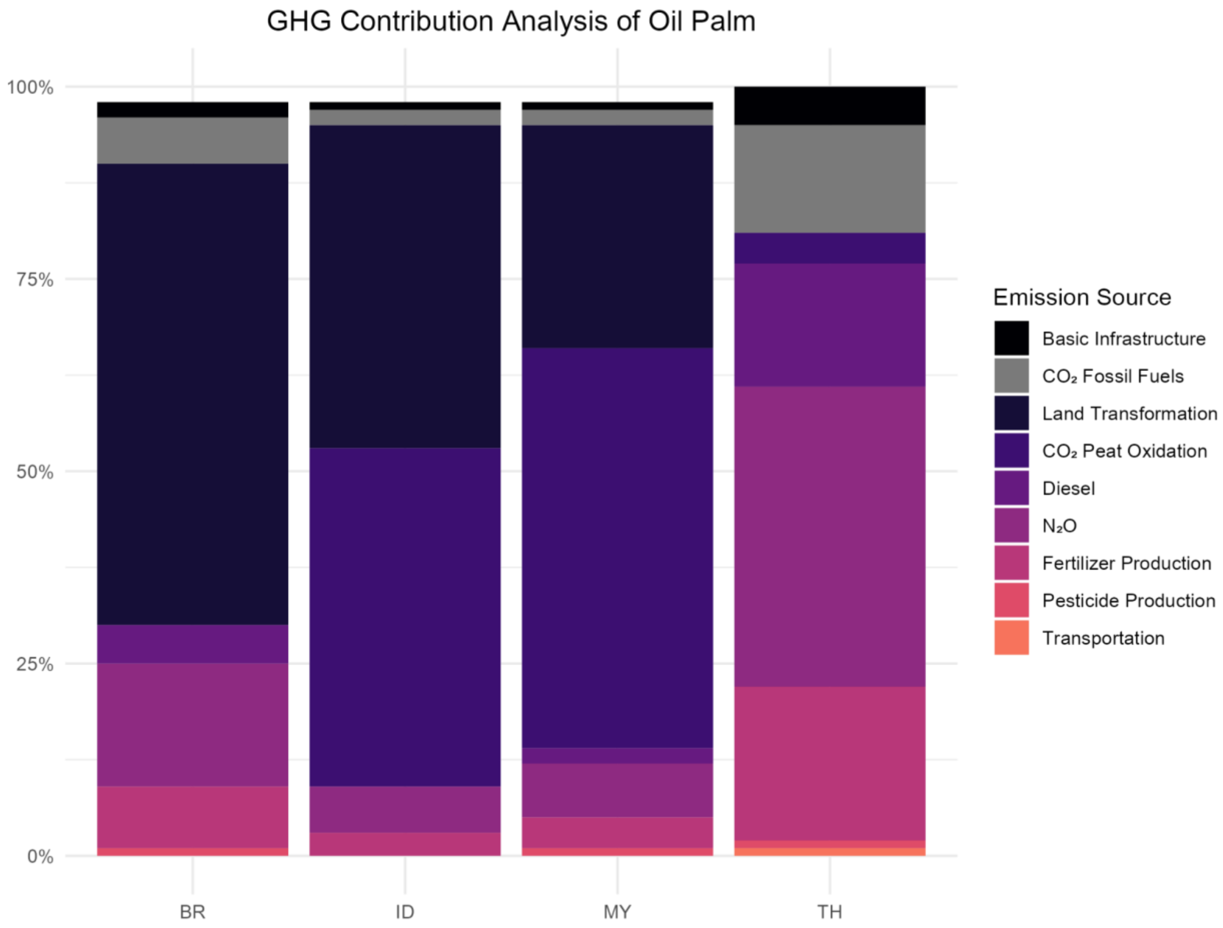


Figure 31: The contribution analysis of oil palm for Brazil, Indonesia, Malaysia, and Thailand is presented in the figure. The analysis reveals that for Brazil, the majority (60%) of the impact comes from land transformation. On the other hand, for Indonesia and Malaysia, the majority of the impact results from peat oxidation, at 44% and 52%, respectively. For Thailand, 42% of the impact results from dinitrogen monoxide emissions.

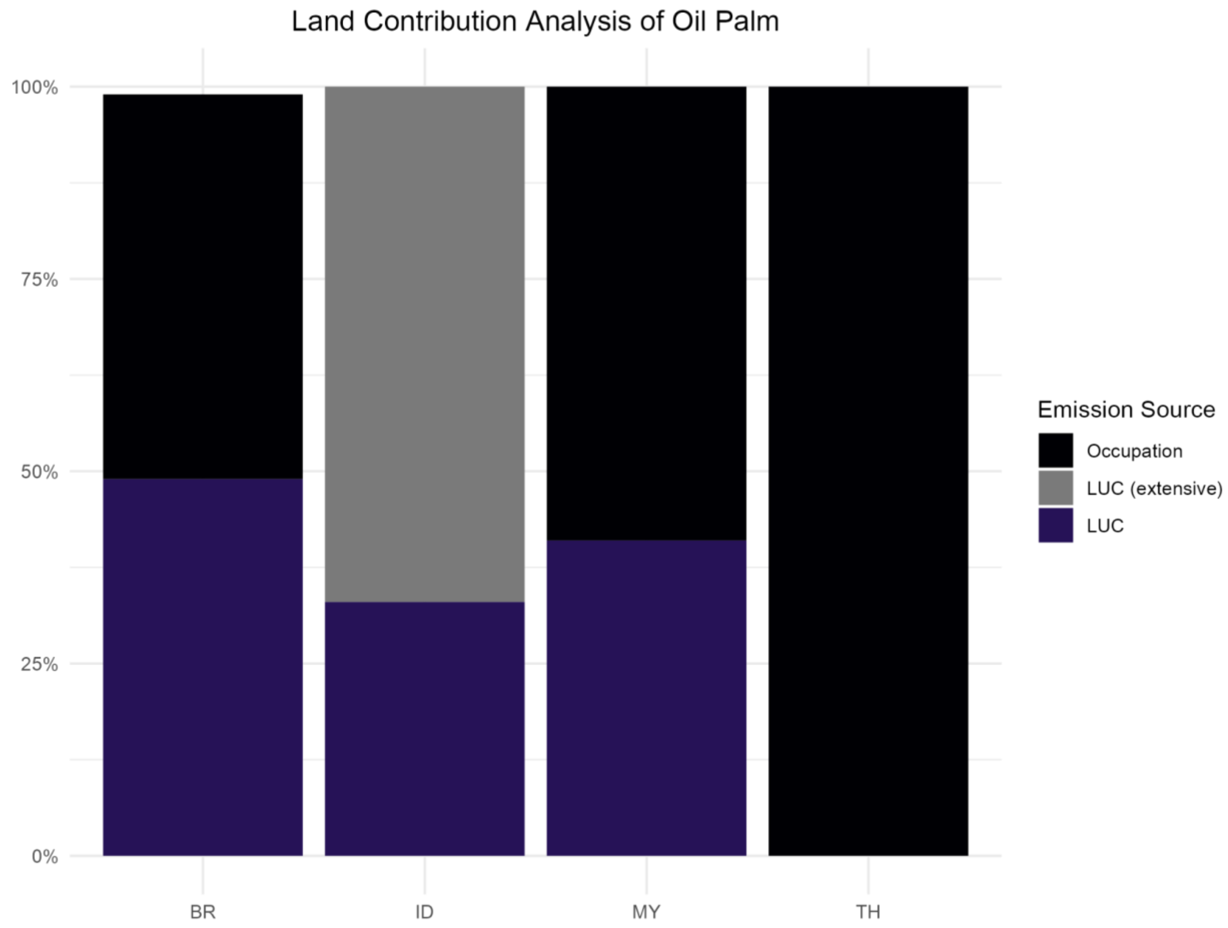


Figure 32: This figure illustrates the land use impacts of oil palm from Brazil, Indonesia, Malaysia, and Thailand. The majority of the impact in all locations is due to land occupation except for Indonesia, where the main impact is due to land transformation, specifically extensive transformation of forests.

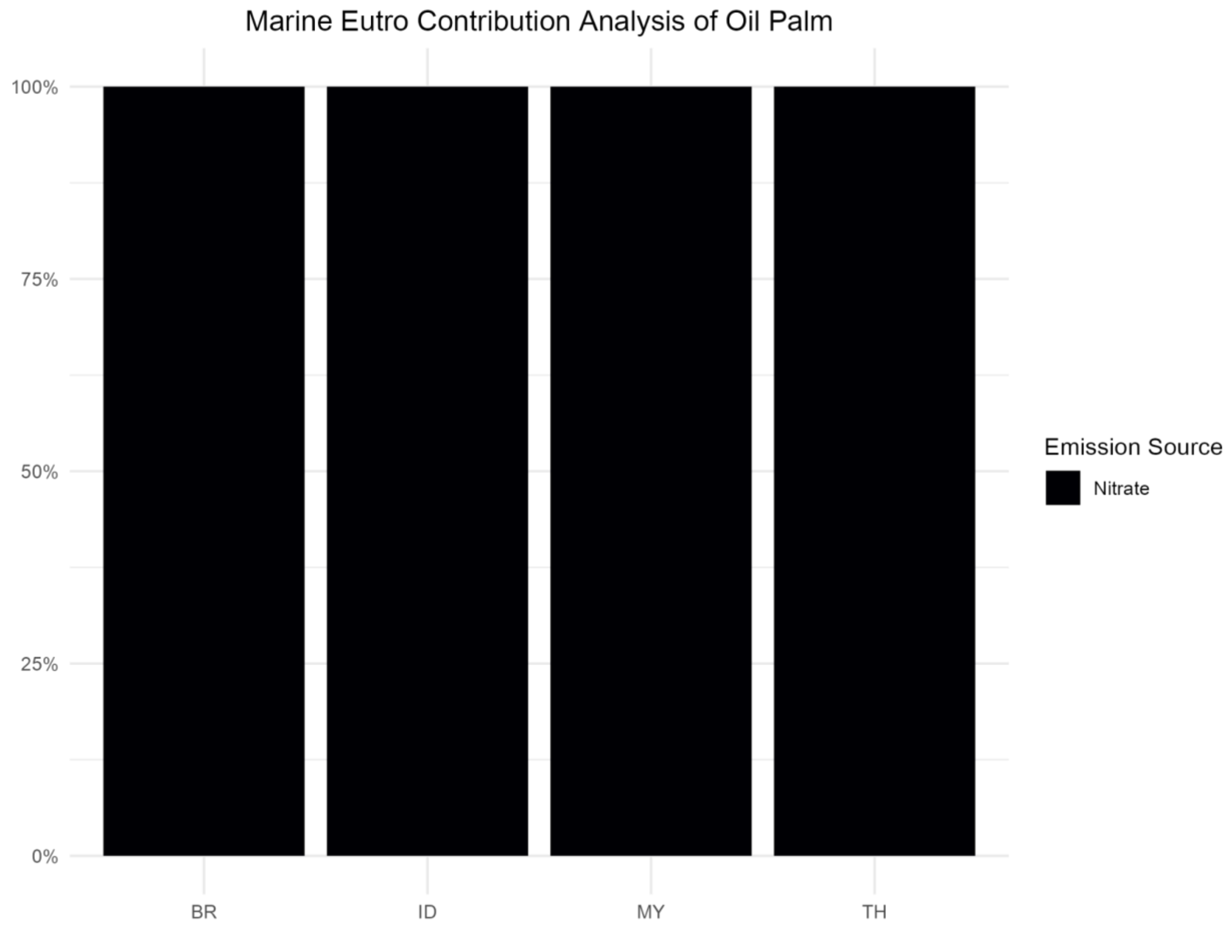


Figure 33: This figure illustrates the impact of oil palm cultivation on marine eutrophication in Brazil, Indonesia, Malaysia, and Thailand. Nitrate in fertilizer applications causes 100% of all marine eutrophication.

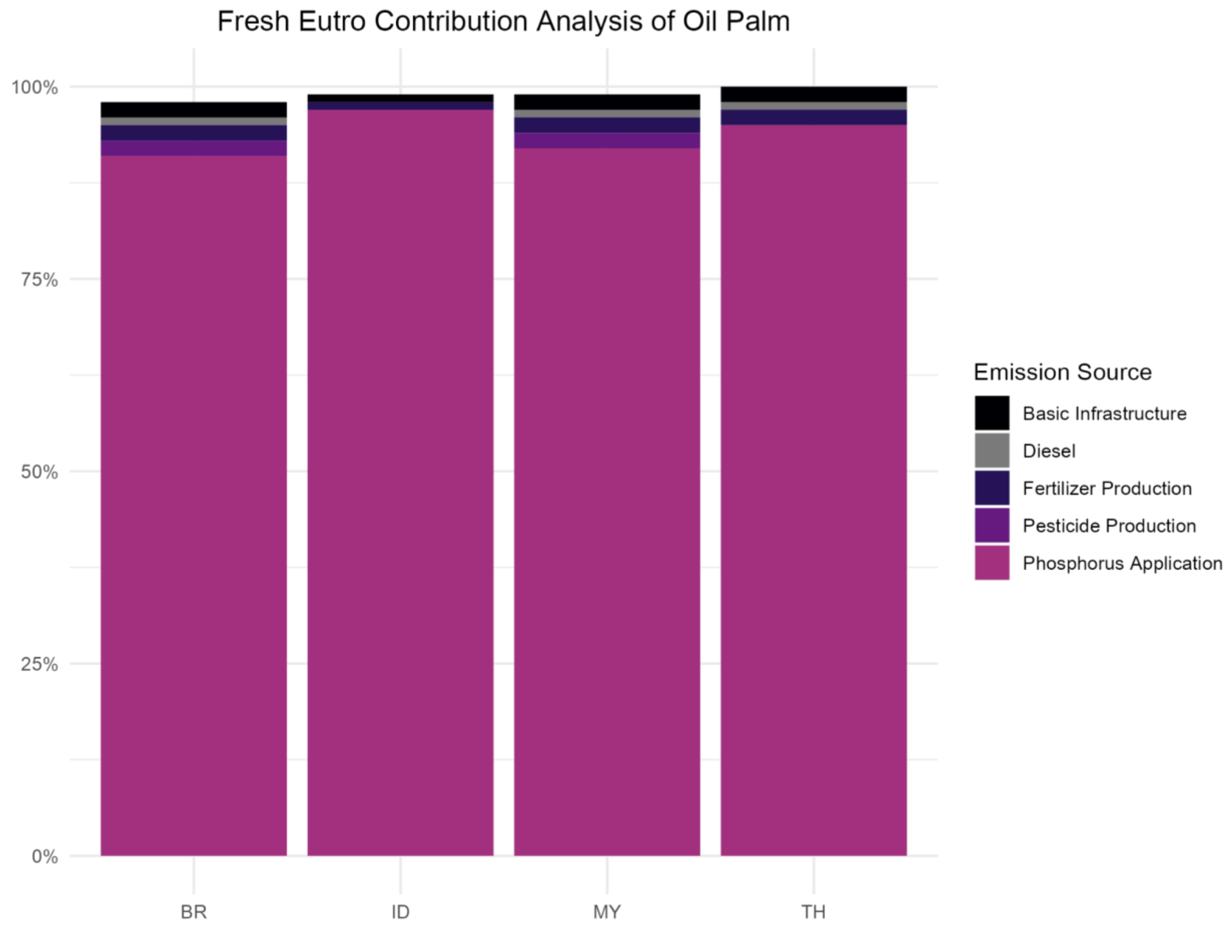


Figure 34: This figure illustrates the impact of oil palm cultivation on marine eutrophication in Brazil, Indonesia, Malaysia, and Thailand. Phosphorus in fertilizer applications constitutes most of all freshwater eutrophication.

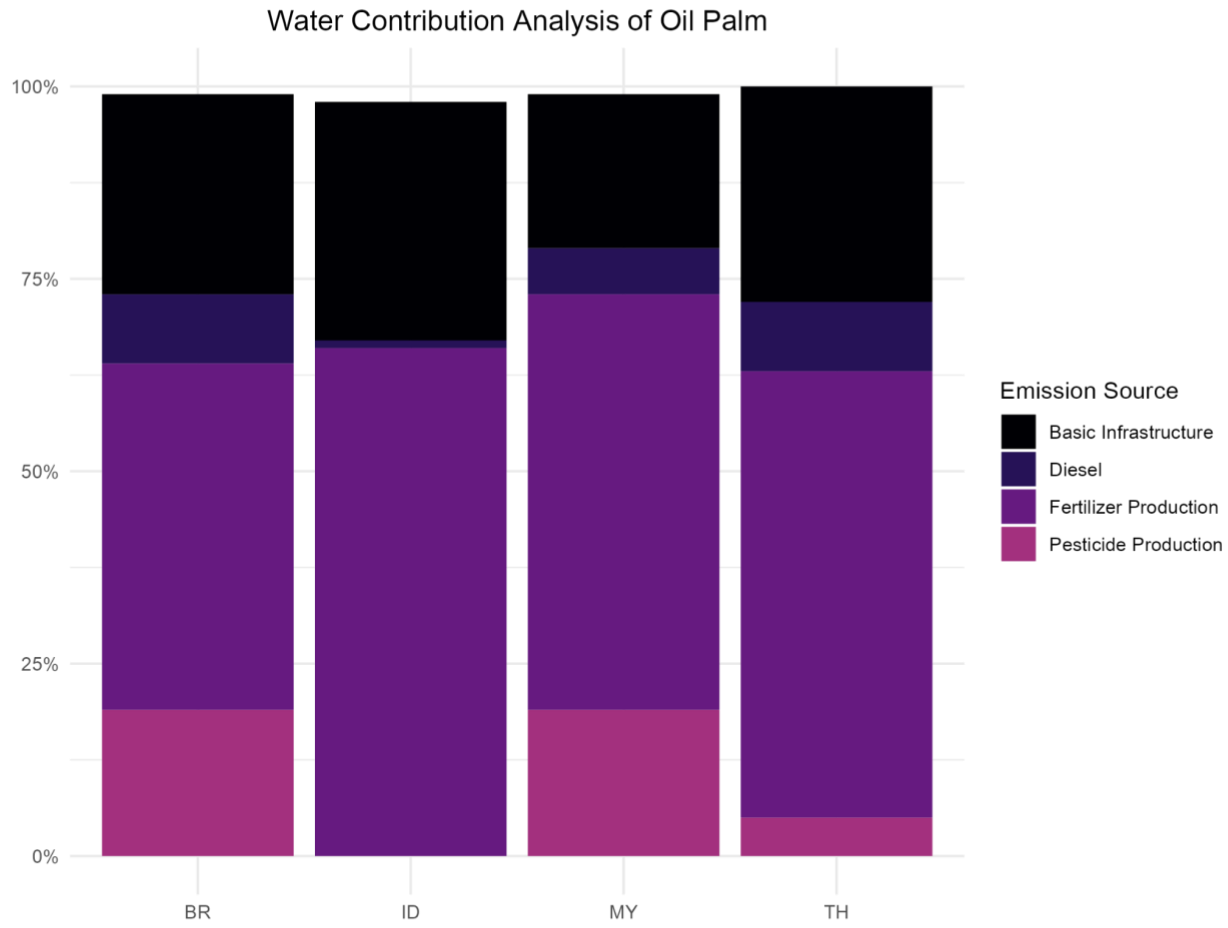


Figure 35: This figure illustrates the impact of oil palm cultivation on water use in Brazil, Indonesia, Malaysia, and Thailand. Fertilizer production accounts for most of the water use across all of the countries.

Mitigation Analysis - Oil Palm

There are numerous practices that can be adopted to reduce the GHG intensity of oil palm cultivation, which is a significant agricultural activity in countries like Indonesia and Malaysia, where it is a major contributor to their economies. One of the most effective ways to do this is by growing oil palm on grasslands instead of forests. This is because forests play a critical role in carbon sequestration, and transforming natural vegetation into agricultural land typically results in a substantial loss of carbon sequestration, leading to a high GHG intensity.

Schmidt et al highlighted this approach, and our own analysis supports it, as we found that land transformation has the most significant impact on the GWP of oil palm cultivation in Brazil, which is another major producer of the crop. Interestingly, Brazil has a vast forest cover of around 497 million hectares, according to the (FAO, 2020).

Therefore, to reduce the GHG intensity of oil palm farming, it is highly recommended to avoid the cultivation of peat soils and focus on mineral soils instead, as per Schmidt's recommendations. Peatlands have a high carbon stock and converting them into oil palm plantations leads to significant carbon emissions. Similarly, Hashim et al have suggested that GHG emissions from oil palm cultivation could be reduced by establishing plantations on degraded grassland with low carbon stock. This is because degraded grasslands have lower carbon stock and thus lower carbon emissions associated with land conversion.

In addition to land-use practices, the use of excess fertilizers is a significant source of emissions associated with oil palm cultivation, as with other conventionally grown crops. To tackle this issue, certain management practices can be implemented. For instance, reduced tillage can reduce soil disturbance and, therefore, prevent soil carbon loss. Organic fertilizers can increase soil organic matter and, hence, sequester more carbon. Crop rotation can reduce soil erosion and increase soil fertility, leading to higher yields and lower fertilizer application rates. Fertigation can also be used to apply water and nutrients at the same time, reducing nutrient leaching and minimizing GHG emissions. Bok et al and Rajanna et al have both highlighted the effectiveness of these measures in reducing GHG emissions from oil palm cultivation.

In summary, reducing the GHG intensity of oil palm farming is crucial for sustainable development and environmental protection. It can be achieved by avoiding deforestation and peatland conversion, focusing on degraded grasslands, and adopting sustainable management practices for fertilizer use. By implementing these measures, we can ensure that oil palm cultivation becomes more sustainable and environmentally friendly in the future.

Contribution Analysis - Wheat

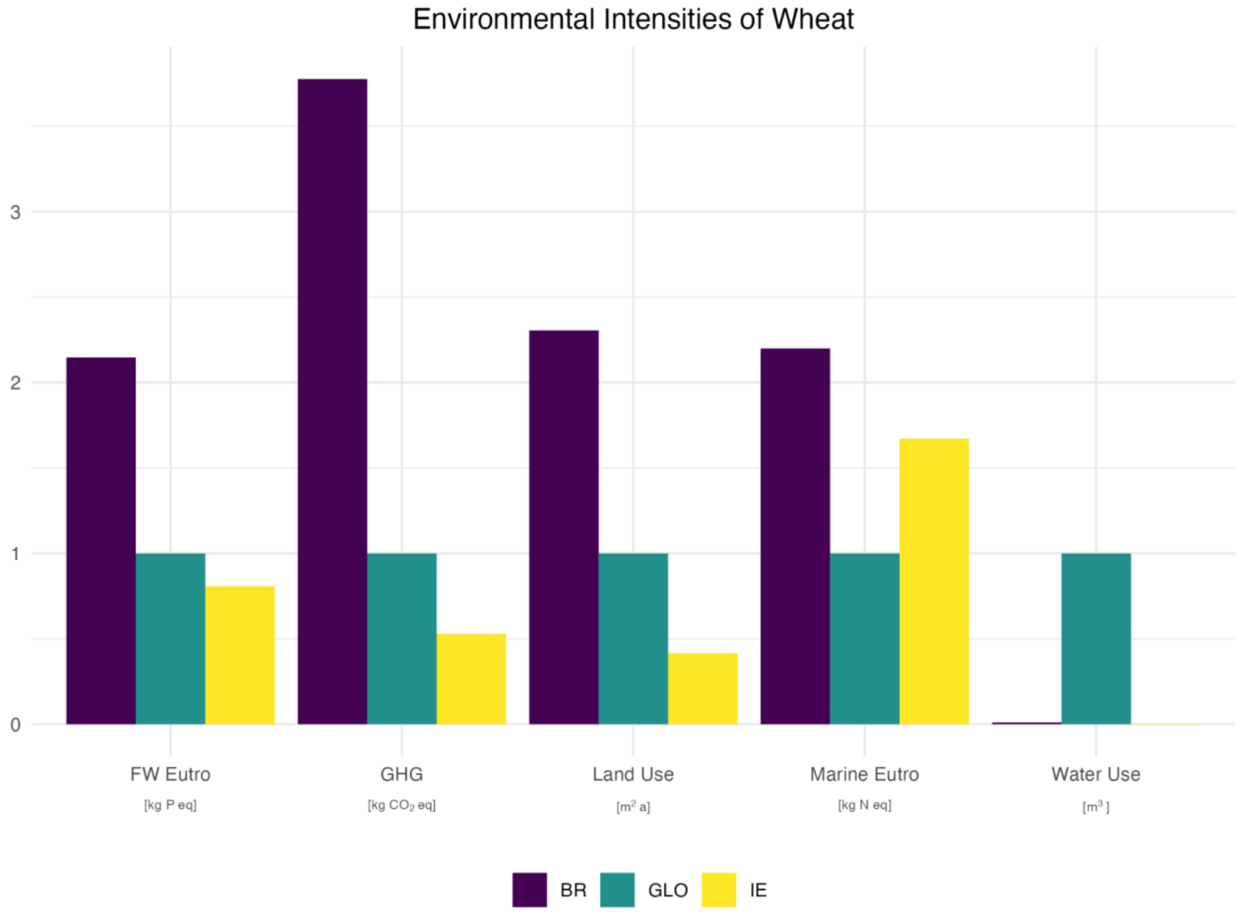


Figure 36: The figure presented depicts Brazil and Ireland normalized against the weighted global average of our dataset. Among all impact categories, Ireland has the lowest intensity except for marine eutrophication. On the other hand, Brazil has the highest intensity across all impact categories.

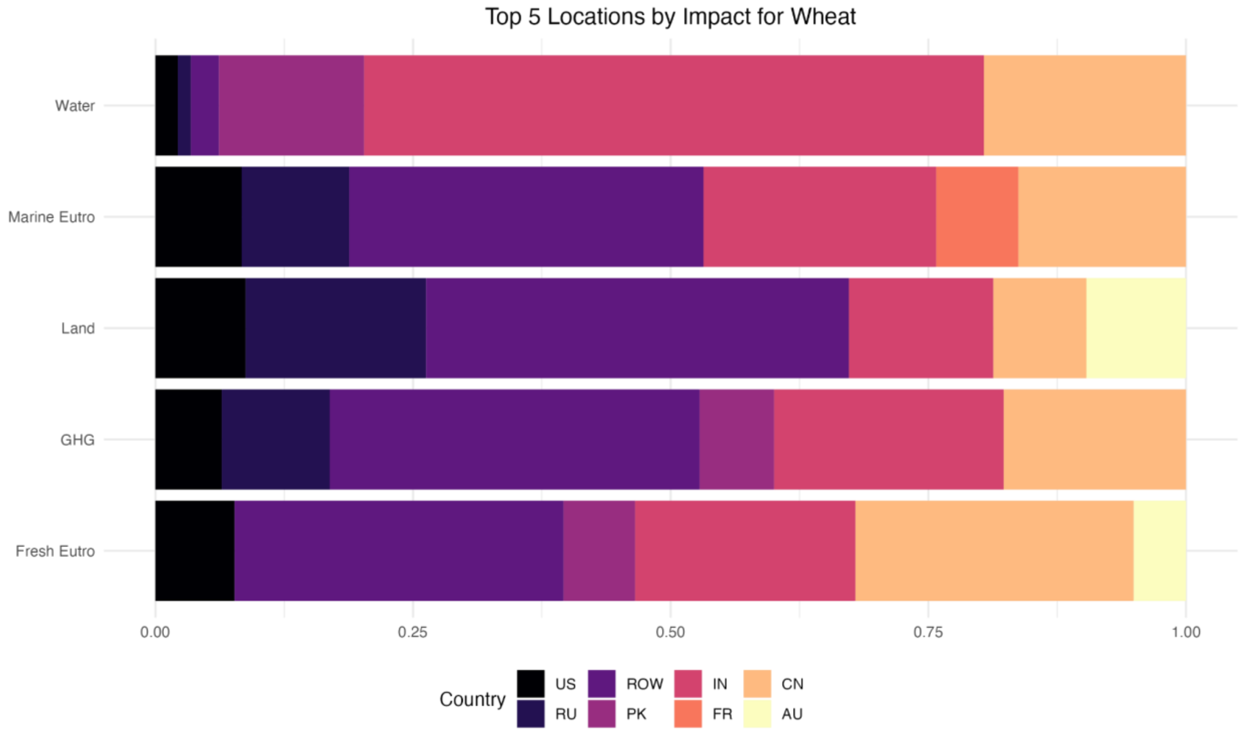


Figure 37: The figure illustrates the top five contributing countries to the global impact for each impact category. India, Canada, and Russia contribute the most across all impact categories.

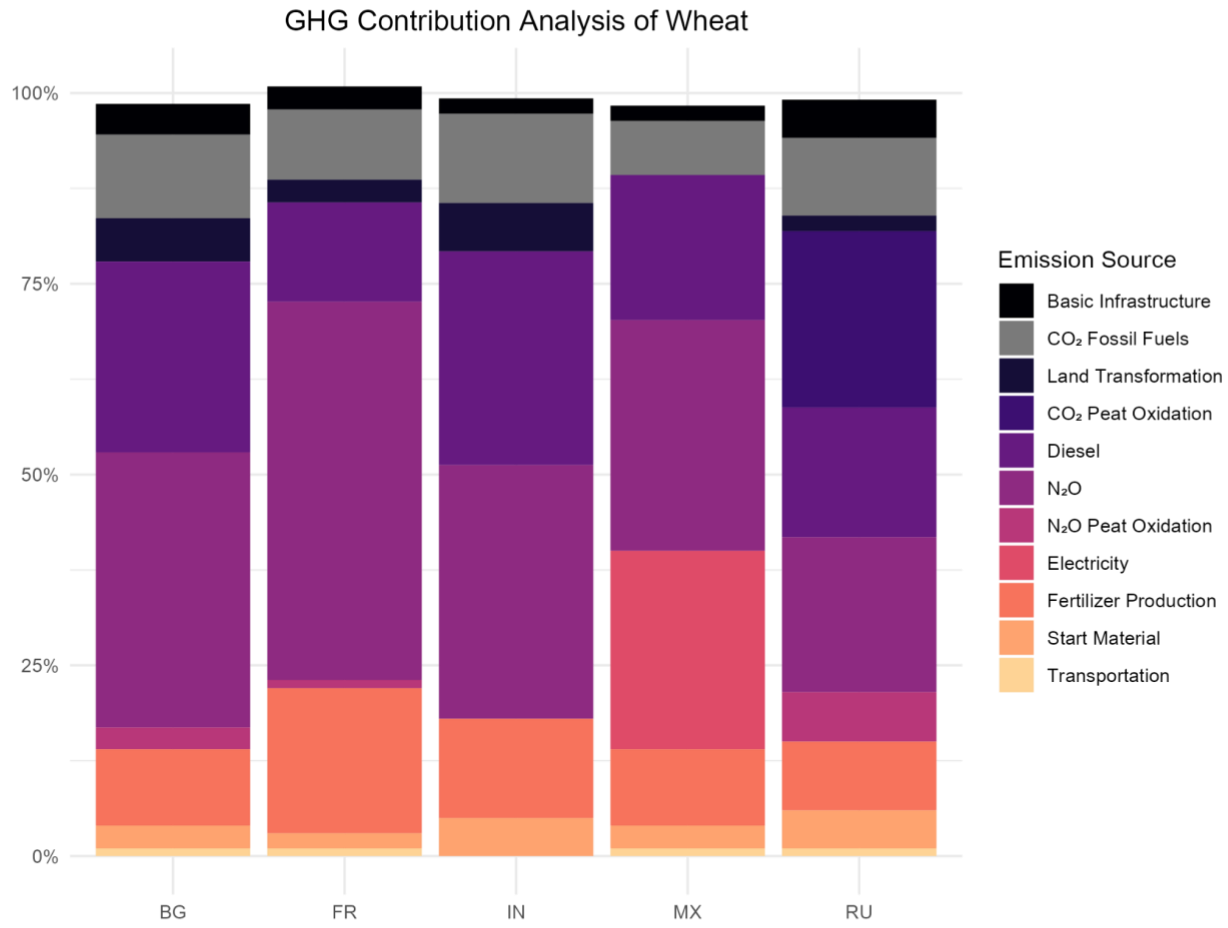


Figure 38: The contribution analysis of wheat for Bulgaria, France, India, Mexico, and Russia is presented in the figure. The analysis reveals that for Bulgaria, France, India, and Mexico, the majority of the impact comes from dinitrogen monoxide at 36%, 50%, 33%, and 30% respectively. While, for Russia, the majority of the impact results from peat oxidation, at 23%.

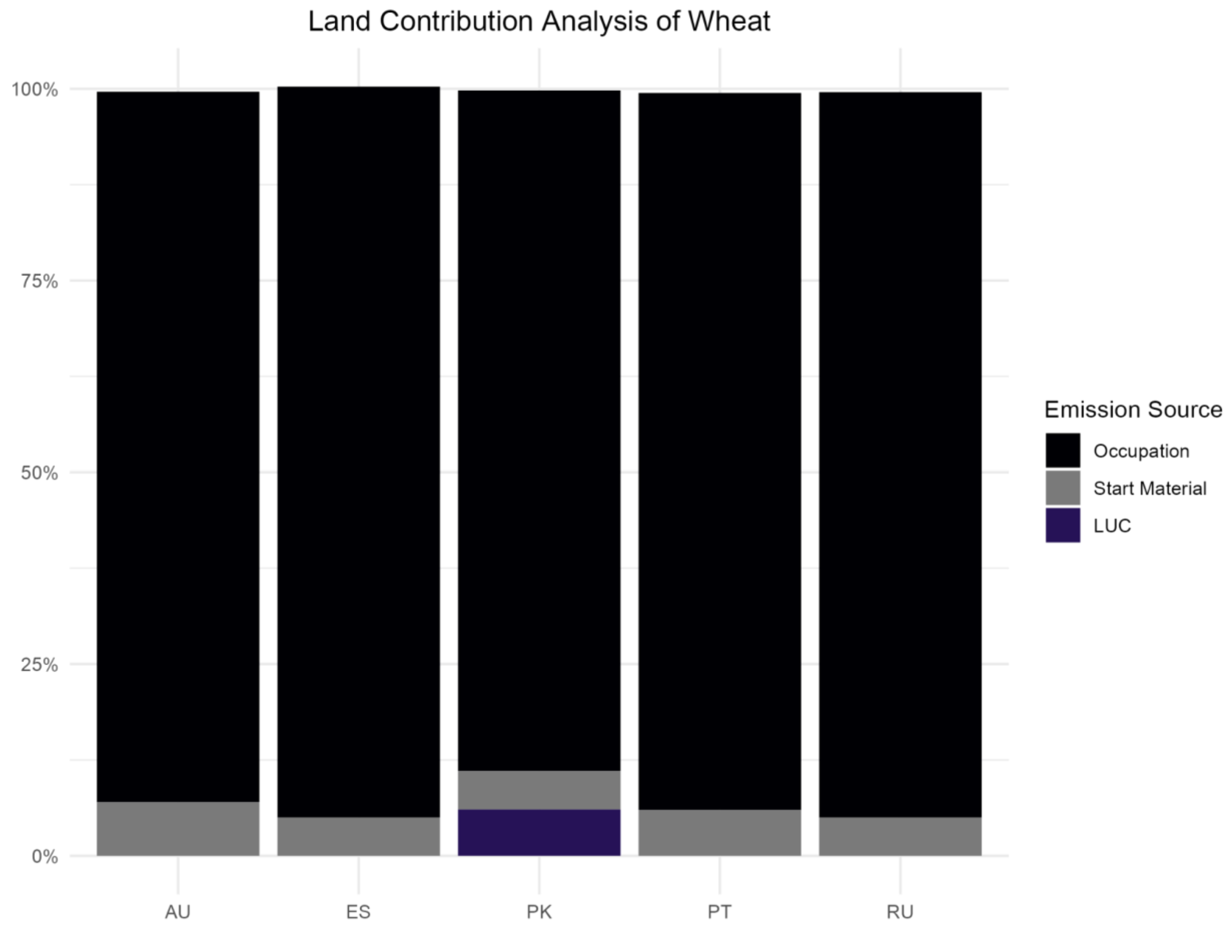


Figure 39: Land use impacts of Australia, Spain, Pakistan, Portugal, and Russia. The majority of the impact in all locations is due to land occupation.

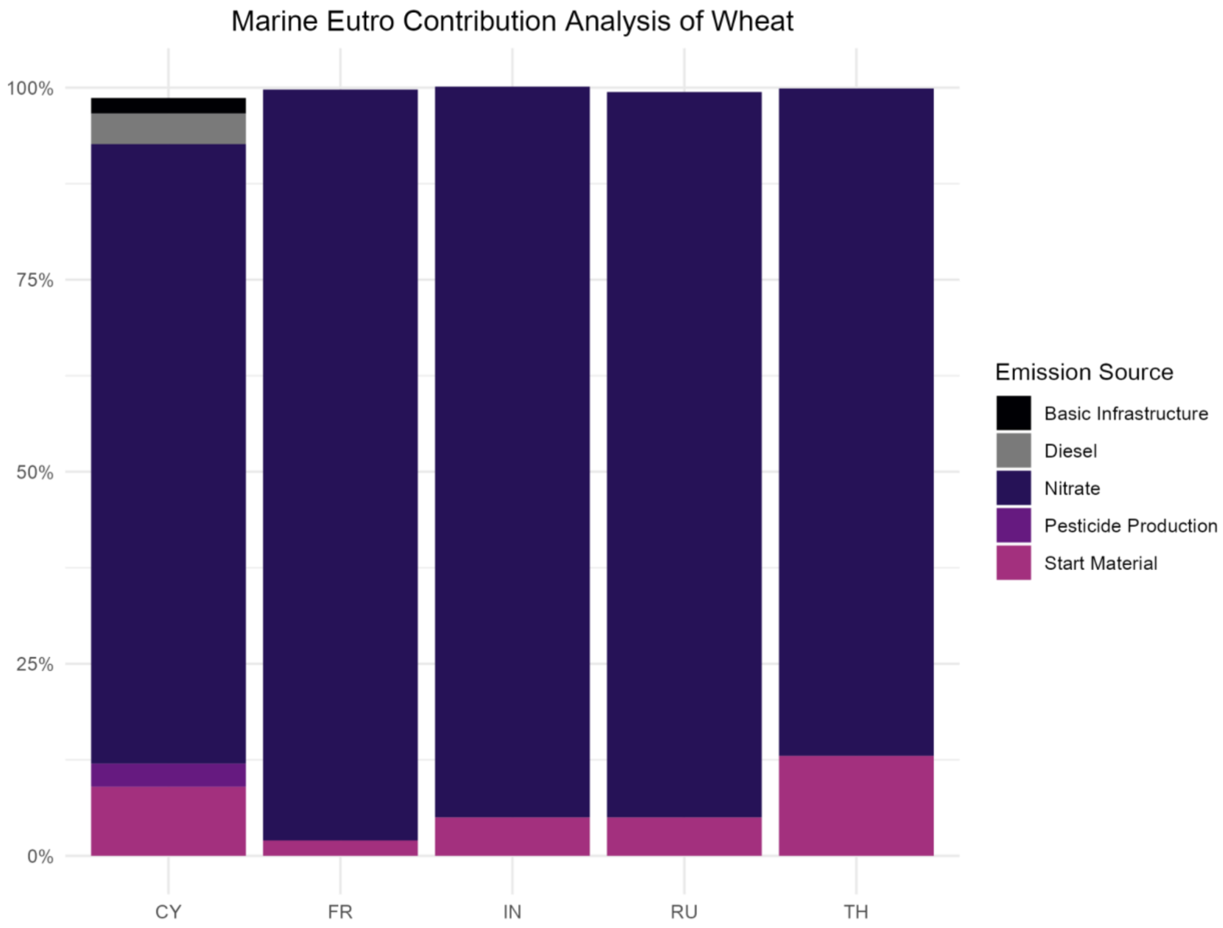


Figure 40: Illustrates the impact of wheat cultivation on marine eutrophication in Cyprus, France, India, Russia, and Thailand. Nitrate in fertilizer applications causes most of all marine eutrophication.

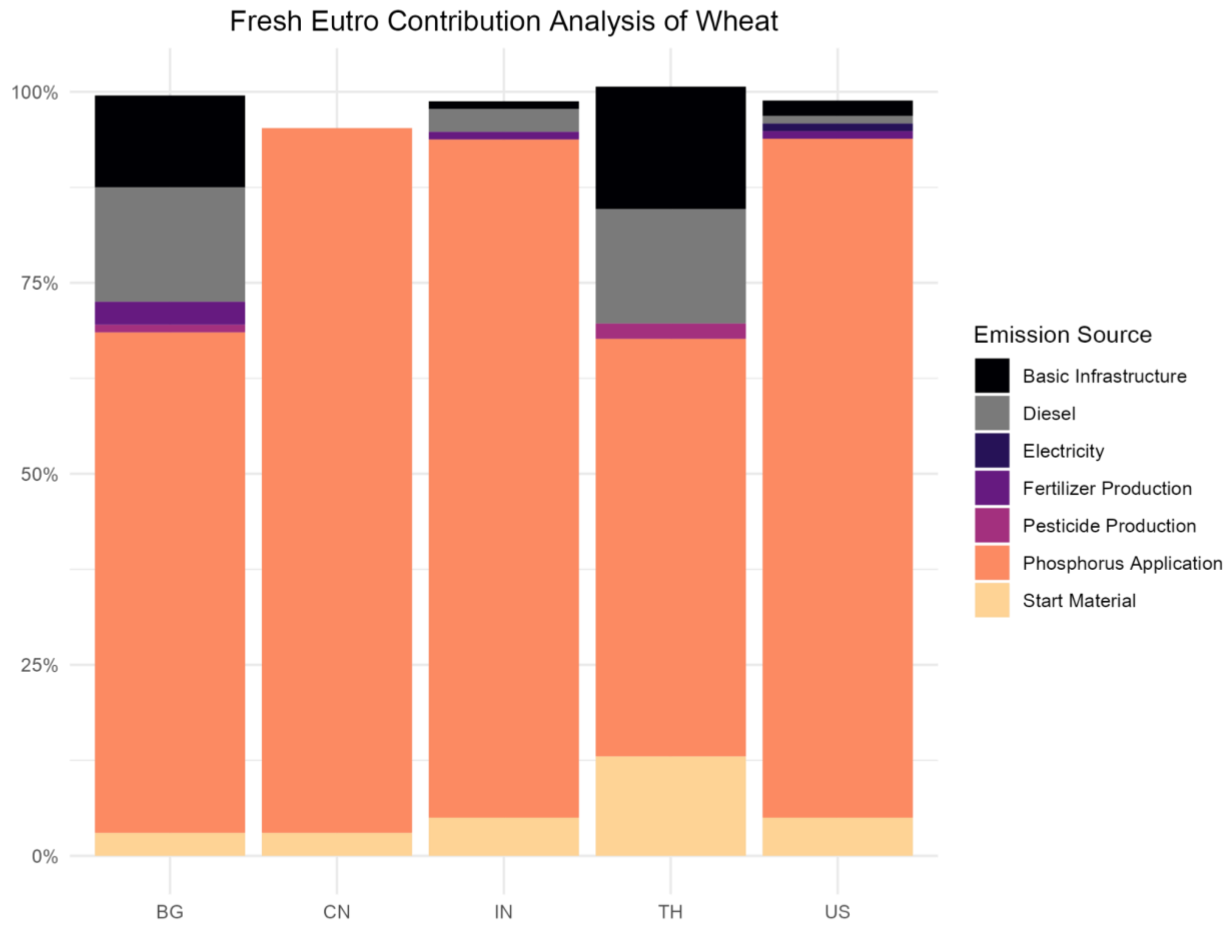


Figure 41: Illustrates the impact of wheat cultivation on freshwater eutrophication in Bulgaria, Canada, India, Thailand, and the United States. Phosphorus in fertilizer applications causes most of all freshwater eutrophication.

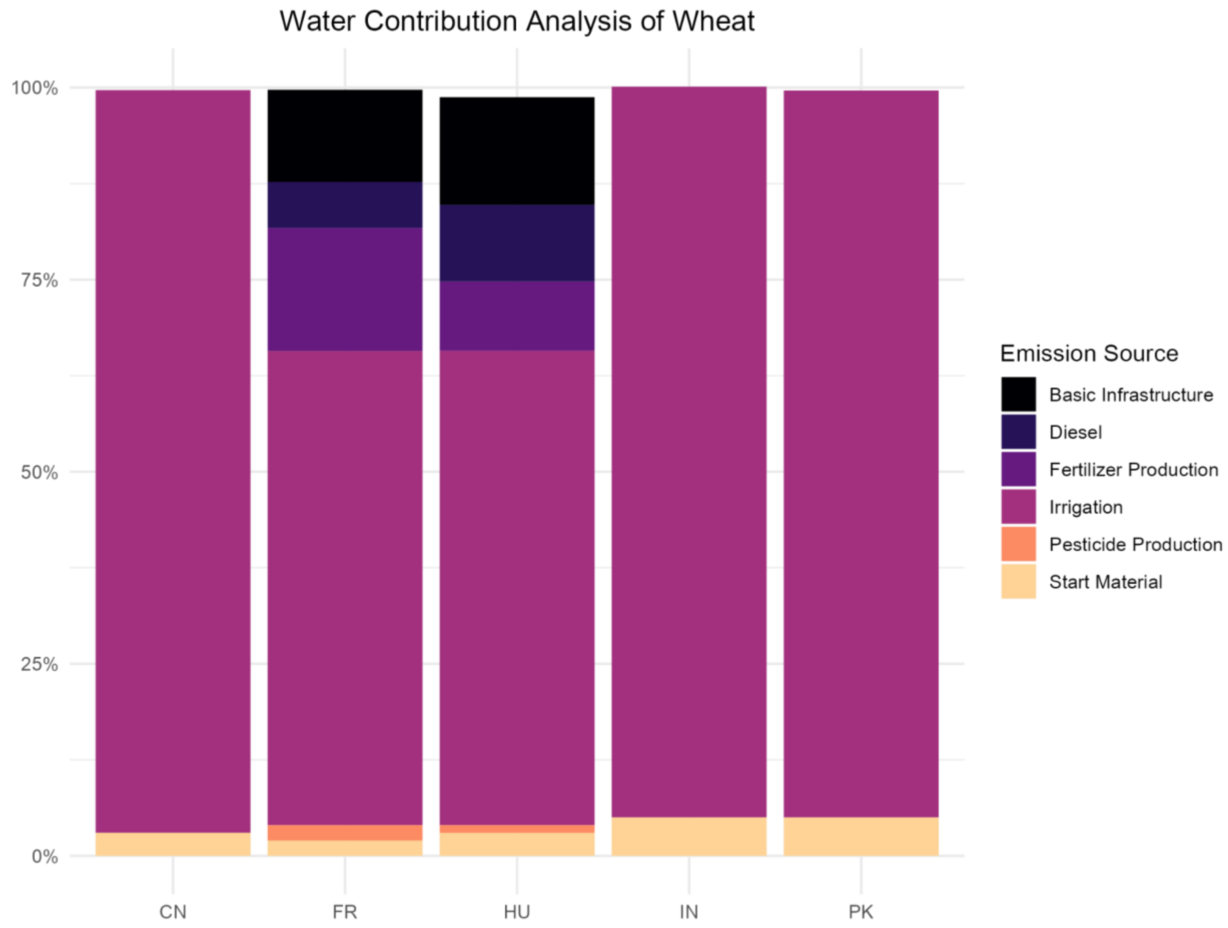


Figure 42: Illustrates the impact of wheat cultivation on water use in Canada, France, Hungary, India, and Pakistan. Irrigation is the major use of water in all locations.

Mitigation Analysis - Wheat

Wheat production is known to be a significant contributor to GHG emissions, with N2O and diesel from machinery being the primary sources. A comprehensive global meta-analysis conducted by Yao et al. in 2024 revealed that by reducing nitrogen fertilization by up to 30% and optimizing the timing and placement of fertilizer application, it is possible to significantly decrease yield-scaled N2O emissions while maintaining similar or even higher yields.

Moreover, the same study also found that water-saving irrigation and plastic film mulching could reduce yield-scaled N2O emissions by 13.7%–41.0% (Yao et al., 2024). This highlights the potential for sustainable farming practices that can help reduce the impact of wheat production on the environment.

In the case of rice-wheat systems, Bhatia et al. in 2012 suggested that using a simple leaf color chart could improve nitrogen use efficiency and decrease N2O emissions by 16% and 18% for urea and nitrogen fertilization, respectively, compared to the conventional blanket fertilizer application methods. This method involves using a chart that helps farmers determine the correct time and amount of fertilizer to apply based on the color of the plant leaves, resulting in more efficient use of nitrogen and lower GHG emissions.

Overall, these findings demonstrate the potential of implementing sustainable farming practices to reduce the environmental impact of wheat production and improve overall crop yields.

Contribution Analysis - Soybean

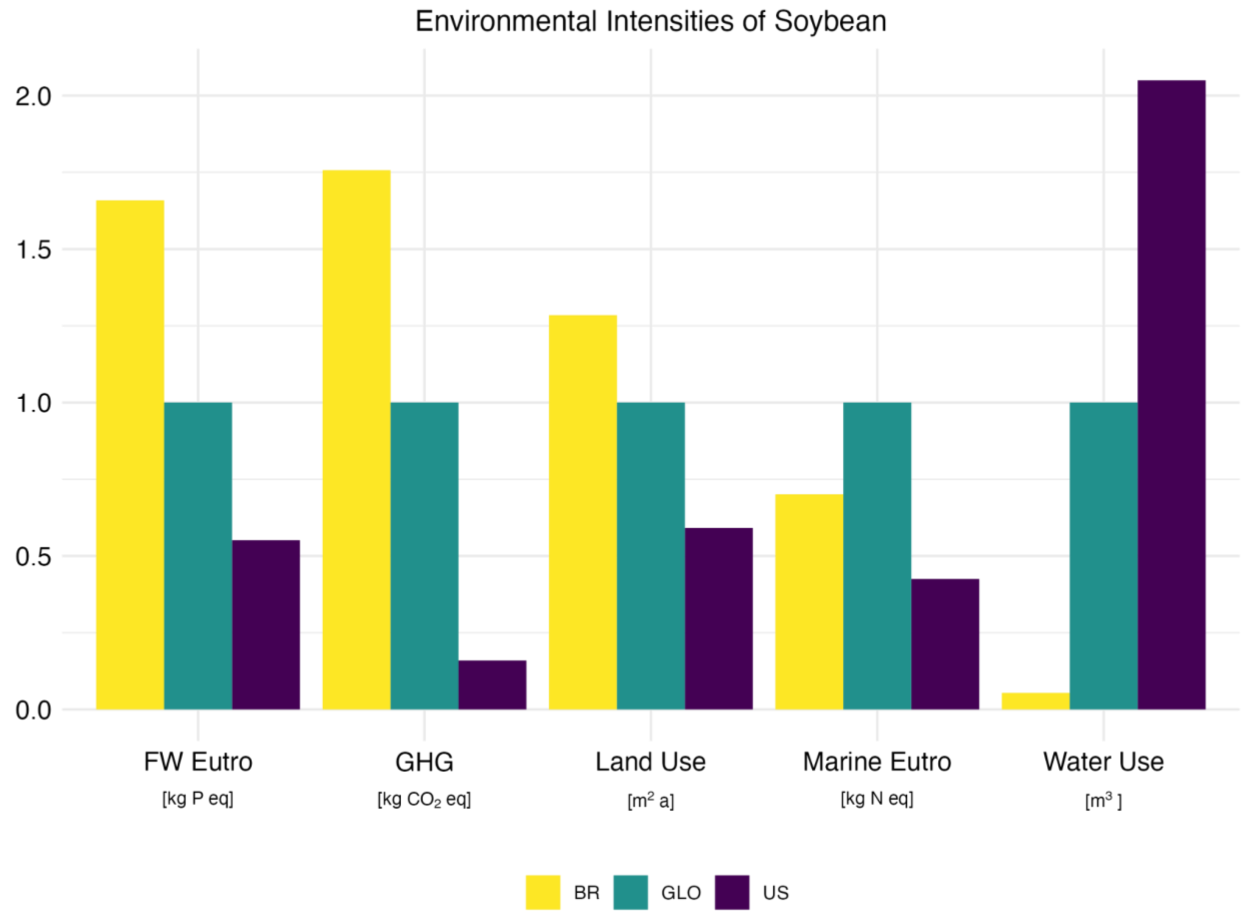


Figure 43: The presented figure compares the environmental impact of soybean production in Brazil and the United States, normalized against the weighted global average of our dataset. Brazil has the highest intensity for freshwater eutrophication, greenhouse gas emissions, and land use. On the other hand, the US has the lowest intensity across all categories, except for water use where it has twice the global weighted average and more than ten times that of Brazil.

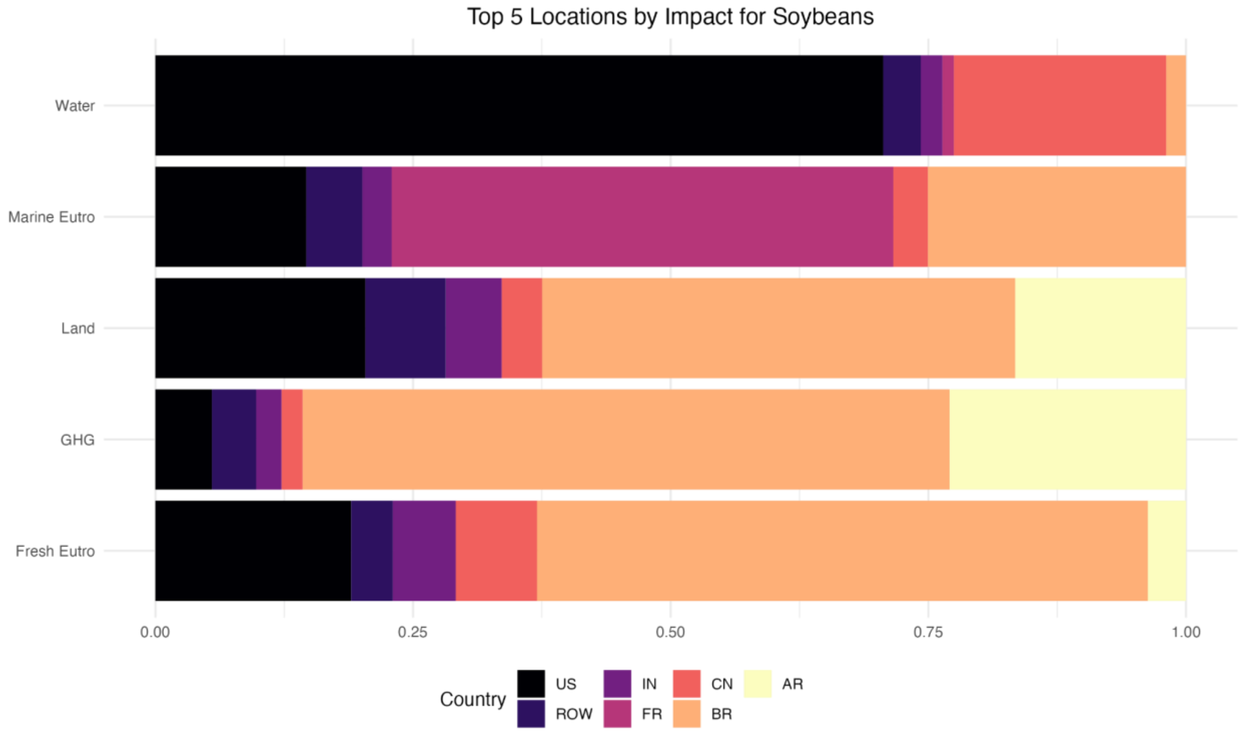


Figure 44: The figure illustrates the top five contributing countries to the global impact for each impact category for soybean production. The US alone makes up for almost 75% of the world's water consumption for soybeans. France and Brazil dominate the rest of the impact categories.

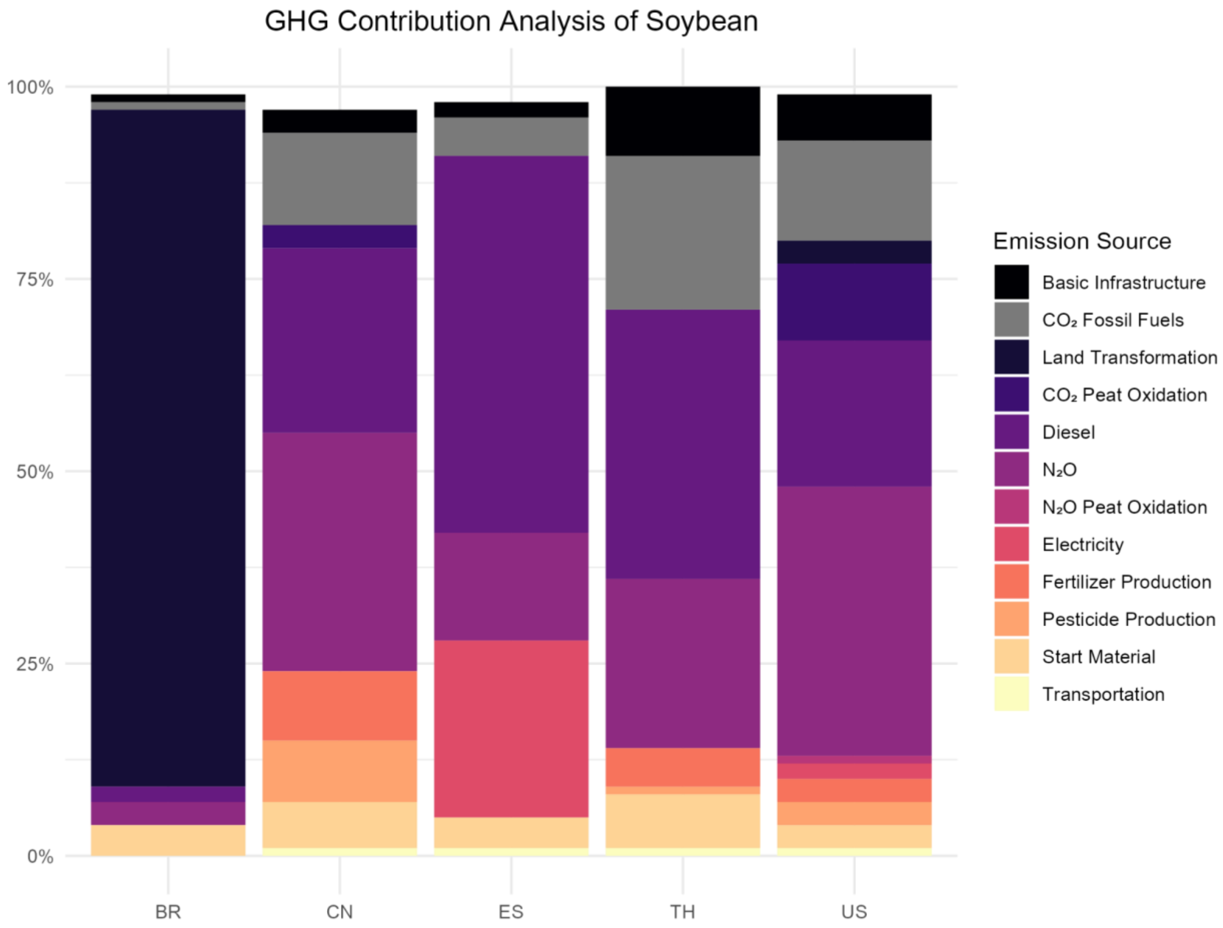


Figure 45: The contribution analysis of soybeans for Brazil, Canada, Spain, Thailand, and the US is presented in the figure. The analysis reveals that for Brazil the majority of the impact comes from land transformation. For the rest of the countries, the majority of the impact comes from dinitrogen monoxide, and diesel.

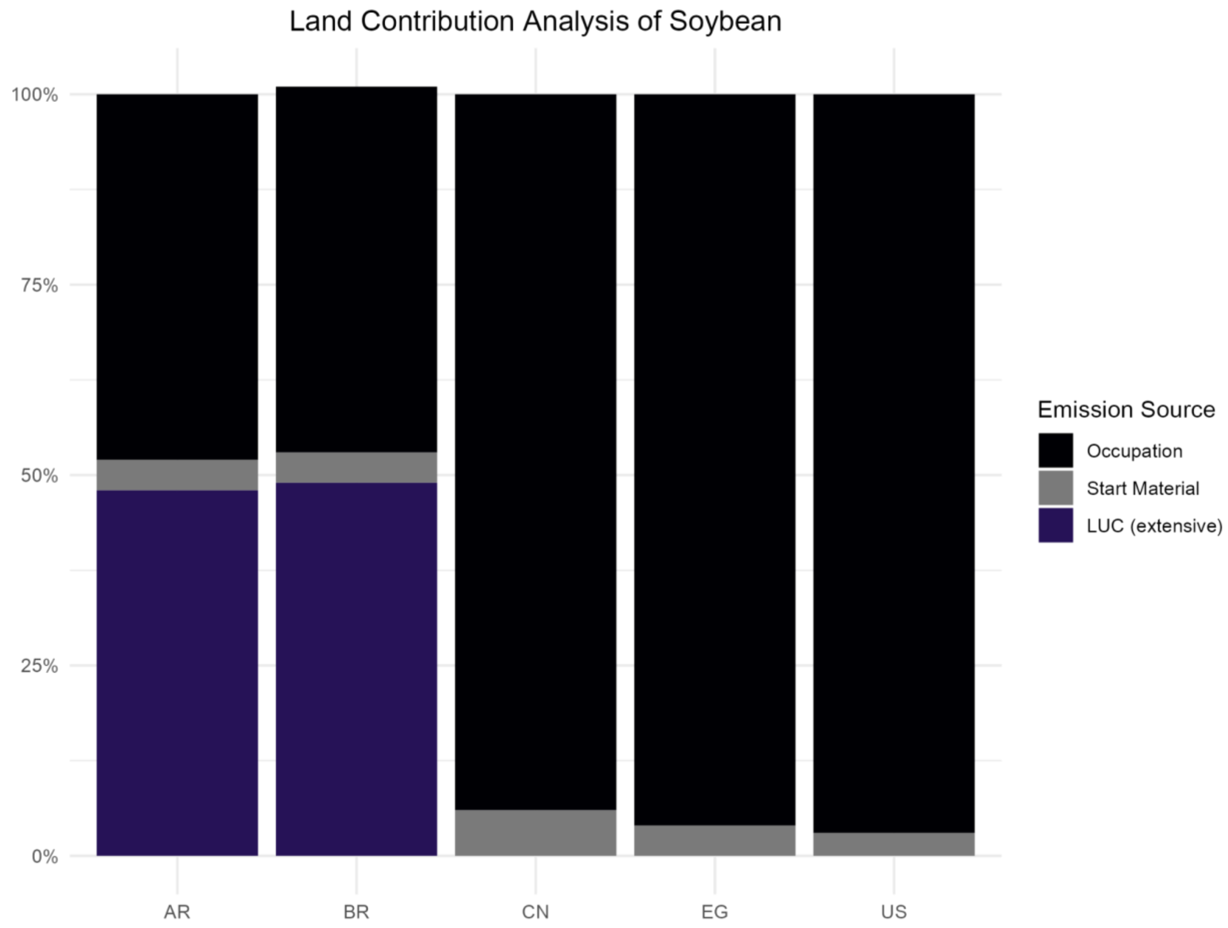


Figure 46: This figure illustrates the land use impacts of soybean from Argentina, Brazil, Canada, Egypt, and the US. The majority of the impact in all locations is due to land occupation.

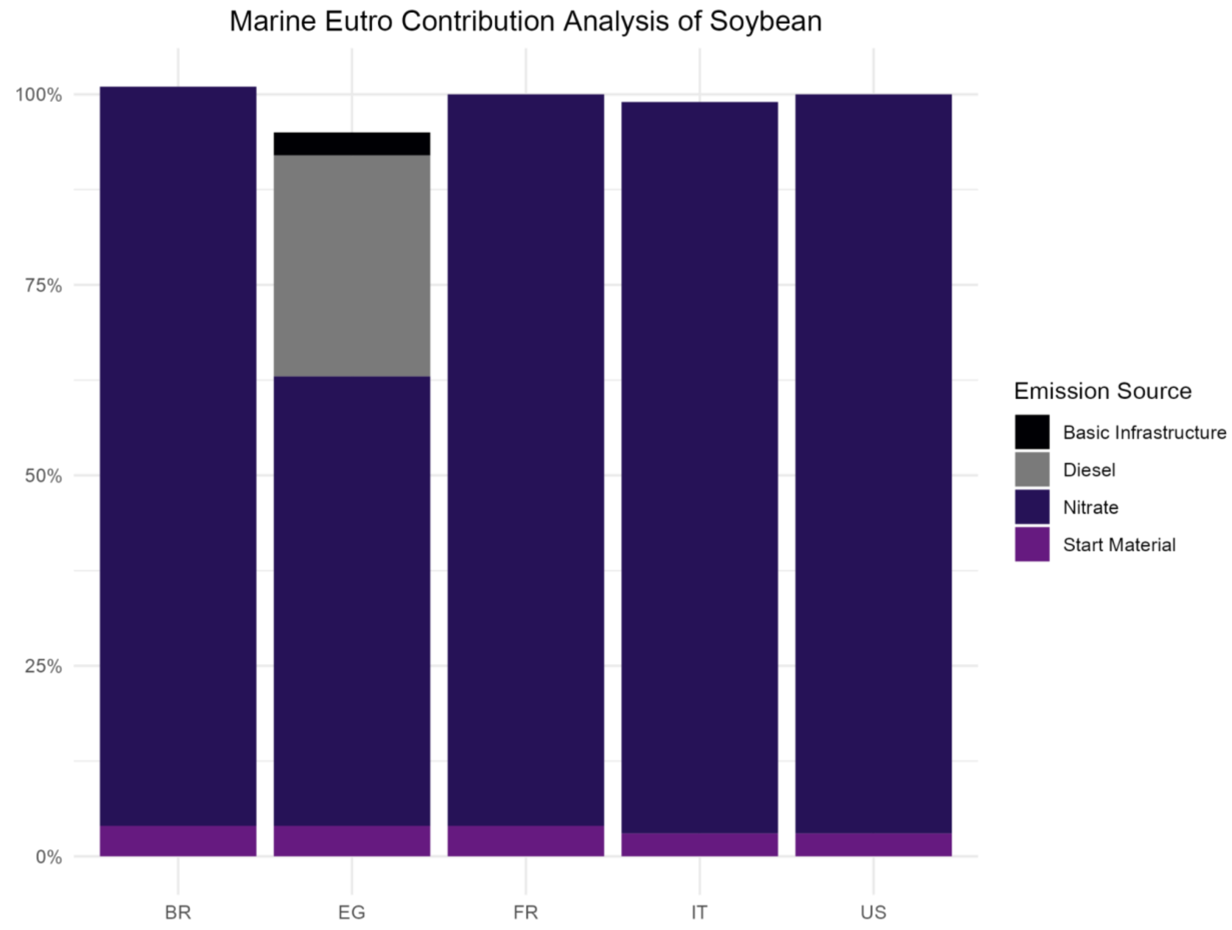


Figure 47: Illustrates the impact of soybean cultivation on marine eutrophication in Brazil, Egypt, France, Italy, and the US. Nitrate in fertilizer applications causes most of all marine eutrophication.

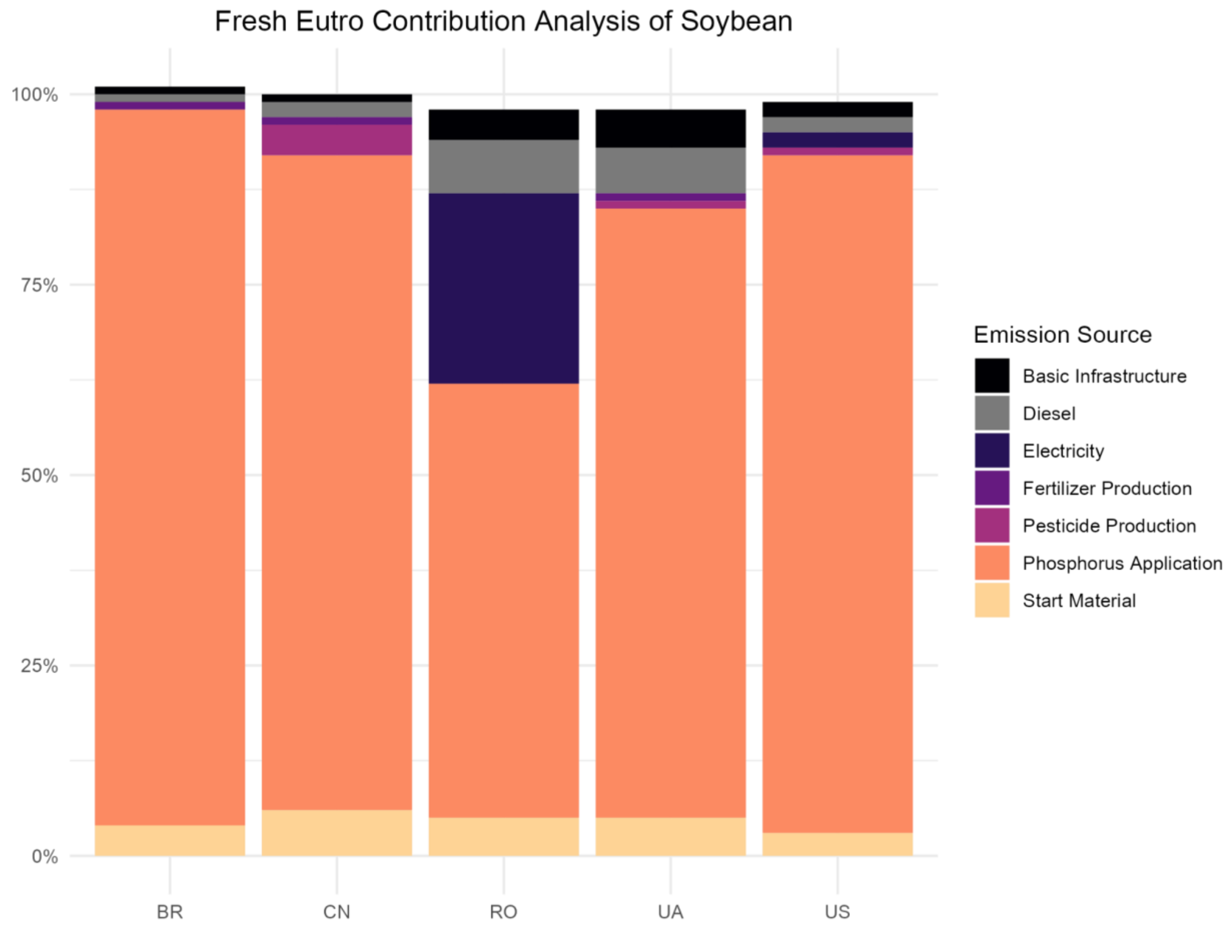


Figure 48: Illustrates the impact of soybean cultivation on freshwater eutrophication in Brazil, Canada, Romania, Ukraine, and the US. Phosphorus in fertilizer applications contribute the most to freshwater eutrophication.

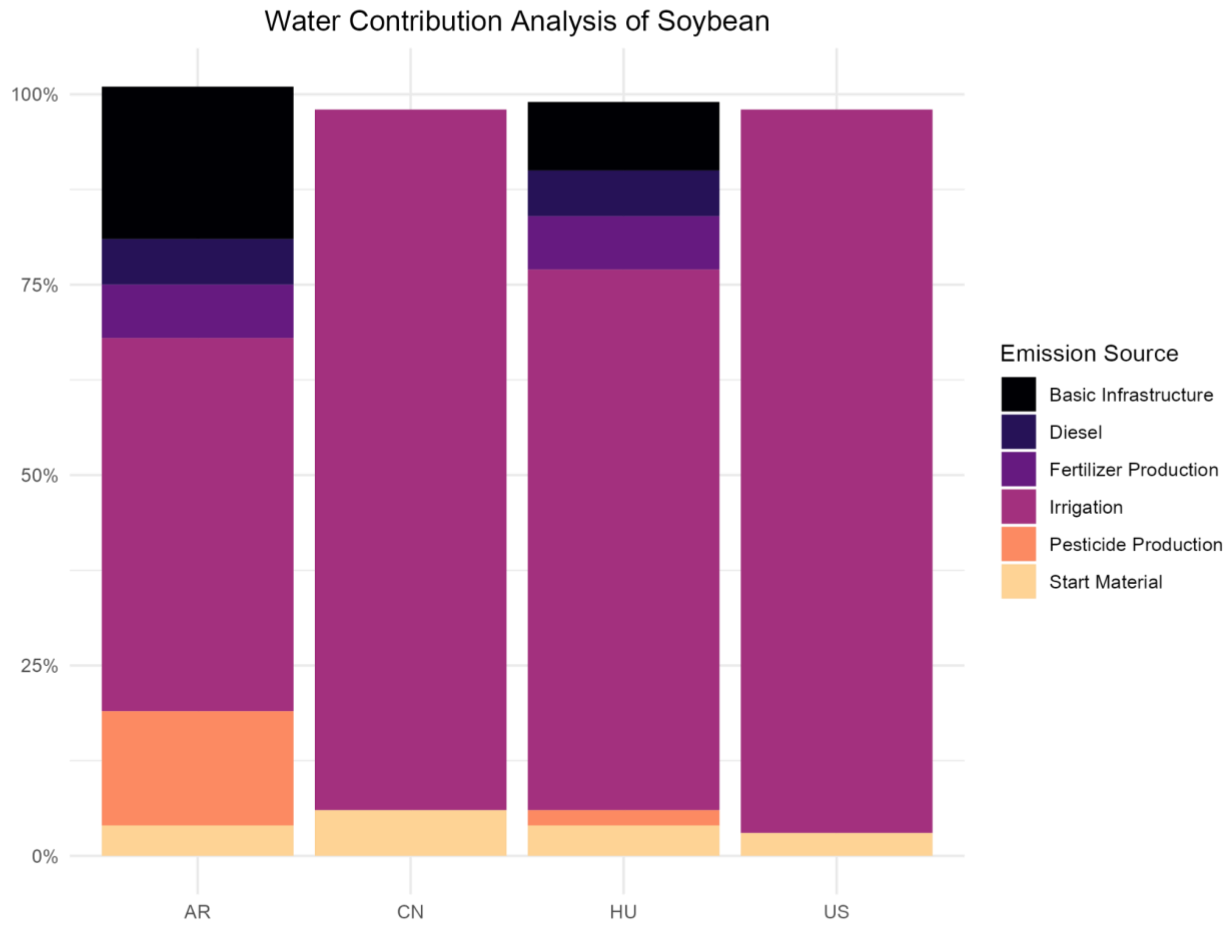


Figure 49: Illustrates the impact of soybean cultivation on water use in Argentina, Canada, Hungary, and the US. Irrigation is the major use of water in all locations.

Mitigation Analysis - Soybeans

Soybeans are a highly nutritious and protein-rich crop widely cultivated worldwide. However, to ensure long-term sustainability, the environmental impact of soybean cultivation must be reduced. One promising approach to this is fixed plant spacing, which involves planting soybean seeds at specific distances from each other.

In a study involving 86 sites, researchers found that fixed plant spacing significantly increased soybean yield compared to broadcast seeding sites. On average, yield increased by

42% with fixed plant spacing, which is a substantial improvement (Van Den Berg & Lestari, 2001). This finding suggests that fixed plant spacing can be an effective strategy for enhancing soybean productivity while reducing the environmental impact of cultivation.

The study also found that using rice straw for mulching increased soybean yield by 41% (Van Den Berg & Lestari, 2001). Mulching helps to retain soil moisture, suppress weeds, and improve soil fertility, all of which can contribute to higher crop yields (Sanchez & Eaton, 2001). However, the effect of rice straw mulching varies depending on the site, and further research is needed to determine the optimal conditions for this practice.

In addition to fixed plant spacing and mulching, crop rotation is another effective strategy for improving soybean productivity and reducing environmental impact. Rotating soybeans with corn is particularly beneficial due to the high nitrogen demand of corn, which soybeans can support through nitrogen fixation (Shea et al., 2020). Other crop rotations that improve environmental and economic gains include wheat, oats, barley, cotton, and forageable pasture (Shea et al., 2020).

Advances in technology have also enabled more precise and efficient soybean cultivation practices. Sun et al. utilized various machine learning algorithms combined with unmanned aerial vehicle (UAV) cross-circling oblique photography to improve soybean yield prediction. This technology enables rapid and accurate assessment of crop performances, enhancing breeding efficiency and optimizing resource allocation (Sun et al., 2024). Combining traditional cultivation practices with cutting-edge technologies makes it possible to increase sustainability and productivity of soybean cultivation to the benefit of both farmers and the environment.

Contribution Analysis - Milk

Raw milk from cattle had an estimated total annual production of 7.53 E+11 kg in 2022. That was the sixth largest food item produced out of the 222 FAO crop, fish, and livestock items from the aggregated production data used for this report. When multiplied by its FAO 2021 global GHG value, 0.96 kg CO2-eq/kg, raw milk's total impact value reached 7.23 E+11 kg CO2-eq, which placed raw milk from cattle as the fifth largest environmentally impactful food item, globally. That is quite a significant placement, especially as the food and agriculture sector accounts for up to one-third of global greenhouse gas emissions (IPCC, 2019).

For many food products, a GHG intensity of 0.96 kg CO2-eq/kg (raw milk's FAO 2021 global GHG intensity) can be considered high. Animal-based products generally have higher GHG emissions due to factors like feed production, enteric fermentation in ruminants, and manure management. For comparison, plant-based foods typically have much lower GHG intensities. For example, field grown vegetables harbor a GHG intensity of around 0.47 kg CO2-eq/kg (Clune et al., 2017).

Raw milk of cattle is defined as, "raw milk from cattle that does not include milk with a fat content of less than 3.5%, skimmed or partially skimmed." Cattle is defined as, "cattle, species of Bos, mainly bovis, taurus, indicus, grunniens, gaurus, grontalis and sondaicus, known with many different names: ox, zebu, yak, gaur, gayal, banteng, etc. This subclass does not include: - buffalo, species of Bubalus, Syncerus and bisons, species of Bison. Dairy cattle are animals of the genus' listed that are producing milk in commercial quantities for human consumption" (FAO, 2020).

According to official 2022 FAO production data, India produces the most raw milk of cattle, at 14.39% of the world production value. This is followed by the United States, producing 13.6% of the world total, and then Brazil, producing 4.73% of the world total. The Agri-footprint database only includes data for 13 countries, accounting for roughly 39.96% of global raw milk of cattle production. This is still good coverage, per similar coverages are seen in the aluminum, steel, and plastic industries (Wu, 2019). Of the top 15 producers of raw milk of cattle, Agri-footprint has data for nine of these countries. The two countries that produce the most raw milk of cattle following Brazil are China and Russia, at 4.73% and 4.35% respectively. India, China, and Russia are the only top producing countries Agri-footprint does not supply raw milk of cattle data for.

Agri-footprint has data available for the “Milk Raw” process, but the processes are only included for “Rest of World” and there is no specific country process data provided. “Dairy Cow,” which is what was utilized for this analysis, has data for a majority of countries and is the first process under “Milk Raw.” Regardless, when examining raw milk production, the majority of environmental impacts come from the management of the cattle themselves, with the largest impacts coming from manure, feed, and land management practices.

These involve processes such as methane emissions from enteric fermentation (cow digestion) and the handling and storage of cattle manure, carbon dioxide from land transformed for feed production and cattle occupation, water consumption for feed production and cattle farming, and nitrate and phosphorus nutrient runoff from feed production and manure that lead to marine and freshwater eutrophication.

Figures 52, 53, 54, 55, and 56 below show data for four countries from Agri-footprint for further focus, the United States, Brazil, Denmark, and Belgium. These countries were chosen as both the United States and Brazil are amongst the countries with the highest raw milk of cattle production and higher environmental impacts, while Denmark and Belgium are on the lower end for raw milk production quantity and gravity of environmental impact.

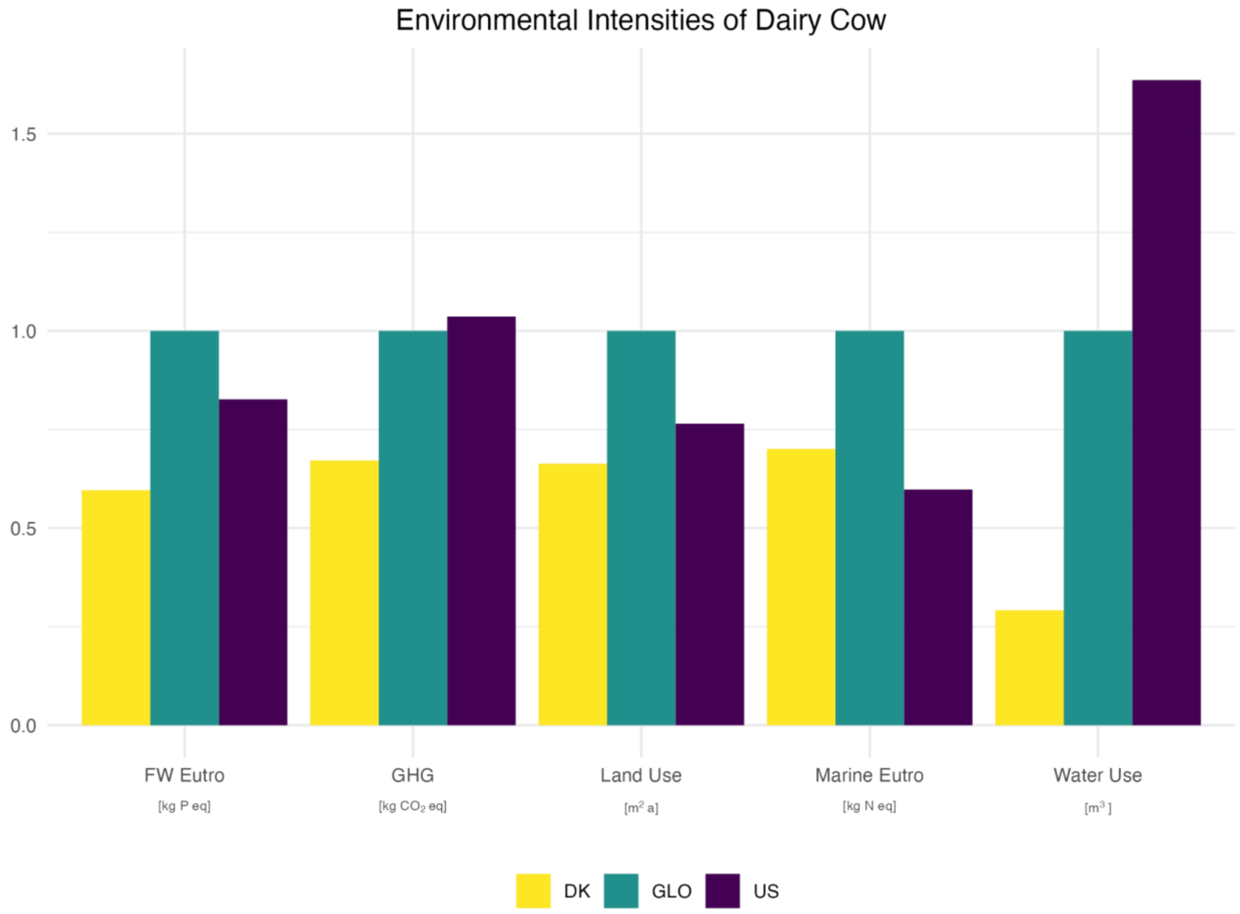


Figure 50: The figure presented depicts Denmark and the US normalized against the weighted global average of our dataset. Among all impact categories, Denmark has the lowest intensity except for marine eutrophication. The US has remarkably high water use compared to the rest of the world, while Denmark has a remarkably low water use intensity compared to the rest of the world.

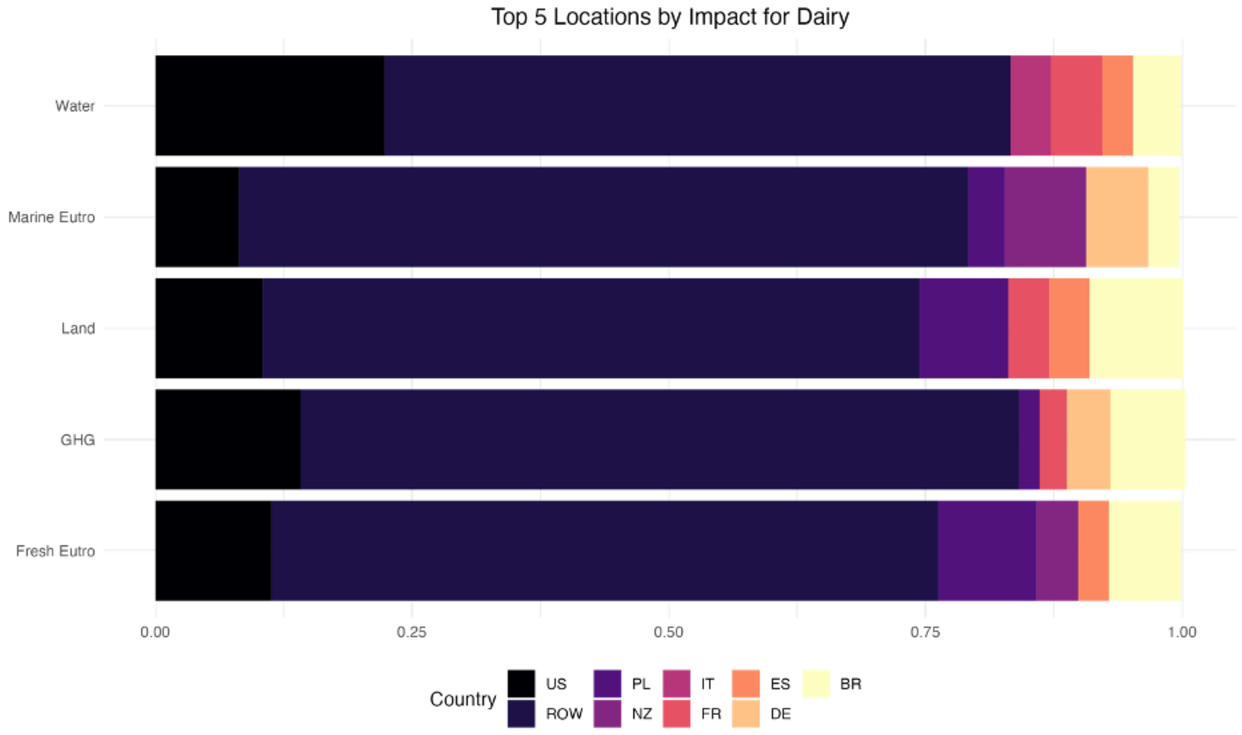


Figure 51: This figure illustrates the top five contributing countries to the global impact for each impact category. Across all categories, ROW has the highest impact, due to the 39.96% global coverage in Agri-footprint, followed by the US. Brazil has the next largest impact for GHG and land use. Poland has the next largest impact for freshwater eutrophication. New Zealand has the next largest impact for marine eutrophication. France has the next largest water impact.

Out of the 13 countries Agri-footprint provides data for, Brazil and Poland have the highest GHG intensity, while Denmark and Belgium have the lowest. For total impact (GHG intensity X production quantity), though, the US and Brazil have the highest GHG total impact, with Denmark and Belgium with the lowest.

For freshwater eutrophication, Poland and Spain have the highest intensities, while Denmark and the Netherlands have the lowest. For total impact, though, the US and Poland have the highest freshwater eutrophication total, with Belgium and Denmark having the lowest.

For land use, Poland and Brazil have the highest intensities, with the Netherlands and New Zealand with the lowest. For total impact, though, the US and Brazil have the highest land total, with Denmark and Belgium having the lowest.

For marine eutrophication, New Zealand and Spain have the highest intensities, with Denmark and the US having the lowest. For total impact, though, the US and New Zealand have the highest marine eutrophication total, with Belgium and Denmark having the lowest.

Lastly, for water consumption, Spain and the US have the highest intensities, with Denmark and Belgium having the lowest. For total impact, though, the US and France have the highest water consumption total, with Denmark and Belgium having the lowest.

This is important information to point out, as having high intensities for these impacts does not simply equate to having the largest environmental impacts. For example, Poland and Spain have repeating high intensities for these indicators, but do not come to the top of the list for any total impact. Having a large environmental intensity does not necessarily emphasize a commodity's importance. Production quantity, country practices, and climate conditions play a huge role as well.

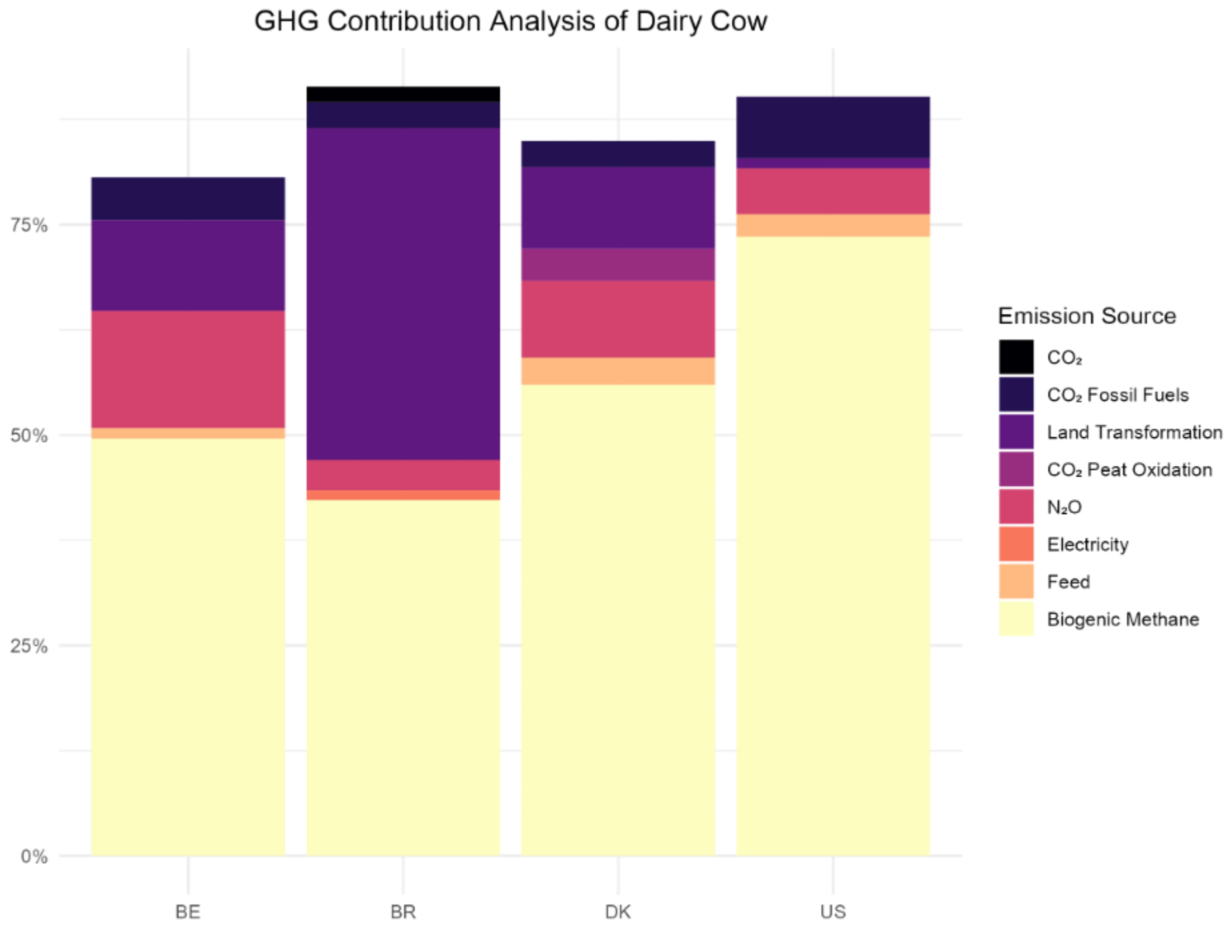


Figure 52: The contribution analysis of milk production for Belgium, Brazil, Denmark, and the US is presented in the figure. The analysis reveals that for each of the countries, the majority of the impact (~74% - 85%) comes from the dairy cow housing system process. Within this process, the majority of emissions are coming from biogenic methane (methane produced by biological processes). Carbon dioxide (CO2) is the next largest emission type after methane, followed by dinitrogen monoxide (nitrous oxide, N2O). Carbon dioxide from land transformation makes up the largest CO2 process source for all countries besides the US. Carbon dioxide from fossil fuel combustion for things such as heat, electricity, and energy from diesel burned in machinery make up a negligible percentage of these greenhouse gas emissions. The feed emission source shown in the graph encapsulates process emissions from rapeseed, maize, and oat grain production. These were grouped separately as a process as their emissions represent less than 1%.

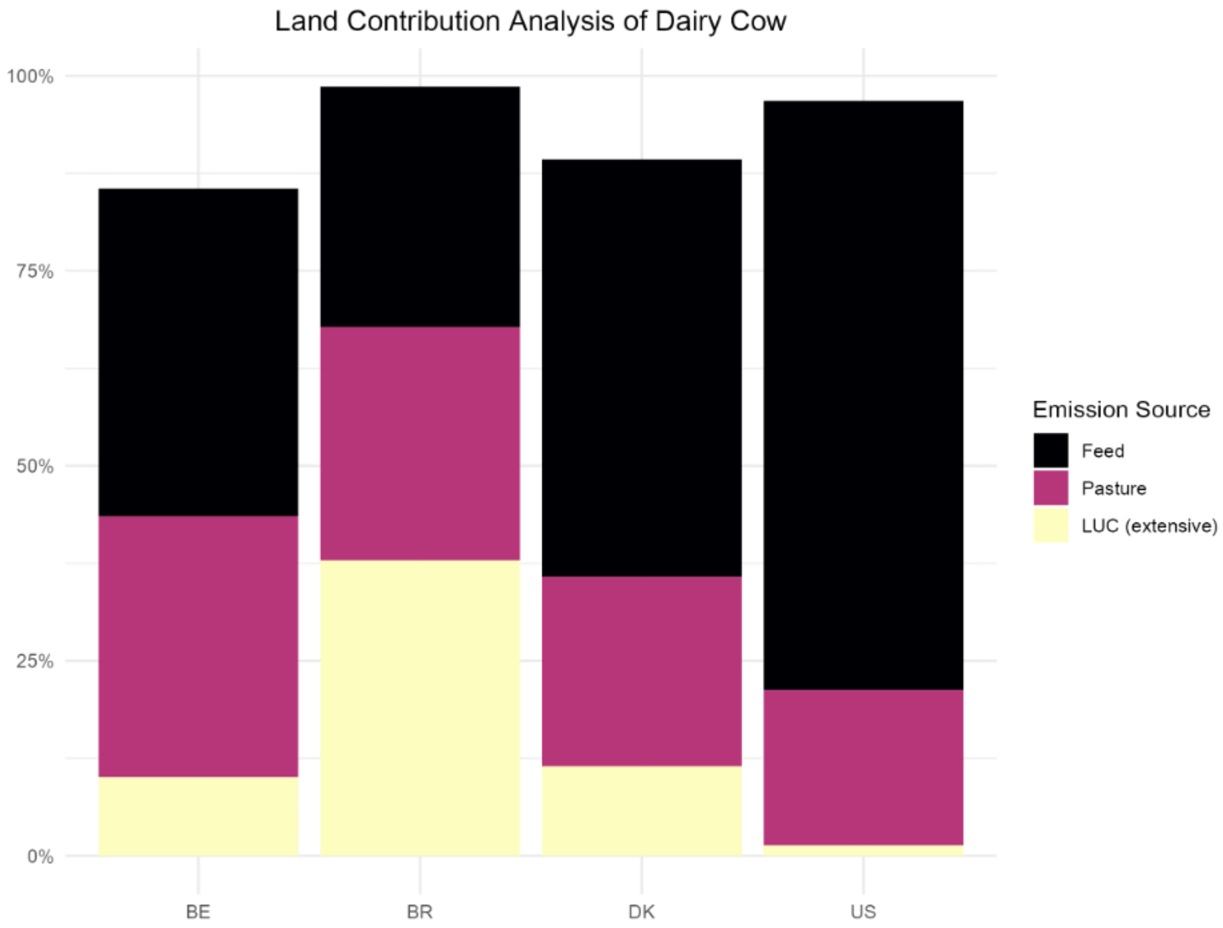


Figure 53: This figure illustrates the land use impacts of milk production from Belgium, Brazil, Denmark, and the US. The majority of the impact in all locations is due to the dairy cow housing system process. Within this process, the majority of impact is from land occupation for feed crops, such as rapeseed, maize, soybeans, wheat grain, oat grain, barley grain, sunflower seeds, lupins, seed cotton, triticale grain, and rye grain. The second largest impact is from land occupation for pasture/grassland/meadows. A smaller percentage of the impact comes from land transformation, specifically extensive transformation of forests, for these crops, except for Brazil, where this is the largest process source of land use impact.

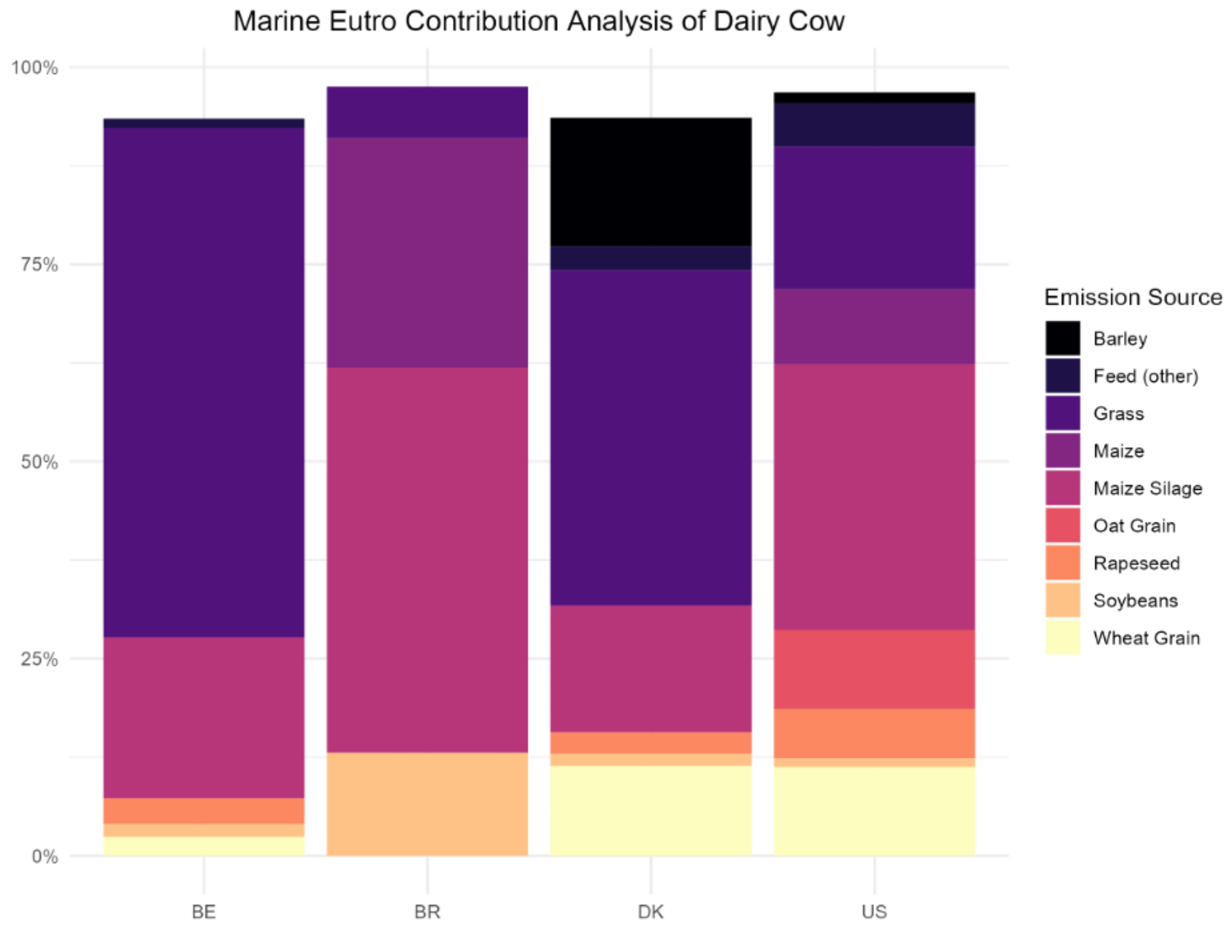


Figure 54: This figure illustrates the impact of milk production on marine eutrophication in Belgium, Brazil, Denmark, and the US. The majority of the impact in all locations is due to the dairy cow housing system process. Nitrate runoff into water bodies from the production of these feed crops causes all of the marine eutrophication for these countries. For the US and Brazil, maize silage causes the most marine eutrophication. For Denmark and Belgium, grass causes the most marine eutrophication. The small percentages of feed included in the “other” category vary between lucerne, rye grain, fodder beet (sugar beet), and triticale grain.

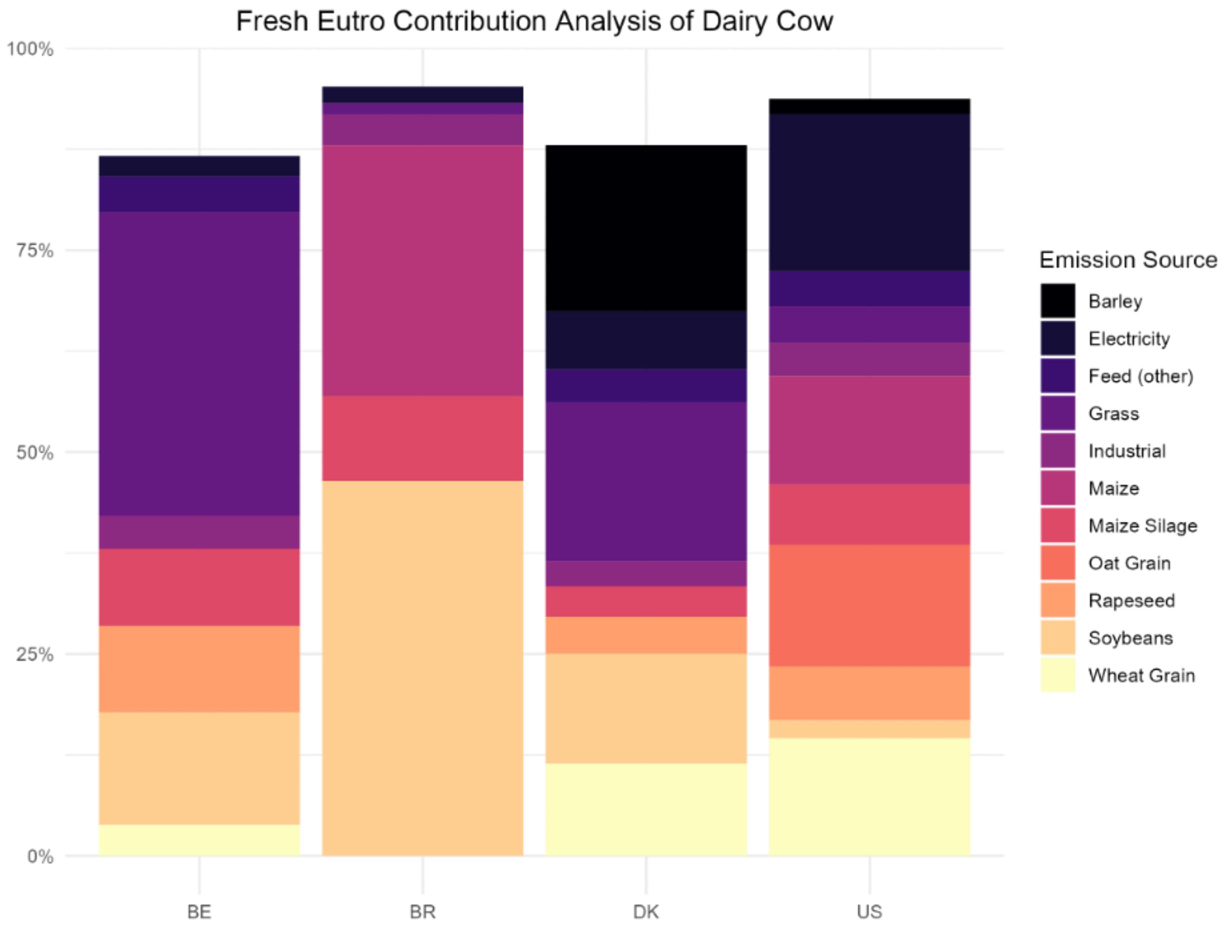


Figure 55: This figure illustrates the impact of milk production on freshwater eutrophication in Belgium, Brazil, Denmark, and the US. The majority of the impact in all locations is due to the dairy cow housing system process. Phosphorus from agricultural runoff and leaching into groundwater from industrial processes, such as electricity and machine usage, constitutes most of the freshwater eutrophication for these countries. Phosphate runoff into water bodies from electricity constitutes the majority of US freshwater eutrophication, followed by phosphorus runoff from oat grain. Phosphorus runoff from soybeans contribute the majority of freshwater eutrophication for Brazil, followed by maize. Phosphorus runoff from grass contributes the majority of freshwater eutrophication for both Belgium and Denmark, followed by soybeans. For all countries, negligible percentages of freshwater eutrophication are from industrial processes such as feed additives, tractor usage, and construction. The small percentages of feed included in the "other" category vary between lucerne, rye grain, lupins, fodder beet (sugar beet), and triticale grain.

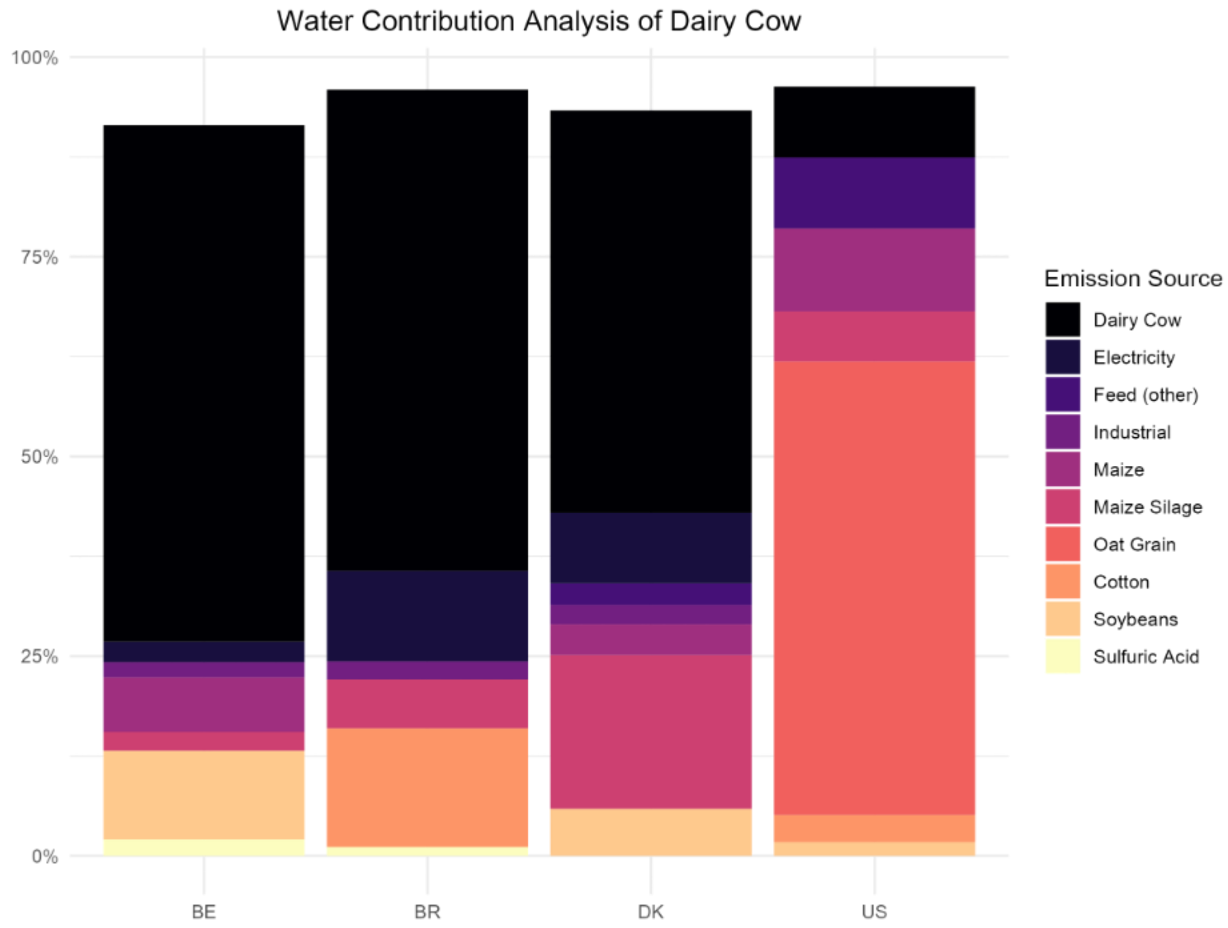


Figure 56: This figure illustrates the impact of milk production on water consumption in Belgium, Brazil, Denmark, and the US. For all countries except the US, the majority of water consumption is by the dairy cows, at farm. For the US, the majority of the water consumption is used for oat grain feed. For all countries, negligible percentages of water consumption are used for industrial processes such as feed additives, packaging, and construction.

Mitigation Analysis - Milk

The environmental impact of raw milk production from dairy cows is multifaceted, and the extent of each impact can vary depending on local agricultural practices and intensity of farming methods, geographic and climatic conditions, and environmental regulations.

Among these impacts, greenhouse gas emissions are particularly noteworthy due to their direct contribution to climate change, which has wide-reaching effects on weather patterns, global temperatures, sea levels, and ecosystems worldwide. Methane from dairy cows, in particular, is a significant concern as methane is about 34 times more potent than CO2 over a 100-year period (FAO, 2020). Temperature is positively correlated with CH4 emissions, and since cows are seen to be more productive in cooler states, global warming presents a huge issue for the dairy industry (Niles et al., 2019). However, as seen in the contribution analyses, the most significant impact can vary regionally. For example, in areas with acute water shortages, like locations in the Western United States, water consumption may be the most pressing issue, while in regions with large numbers of dairy farms, like Denmark and Belgium, nutrient runoff and the resulting eutrophication might be of greater immediate concern.

The majority of the environmental impacts from raw milk production come from manure management, cow digestion, and agricultural processes related to dairy cows. To address the impacts of these agricultural processes, sustainable agricultural practices pertaining to the production of feed needs to be further prioritized. Mitigation for crops such as soybeans, maize, and sugar beet can be found in the sections above to address this issue.

It is well understood that GHG emissions produced from feed production and industrial operations for dairy cow farming are important environmental problems to mitigate. However, as our findings show, they are actually quite a small makeup of the totality of GHGs emitted. The majority of each country's GHG emissions was found to be biogenic methane that comes from cow digestion and the management of their manure, with the US contributing the highest percentage, at 74%. Globally, nearly 10% of agricultural greenhouse gas emissions are attributed to livestock manure management (Owen, 2015). According to recent regression analyses using a global warming potential methodology, methane emissions from manure in the US have been on the rise, while emissions from enteric fermentation have stayed relatively stable. Between 2010 and 2020, methane emissions from manure have had a greater impact on global warming compared to methane from enteric sources. This indicates that methane from manure is playing a more significant role in climate warming than previously thought, highlighting the need for increased efforts to mitigate this source of emissions (Beck et al., 2023). Traditional emissions inventories tend to rely on factors derived from small-scale lab experiments, which often haven't been evaluated against larger-scale field measurements. It has been found that these types of modeled methane emissions typically fell below those measured in the field for most manure management practices, indicating that the current emission factors for GHG from dairy manure are generally underestimated (Owen, 2015). This significant discrepancy highlights a serious oversight in our environmental impact assessments, underscoring the urgent need for revised methodologies and increased regulatory attention.

The US has one of the largest dairy industries in the world (Niles et al., 2019). Of the 13 countries in Agri-footprint, it contributes to 35% of the global emissions, the largest contributor of all 13 countries, and has the third highest GHG intensity, making it of grave importance to mitigate large scale emissions.

A significant amount of dairy GHG emissions are coming from manure management, which varies regionally and farm to farm (Niles et al., 2019). Greenhouse gas emissions are significantly influenced by the waste management system (WMS) employed. For instance, methane emissions tend to rise considerably in the anaerobic (oxygen free) environments prevalent in numerous WMSs (Wightman, 2016).

When looking between these four countries, they all have different manure management systems (MMS) that yield different measures of methane releases. MMS are currently an understudied topic, further noting the importance of this mitigation focus. We need to shift our efforts, as dairy production is only increasing, and MMS are becoming a larger portion of the problem (Niles et al., 2019).

Denmark and Belgium are both known for their efficient agriculture. They both contribute ~1% to the global emissions out of the 13 countries in Agri-footprint, the lowest emitters of all the countries. Additionally, they both have the lowest GHG intensities compared to these 13 countries.

The manure management for dairy cows in Denmark involves a liquid slurry system with a natural crust cover. In this setup, manure from dairy cows is collected and stored as a liquid slurry, consisting of manure mixed with water and usually other organic materials. The mixture is kept in a storage facility, such as a lagoon or a concrete tank. Over time, a natural crust forms on the surface of the slurry. This crust is composed of the solid parts of the manure that float to the top and gradually dry out.

In Belgium, they mainly utilize pit storage systems for manure over periods longer than one month. In this system, manure from dairy cows is collected and stored in covered pits.

In both of these systems, they employ distinct manure management strategies tailored to specific environmental and regulatory conditions. Both have “pits” or “lagoons” used to collect the manure, but the key to both management techniques are that these pits are sealed (by either the natural crust from the liquid slurry in Denmark or just the physically covered pits in Belgium). This is done to reduce the methane emissions that result from the breakdown of manure. These pits and lagoons are often designed to be anaerobic, meaning they operate without the presence of oxygen, which optimizes the breakdown of organic matter (manure) that are processed by anaerobic bacteria (bacteria that do not require oxygen to live). This allows anaerobic digestion to occur, which breaks down the manure and produces biogas (which is mainly methane and carbon dioxide). The biogas produced during anaerobic digestion can then be captured and used as a source of renewable energy on the farm. This not only provides a sustainable energy source, but also helps reduce greenhouse gas emissions.

Anaerobic lagoons are widely used in the US for managing livestock waste, particularly in large dairy operations (Niles et al., 2019). Anaerobic lagoons collect manure and other liquid and solid wastes from dairy operations and utilize natural processes, like the anaerobic activities mentioned above, to address waste. This process significantly reduces the volume of waste and treats it by converting many of the pollutants into simpler, less harmful compounds.

After treatment, the effluent from the lagoon can be used to irrigate crops, providing a valuable source of fertilization.

While anaerobic lagoons are effective (simple, low operational costs, and are more affordable for larger operations) for waste breakdown, they pose significant environmental risks, particularly methane emissions, as the lagoon systems are traditionally uncovered in the US (Pfost, 2000). There has been a significant increase in the adoption of anaerobic lagoon systems in the US, as they are seen to be positively related to higher per-cow productivity, larger herd sizes, and lower labor costs than other storage systems. This significant adoption of anaerobic lagoon systems is largely associated with the overall GHG emission increases associated with overall US dairy manure management (Niles et al., 2019).

Farmers are seemingly adjusting their manure management strategies to align with state and federal water quality policies, aiming to meet or anticipate water regulation changes. Winter manure spreading, which can increase phosphorus runoff, has become increasingly scrutinized across the US. Instead, liquid storage systems, like anaerobic lagoons, allow farmers to store manure longer and time their applications better. Some states, like Maine and Vermont, have banned winter spreading, while 26 other states have imposed stricter manure spreading regulations on larger farms. These policies, especially those targeting large farms, prompt shifts towards these anaerobic lagoon MMS and longer-term storage solutions, where previous daily spread methods were seen with significantly decreasing GHG emission intensities. This shift raises a dilemma: are these regulations aimed more at enhancing water quality or reducing greenhouse gas emissions? The different focuses can create conflicting priorities at the farm level, making it difficult to achieve a balance between nutrient management and other environmental impacts, and complicating the pursuit of universally beneficial outcomes (Niles et al., 2019).

Installing covers on anaerobic lagoons, like those seen in Belgium, can significantly reduce methane emissions by capturing the gas before it escapes into the atmosphere. A 13.7% decrease in GHG emissions was observed on a conventional farm when incorporating manure the day of application and adding a 12-month covered storage unit (Dutreuil et al., 2014). Brazil's MMS is a daily spread system, and according to the Agri-footprint data, emits the least amount of biogenic methane between these four countries, at only 46% of all GHG emissions.

There is also the possibility of exploring alternative waste treatment options, like the solid-liquid separation used in Denmark, as installing and maintaining lagoon covers can be a somewhat costly option and harder to manage as regular maintenance is needed to ensure the integrity of the cover. Even more costly are anaerobic digesters, which is a more complex system designed specifically for optimizing the production of biogas. These systems are generally more technologically advanced and expensive than simply covering a lagoon, offering greater control over the digestion process and efficiency in biogas production. The development of natural and artificial crusts or other covers for manure lagoons has demonstrated a potential GHG emission reduction of up to 20%. Wooden covers can reduce CH4 emissions more than a natural crust, though may have the potential to increase N2O emissions. A solid-liquid slurry system with a natural crust cover can indeed be one of the more cost-effective methods for managing manure, particularly in terms of initial setup and operation costs. Unlike more complex systems such as anaerobic digesters, a solid-liquid slurry system does not require advanced technology or significant infrastructure. It does not require the installation of covers or other more expensive covering methods, as the natural crust that forms over the slurry acts as a natural barrier. Lastly, there is less need for energy input and complex maintenance compared to systems like anaerobic digesters. The natural crust cover is not as effective, though, at capturing gasses for use as energy as a purpose-built biogas capture system (Niles et al., 2019). Methane emissions were even seen to be overestimated in many slurry storage MMS, furthering the justification of their effectiveness (Owen, 2015).

Although setup and maintenance costs of anaerobic digesters are high, they have proven effective in significantly cutting GHG emissions, by up to 80%, through reduced methane from manure and displaced fossil fuel electricity. However, their adoption varies due to different digester types, management approaches, and feedstocks, and the high costs involved pose a significant barrier, exacerbated by the instability of milk prices (Niles et al., 2019).

Despite these challenges, the potential of digesters and other innovative manure management methods to mitigate emissions is considerable, especially on larger, more productive dairy farms which typically have the resources to invest in such capital-intensive systems. Surveys in Louisiana and New York indicate that the largest and most efficient farms are most likely to adopt advanced manure management systems like anaerobic digesters. However, with only 265 such systems currently in operation across the US, focusing on overcoming barriers to adoption could be crucial for broader implementation (Niles et al., 2019).

In the use of all of these systems, greenhouse gasses, particularly CH4, are seen to be reduced more effectively in colder temperatures, and draining manure lagoons in early spring, before it warms up, could be a strategy to further decrease emissions in these MMS (Niles et al., 2019).

Lastly, in the context of MMS for dairy farms, IFSMs (Integrated Farm System Model) is a helpful tool to emphasize for dairy operations, as it can be utilized for evaluating how changes in management practices, technology, and climate may affect the sustainability of livestock operations. This model, developed by the USDA Agricultural Research Service, simulates the long-term performance, environmental impact, and economics of dairy and beef cattle production systems. It integrates various components of the farm operation, including crop growth, feed use, animal growth and reproduction, manure handling, and the economics of the farming operation (Dutreuil et al., 2014).

In terms of mitigation strategies for enteric sources of methane, the pig mitigation section below focuses on ways to diminish the amount of methane emissions that are released from livestock digestion. The biogenic methane that is a large part of the environmental impact from raw milk production due to dairy cow farming is not only due to manure storage, but is also due to enteric fermentation. Although this produces less methane emissions than those produced from manure storage for the US, it is actually a larger portion of the total methane emissions for Denmark and Brazil (Barros, et al., 2022; Vechi, et al., 2022). Brazil is the second highest contributor to GHG emissions from dairy cow farming, at 18% of the global total for the 13 countries included in Agri-footprint, making mitigation solutions impactful for these types of emissions as well.

Contribution Analysis - Eggs

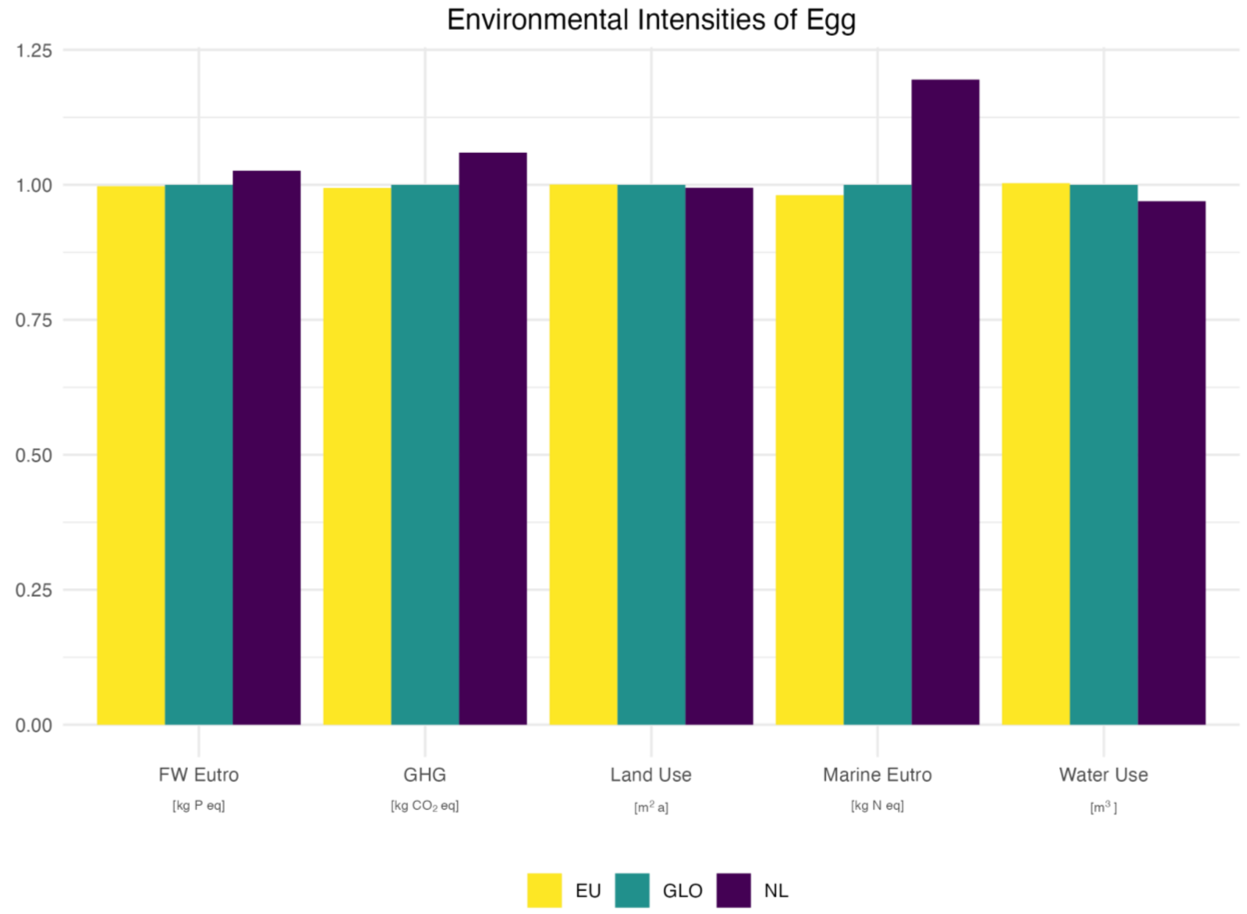


Figure 57: The figure presented depicts the EU and the Netherlands normalized against the weighted global average of our dataset. The Netherlands (NL) has the lowest intensity for water and land use but is higher than the EU in all other categories. NL also has a high impact of marine eutrophication compared to the rest of the world.

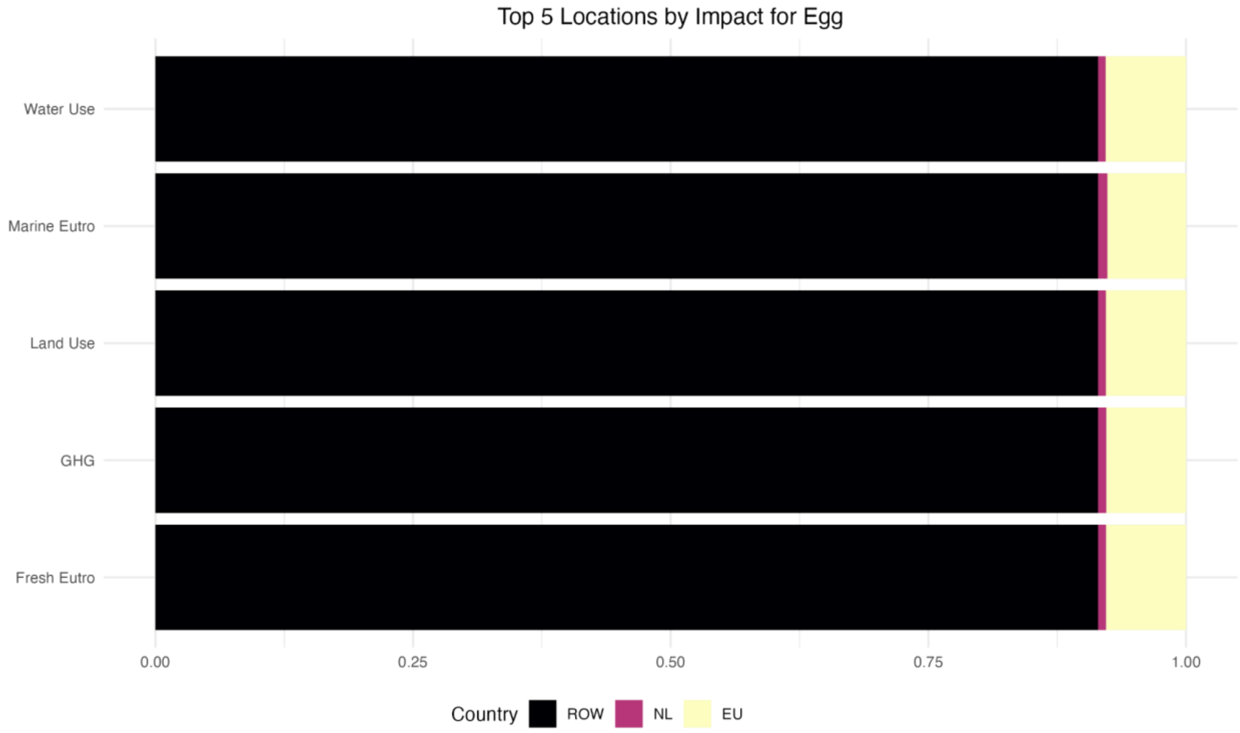


Figure 58: The contribution analysis of eggs for ROW, NL, and EU is presented in the figure. Due to data limitations only 8% coverage was included in the analysis. The graph shows that NL has a lower overall impact than the EU in all categories.

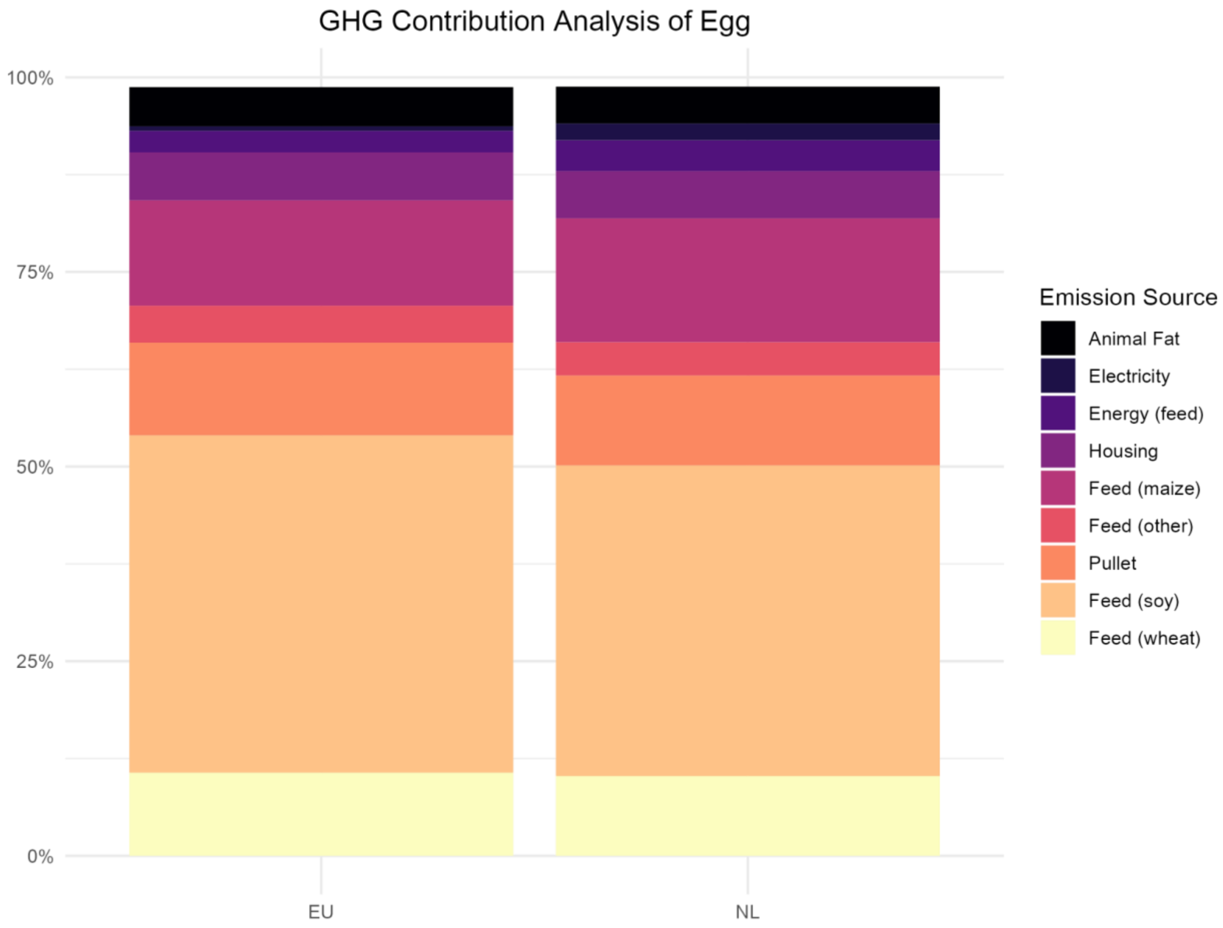


Figure 59: In both EU and NL feed is shown to have the highest contribution to GHG emissions. Electricity is one of the smaller portions of GHG contribution.

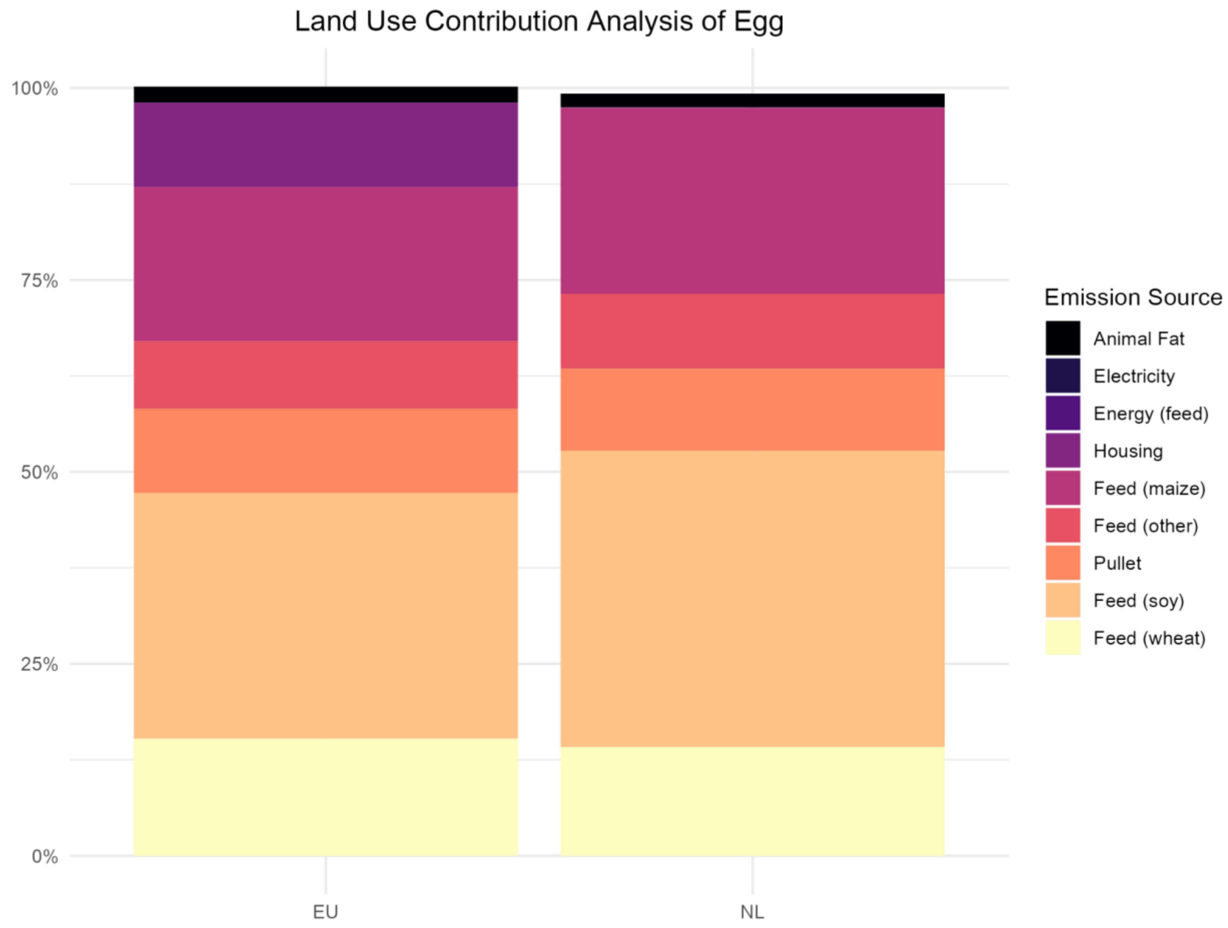


Figure 60: Feed combined is seen to have the highest contribution to land use in both EU and NL. Feed categories have been broken down further to show the largest contribution of feed in both countries is from soy.

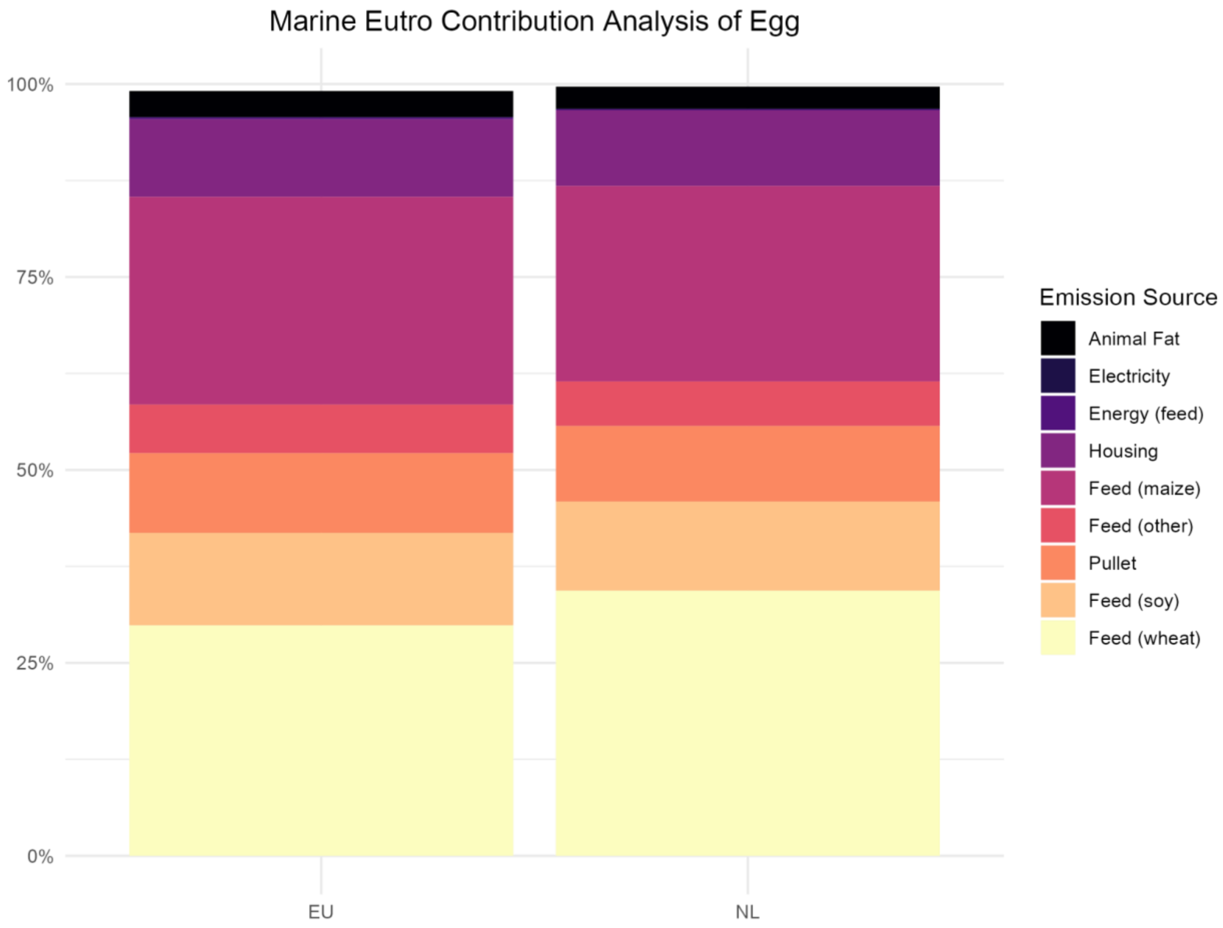


Figure 61: Feed combined is seen to have the highest contribution to marine eutrophication in both EU and NL. Feed categories have been broken down further to show the largest contribution of feed in both countries is from wheat and maize.

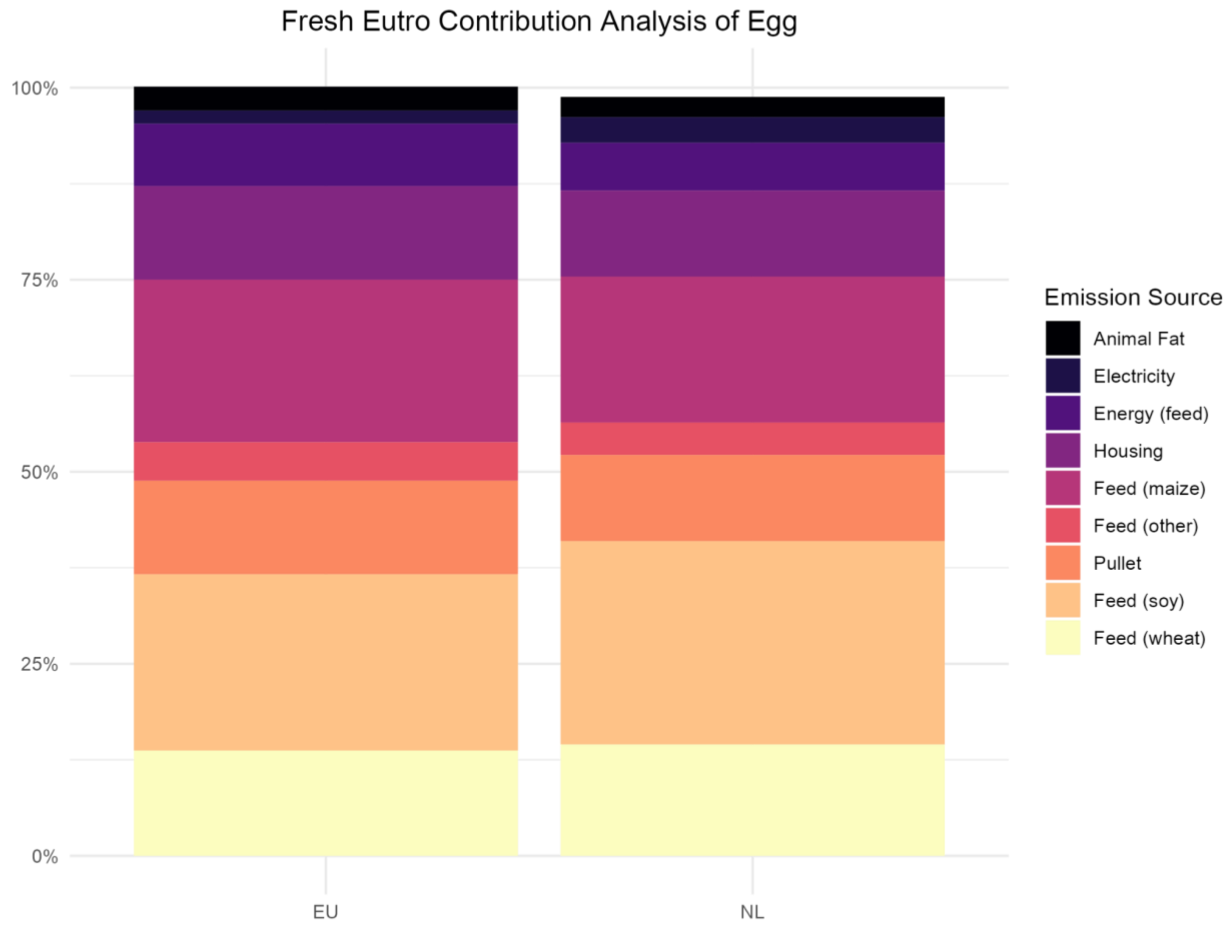


Figure 62: Feed combined is seen to have the highest contribution to freshwater eutrophication in both EU and NL. Feed categories have been broken down further to show the largest contribution of feed in both countries is from soy followed by maize.

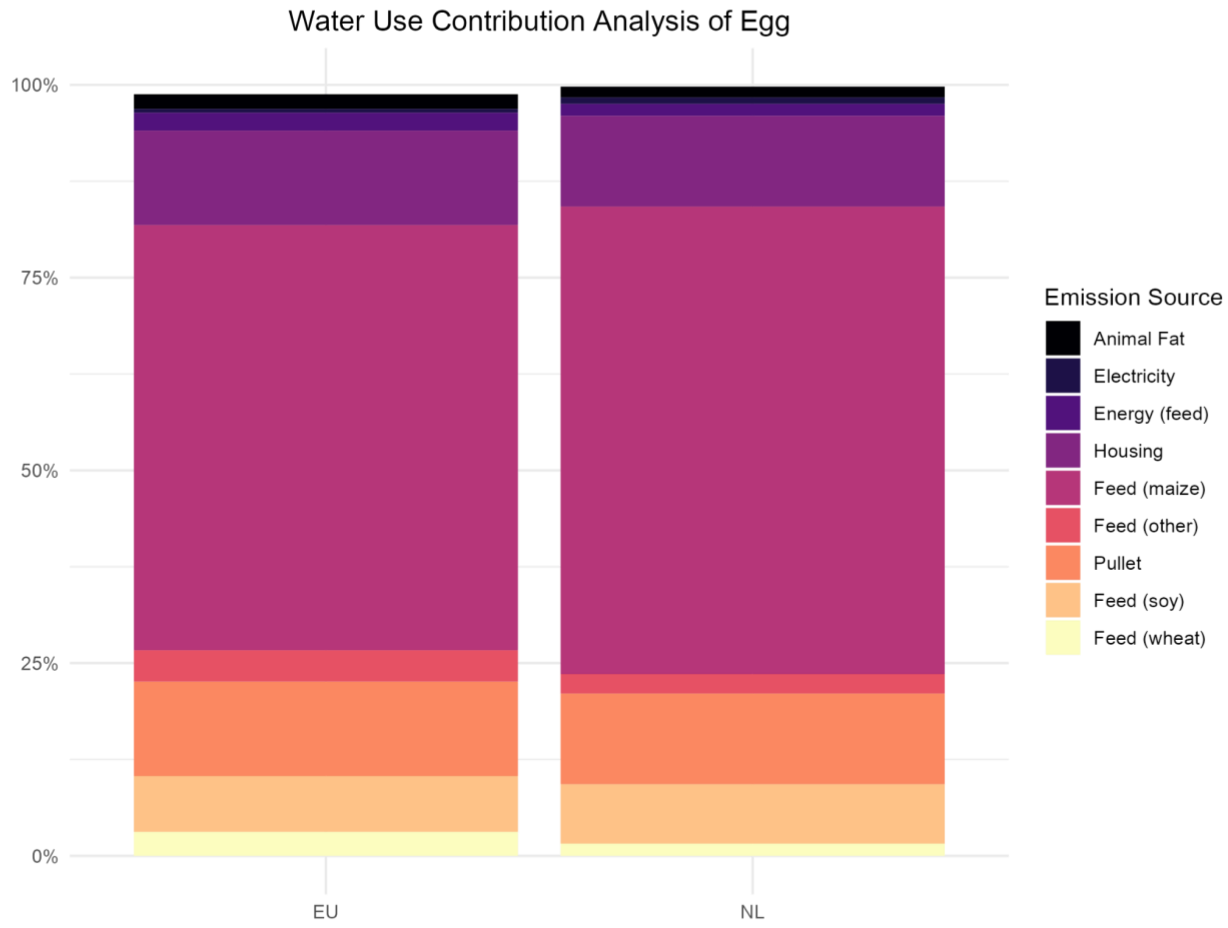


Figure 63: Feed combined is seen to have the highest contribution to water use in both EU and NL. Feed categories have been broken down further to show the largest contribution of feed in both countries is from maize.

Mitigation Analysis - Eggs

Eggs have a relatively low GHG intensity of 0.57 kg CO2e/kg (Clune et al., 2017) and ranked much lower than our top food products. However, as it is one of the most affordable and widely produced forms of protein, we included eggs in our contribution and mitigation analysis. Due to limitations in the Agri-footprint database, only 8% coverage was included in the analysis. Stages of egg production include raising chicks, development of the pullet and the posture phase when laying hens produce eggs. The bulk of the emissions are from the posture phase of egg production at about 80% (Estrada-Gonzalez et al., 2020). From this stage the largest contribution is attributed to feed and is, "the input with the most significant contribution of environmental impact in the entire [egg] system product," (Estrada-Gonzalez et al., 2020).

As energy from renewable sources and highly efficient products are increasingly available, several LCA studies focused on lowering the emissions from the electricity use in the egg posturing phase (Abín et al., 2018) (Quantis, 2014) and (Pelletier, 2017). Utilizing energy efficient LED light bulbs reduce energy use by 50% and is a practical mitigation strategy (Estrada-Gonzalez et al., 2020). A Canadian LCA found that using an organic housing system reduced energy use from 11,248 MJ to 7,951 MJ per ton of eggs produced. Similarly, a study in the UK showed lower use of farm electricity in free range production, as opposed to conventional cages, with the co-benefit of improved animal welfare (Leinonen et al., 2014). Modernized housing alternatives are effective at lowering energy use but only addresses a smaller fraction of the emissions from egg production. Since not all production systems use the same equipment and the amount of energy used varies greatly by location, lowering energy use should not be the main mitigation strategy.

Considering this variation in poultry housing and technologies, a more uniform mitigation strategy is to address the feed– the largest portion of the emissions in egg production. Abín et al agrees, "environmental improvement actions should be directed mainly towards optimizing the hen feed formulation, not only from an economic perspective but also considering the environmental aspects involved (Abín et al., 2018). Feeds that are currently widely used include imported grains and animal-byproducts. Using solely plant-based, nitrogen-fixing legumes such as peas, significantly reduce emissions (Pelletier et al., 2017). Insect-based feed was investigated as an alternative protein for feed but yielded ambiguous results in comparison to conventional feed (Roffeis et al., 2020). Another noteworthy point is that Hy-Line W-36 hens are considered to be the most efficient laying breed worldwide. Selecting breeds that require less maintenance or inputs and have higher yields is also a significant mitigation strategy.

Contribution Analysis - Pigs

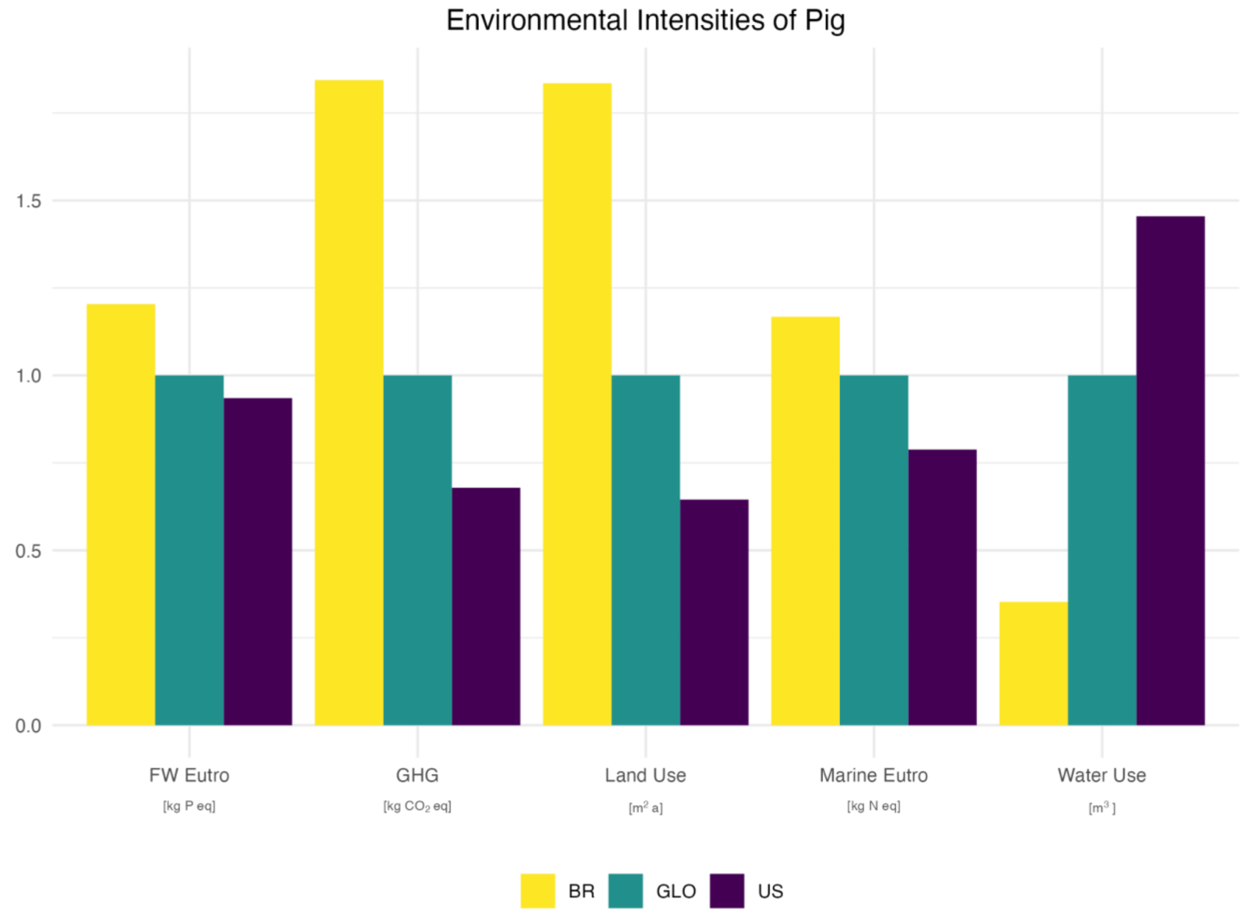


Figure 64: The figure presented depicts Brazil and the US normalized against the weighted global average of our dataset. Among all impact categories, the US has the lowest intensity

except for water use. The US has a lower GHG intensity compared to the rest of the world.

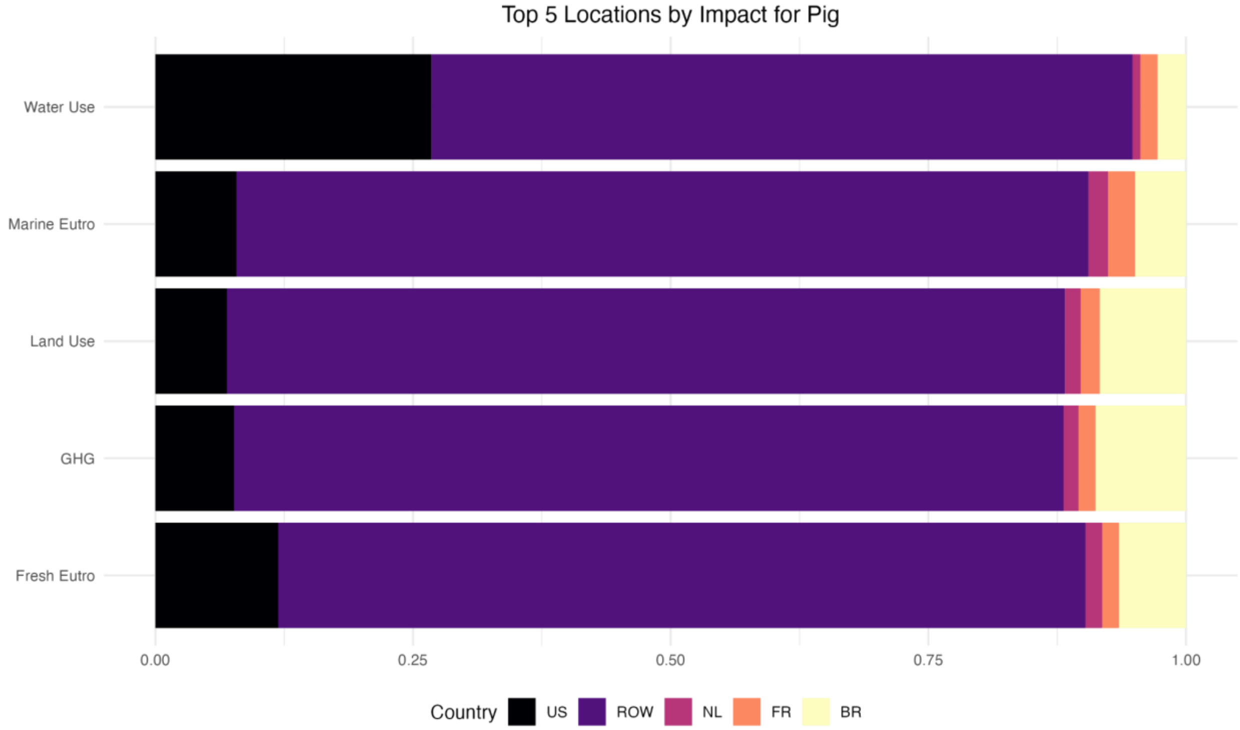


Figure 65: The figure illustrates the top five contributing countries to the global impact for each impact category. Across all categories, the US has the highest impact, followed by Brazil, France, and the Netherlands.

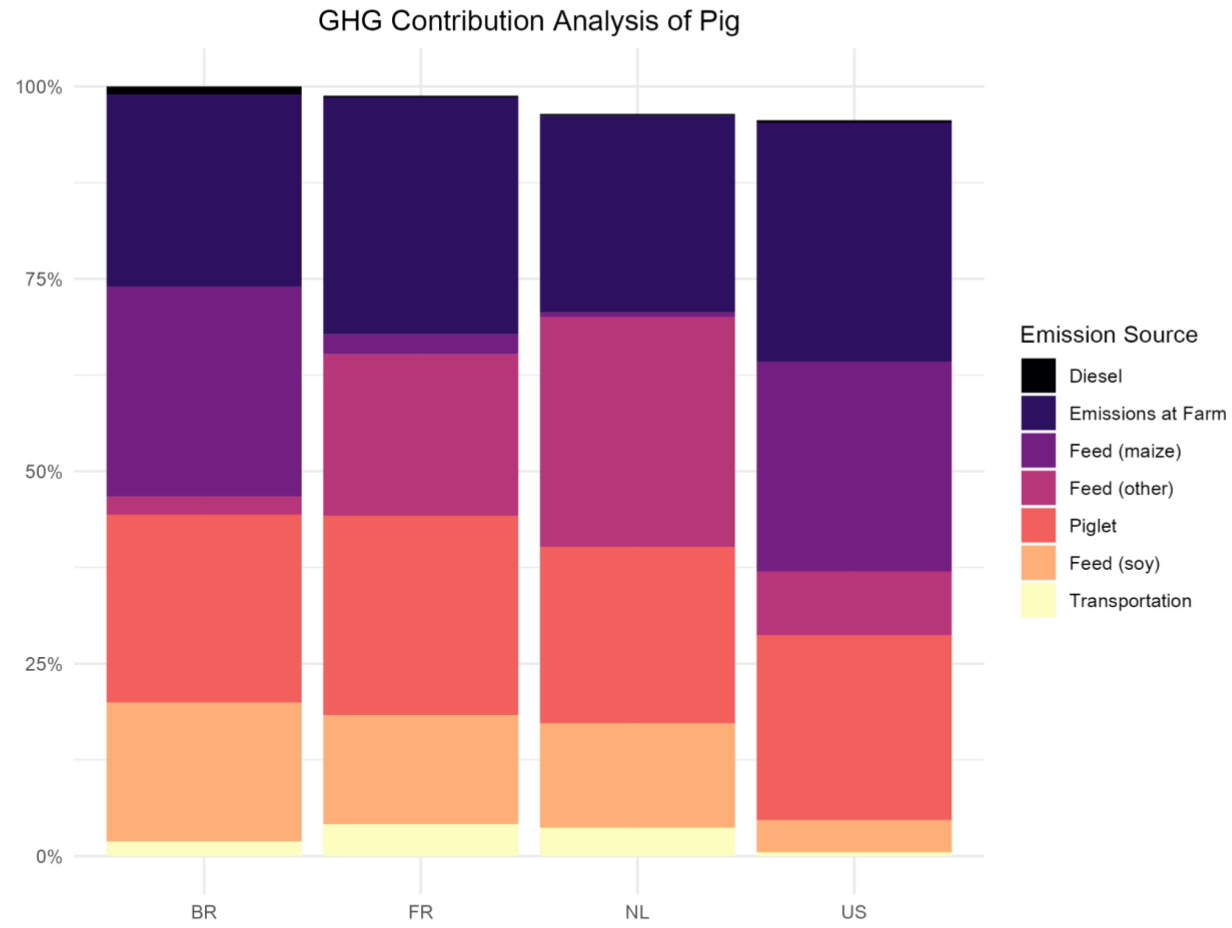


Figure 66: The contribution analysis of pig for Brazil, France, Netherlands, and the United States is presented in the figure. For all countries, the majority of the impact comes from feed and has been broken down further into maize feed, soy feed, and other feed. The analysis reveals that for Brazil and the US, the majority of the impact comes from maize feed. On the other hand, for France and Netherlands, the majority of the impact results of feed are from soy. Emissions at Farm includes methane emissions and housing system.

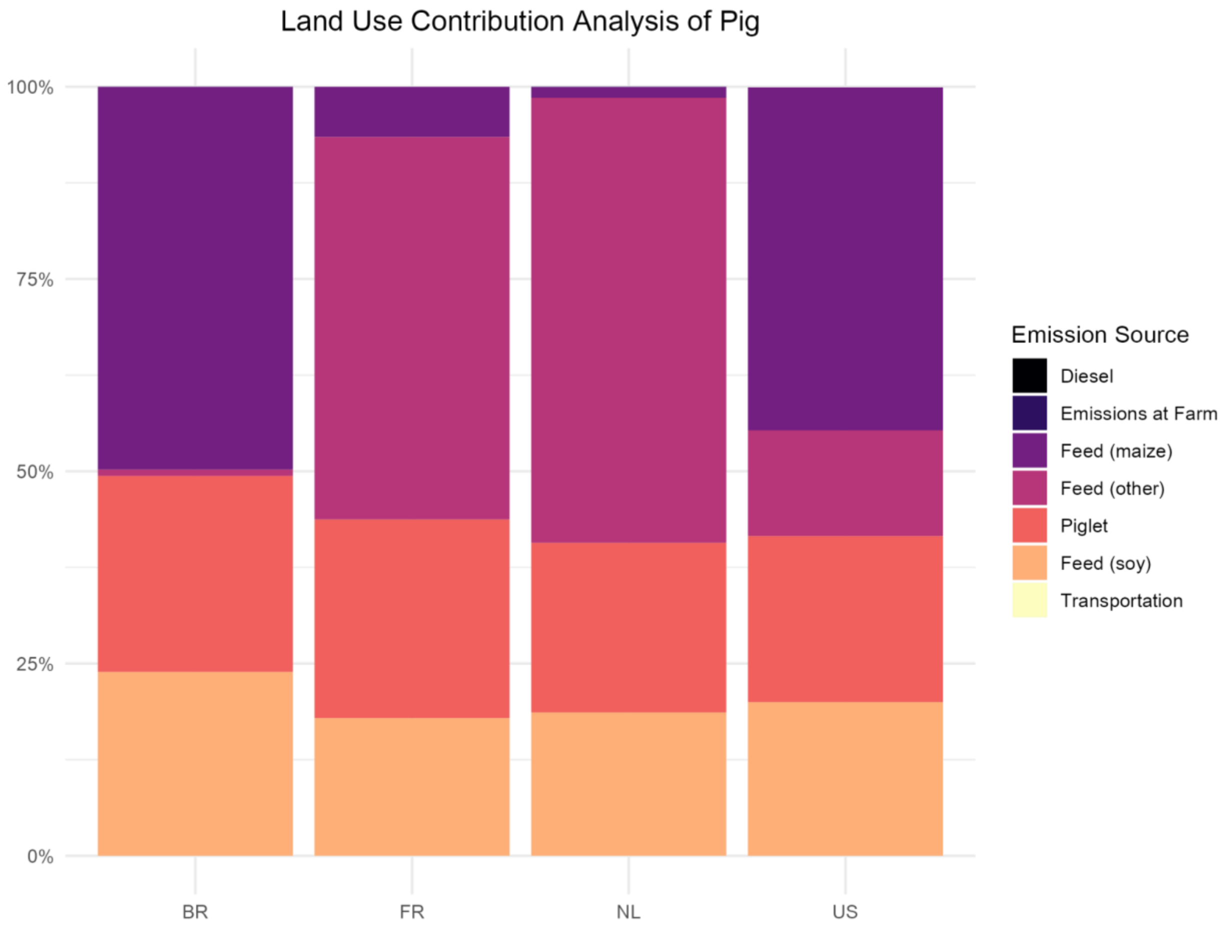


Figure 67: This figure illustrates the land use impacts of pig production from Brazil, France, Netherlands, and the US. Almost all of the impact in all locations is due to feed which has been broken down further into maize, soy and other. BR and US have a large portion from maize whereas FR and NL have almost none.

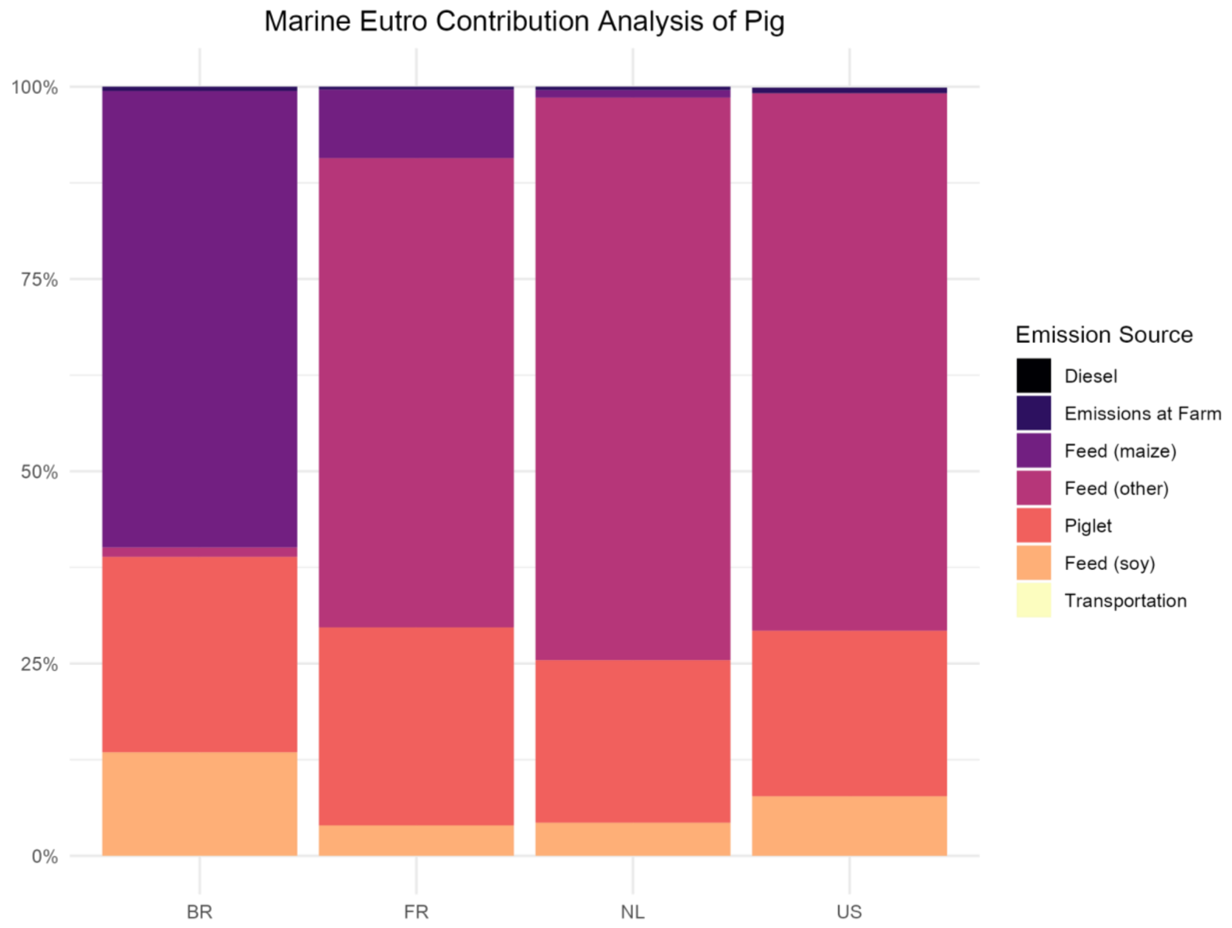


Figure 68: This figure illustrates the impact of pig production on marine eutrophication in Brazil, France, and the Netherlands. Almost all of the impact in all locations is due to feed which has been broken down further into maize, soy and other. BR has a large portion from maize whereas FR, NL, and the US have the highest contribution from other feed.

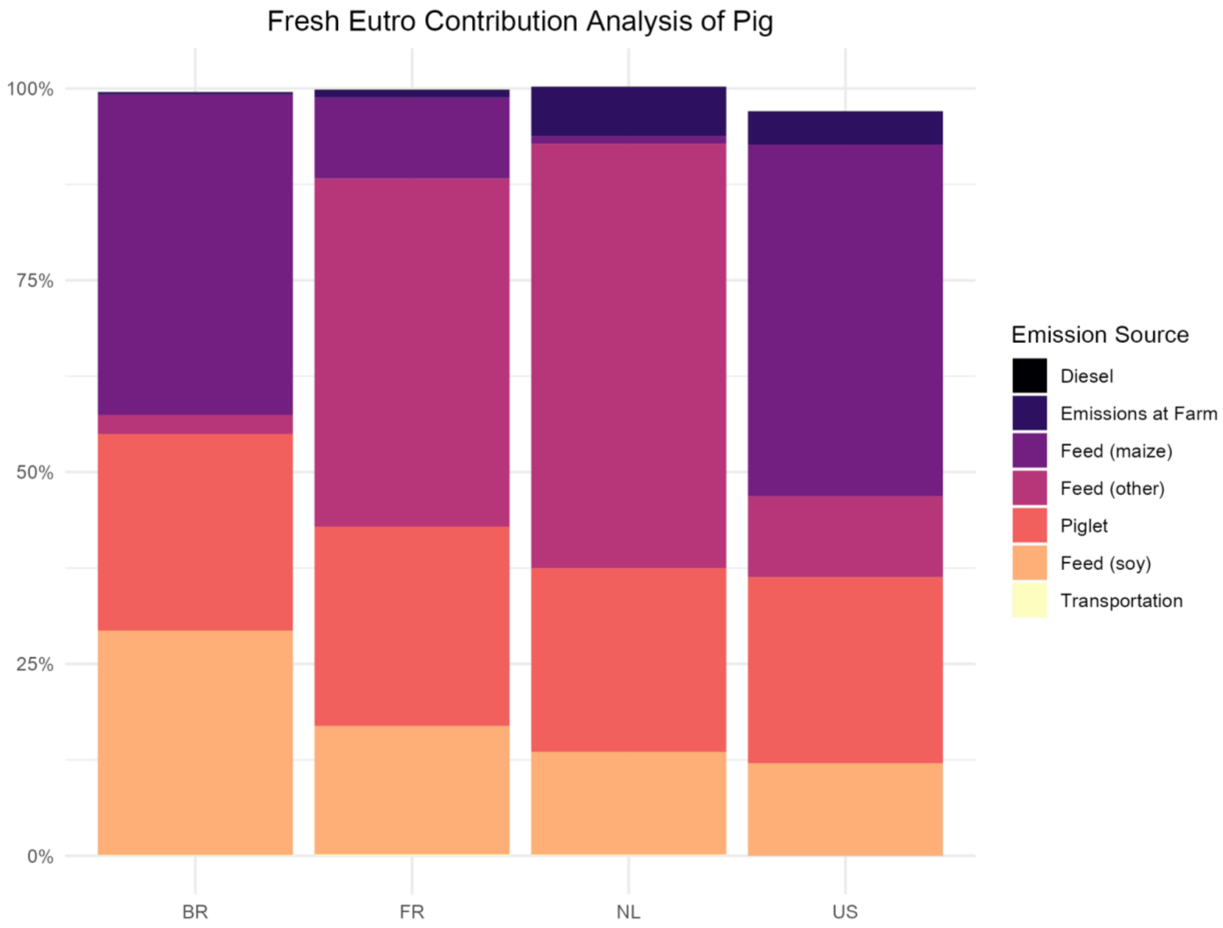


Figure 69: This figure illustrates the impact of pig production on marine eutrophication in Brazil, France, Netherlands, and the US. Almost all of the impact in all locations is due to feed which has been broken down further into maize, soy and other. BR and US have a large portion from maize whereas FR and NL have the highest contribution from other feed.

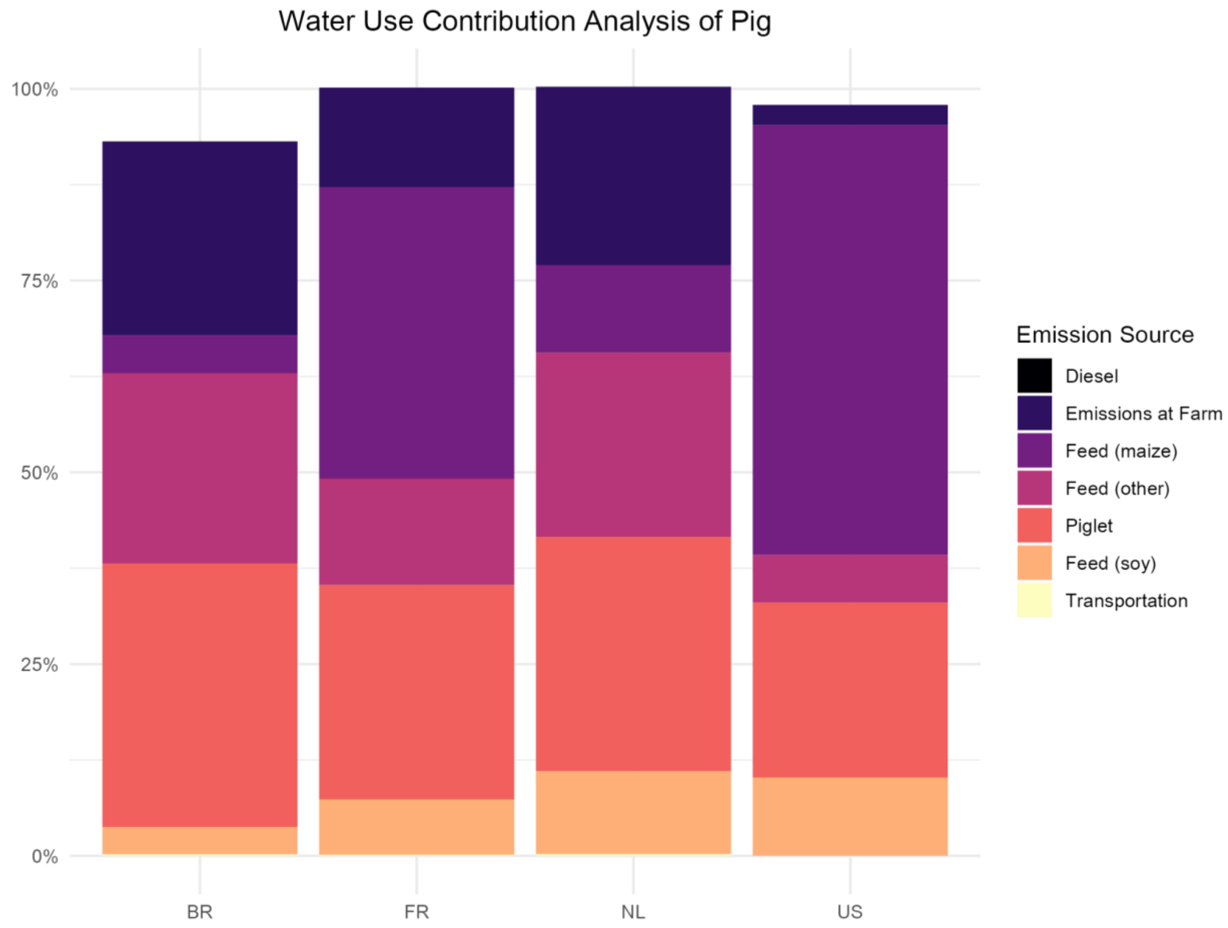


Figure 70: This figure illustrates the pig production on water use in Brazil, France, Netherlands, and the US. Almost all of the impact in all locations is due to feed which has been broken down further into maize, soy and other. The US has a large portion from maize whereas BR and NL have similar amounts from feed and emissions at farm.

Mitigation Analysis - Pigs

Pig meat is the second most demanded meat after poultry, accounting for 34% of global meat (Ndue & Pál, 2022). Rather than CH4 emissions from ruminants which are commonly attributed to cattle, pigs are monogastric and enteric fermentation is minimal (Horillo, 2020). The two largest sources of GHG impact from pig cultivation are N2O emissions from manure and from feed. Whether manure or feed are highest depends on if the feed is imported.

Manure from pig cultivation causes the largest portion of emissions when feed is locally sourced. Feed cultivation increases land use which is a huge driver of deforestation and GHG emissions.

By addressing feed impacts first, a large portion of emissions can be reduced. For example, in Arrieta and González the CO2-eq/ton decreased from 6.06 when a pig was raised in confinement versus 5.17 CO2-eq/ton in paddocks with access to pasture grazing (Horrillo, 2020). This could be due to the fact that, “organic systems maximize pasture exploitation which contributes to the lesser consumption of off-farm feeds and at the same time, the grazing technique improves the quality of the pasture by increasing soil’s carbon sequestration,” (Horillo, 2020). Feed additives such as amino acids, multiphase feeding and protein ratio are a proven method for lowering emissions as manure management. Studies show a negative correlation between the higher protein content in feed and GWP. “The higher the protein, the lower the GWP was reported ranging from 1.39 when pea was used as the main feed to 3.25 under conventional feeds,” (Ndue & Pál, 2022). In France when amino acids like tryptophan and valine were added, emissions with GWP were significantly lowered. A practice known as “swill” is when pigs are given food waste as feed. While directly beneficial to reduce food waste, swill feed practices may counter the benefits of adjusted feed formulas that lessen methane emissions.

The pork industry in the US was responsible for 17,000 ha of LUC in 2017 alone and some have called for a moratorium on agricultural expansion as a mitigation strategy (Pelton et al., 2021). Incentives to prevent more LUC include certifying low land use change suppliers. Additionally, if LUC is unavoidable, areas that are able to be restored could be prioritized over areas that are difficult to remediate. While many have pushed for organic products in particular to improve the quality of life of the animal itself, grazing and free-range systems use more land than conventional systems: conventional systems require almost one third of the land needed by organic systems. Similarly, Monteiro et al evaluated nine case studies of pig production in 2017 and showed that sustainable practices toward efficiency in conventional pig systems can be more environmentally friendly than organic pig systems.

Manure management is a term for any strategy to address the waste created from pig production. An inexpensive solution is to use a deep littering technique instead of an open effluent pond. With deep littering straw or sawdust are layered over soiled areas to reduce the exposure of the effluent to the atmosphere, thereby lowering ammonia emissions. This is an intermediary solution that would still require more biomaterial for the layers and eventual disposal. Another option is to use manure as a resource. While more expensive, biodigesters can generate methane, which can be used as a source of natural gas energy. Rearing insects on manure to be monetized as feed as the process reduces waste volume and recovers nutrients (Roffeis et al., 2020). This scenario is more hypothetical as of yet and would require more land, labor and infrastructure which may offset the benefits of diverted emissions.

To summarize mitigation strategies of pork production systems:

1. Adjusting the feed formula such as adding synthetic amino acids and increasing protein content can reduce CH4 emissions from manure.
2. Sourcing locally sourced, nitrogen fixing leguminous plants instead of imported feed ingredients can reduce CH4 emissions from manure.
3. Multiphase feeding and efficient watering through technological devices at-farm.
4. Implementing “Swill” to recycle food waste as feed.

5. Manure management strategies such as deep littering (inexpensive), use of manure for insect rearing, or use of biodigester technology to harness methane as energy source (expensive).

Discussion

Life cycle thinking is an essential tool to complement existing global food footprint studies that lack the granularity LCAs offer. These LCAs not only help in identifying hotspots within specific food commodity production processes, but also rely on an increasingly standardized approach outlined in regulations and manuals, supplemented by extensively utilized databases and models. Conversely, LCAs adopt a "bottom-up" methodology, frequently offering detailed evaluations of individual products exclusively. To understand system-wide impacts, thus requires combination with global higher level studies of the environmental impacts of food production. This is what this report and analysis overall aimed to achieve and further emphasize the need for using these two types of data sources in tandem to make informed and context-specific decisions. LCAs have the power to be employed by deducing specific streamlined determinations or have the power to be synthesized to make broader conclusions. Despite the rising popularity of LCAs, scholars have pinpointed various barriers obstructing its wider adoption in policymaking (Rajagopal et al., 2017). Alongside the previously mentioned methodological complexities, challenges in implementation include policymakers' skepticism regarding the reliability of life cycle assessments, the challenge of attributing indirect economy-wide effects to specific producers (a focus of consequential LCAs rather than attributional LCAs), occasional deficiencies in alternative selection within LCAs, inadequate communication and engagement among analysts, policymakers, and stakeholders, and the financial costs associated with conducting comprehensive LCAs. Instances where LCA has effectively influenced public policy were marked by extensive stakeholder involvement from the outset, resulting in enhanced understanding and trust. Seidel (2016) argues that the limited impact of LCAs on public policy development is not due to inherent technical flaws but rather to the procedural framework within which LCA is incorporated.

In our analysis, we deliberately excluded beef due to its extensive study in combination with poor data quality available in the Agri-footprint database. Instead, we focused on lesser-studied high impact crops to offer valuable and more novel insights to aid UNEP in their efforts towards developing a sustainable food system strategy. This decision aims to broaden understanding and provide additional information on crops, thereby enhancing comprehension of global food production's environmental impacts. By prioritizing commodities other than beef, we aimed to spotlight mitigation strategies that receive less attention from academia, the private sector, and government initiatives.

This analysis highlights the limitations of data available, which allows for a more nuanced interpretation of results and discussion. We recognize that our data coverage may not be exhaustive, but it's unfortunately standard due to evidence gaps in literature and a lack of studied granularity. We provide percentages of coverage for each crop analyzed. This transparency enables stakeholders to understand the scope and reliability of our findings, facilitating informed decision-making despite inherent data constraints. Achieving 100% data availability is unattainable for a project of this global scope. Therefore, conducting robust research involves recognizing limitations and employing uniform efforts to address them, ultimately facilitating progress and informed decision-making.

Acknowledging data limitations, particularly concerning the Agri-footprint database, we strived to mitigate these gaps by using ROW data to supplement missing global production figures. Throughout our report, we transparently identified areas with data gaps and explained how we addressed them, ensuring consistency in our impact assessment. While recognizing that our data may not encompass all global food production, we remained committed to employing uniform measures to maintain analytical coherence.

Aggregating the data from Agri-footprint for our chosen commodity items also allowed us to compare these commodities against each other for the four other environmental impact categories that we did not use for rankings in phase one. These comparisons and impact category specific rankings serve to bring together all of the phases of our analysis for a unified perspective. This aggregation also allows us to explore the lesser focused on environmental impact categories included in this study, and understand how highly GHG impactful food commodities rank against each other for other important environmental impacts. See Tables 5, 6, 7, and 8 below. The food commodities analyzed in this report do not have full data coverage, indicating there will be some variability in results and a margin of error. Percentage of coverage, referred to as “global” in the contribution analysis, are indicated in all tables below.

Table 5

Global land use impact

Commodity	Global Land Use Impact (m2a crop-eq)	Agri-footprint 6.3 Production Coverage (%)
Dairy Milk	2.36E+12	40%
Maize	1.65E+12	89%
Rice	1.05E+12	72%
Pig	1.64E+11	17%
Sugar Cane	4.45E+10	86%
Sugar Beet	4.28E+10	75%
Eggs	3.20E+10	8%
Soybean	1.77E+09	97%
Wheat	1.75E+09	88%
Oil Palm	4.44E+08	87%
Potatoes	1.91E+08	69%
Cassava	1.73E+08	20%

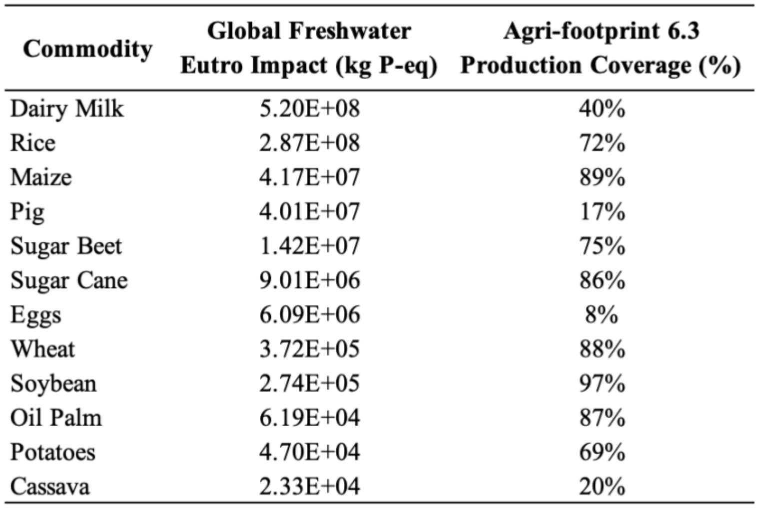
Table 6

Global water use impact

Commodity	Global Water Use Impact (m3)	Agri-footprint 6.3 Production Coverage (%)
Rice	1.13E+11	72%
Dairy Milk	4.80E+10	40%
Maize	4.17E+10	89%
Sugar Cane	6.56E+09	86%
Pig	2.68E+09	17%
Sugar Beet	1.27E+09	75%
Eggs	3.87E+08	8%
Wheat	1.24E+08	88%
Soybean	9.56E+06	97%
Potatoes	6.15E+06	69%
Oil Palm	9.26E+04	87%
Cassava	6.98E+04	20%

Table 7

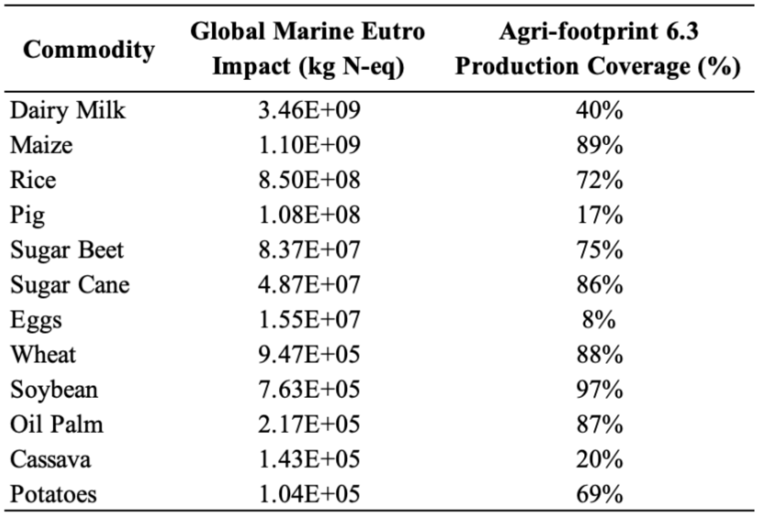
Global freshwater eutrophication impact



Commodity	Global Freshwater Eutro Impact (kg P-eq)	Agri-footprint 6.3 Production Coverage (%)
Dairy Milk	5.20E+08	40%
Rice	2.87E+08	72%
Maize	4.17E+07	89%
Pig	4.01E+07	17%
Sugar Beet	1.42E+07	75%
Sugar Cane	9.01E+06	86%
Eggs	6.09E+06	8%
Wheat	3.72E+05	88%
Soybean	2.74E+05	97%
Oil Palm	6.19E+04	87%
Potatoes	4.70E+04	69%
Cassava	2.33E+04	20%

Table 8

Global marine eutrophication impact



Commodity	Global Marine Eutro Impact (kg N-eq)	Agri-footprint 6.3 Production Coverage (%)
Dairy Milk	3.46E+09	40%
Maize	1.10E+09	89%
Rice	8.50E+08	72%
Pig	1.08E+08	17%
Sugar Beet	8.37E+07	75%
Sugar Cane	4.87E+07	86%
Eggs	1.55E+07	8%
Wheat	9.47E+05	88%
Soybean	7.63E+05	97%
Oil Palm	2.17E+05	87%
Cassava	1.43E+05	20%
Potatoes	1.04E+05	69%

The rankings of these food items change in relative importance as the measure of environmental impact changes. This is important to note from a policy and mitigation standpoint, as the food items to target will be different depending on the environmental mitigation needed. For example, if there is a need to prioritize water conservation, the food item to target would be rice, as indicated in Table 6. Across all impact categories, though, milk production ranks among the highest environmentally impactful food items, indicating a further focus on the dairy industry and the need to adopt sustainable production practices.

It is important to note once again that this report focused solely on a farm-to-gate boundary, meaning that all agricultural and operational processes attributed to each food commodity after leaving the farm were excluded from analysis. This leaves out large and environmentally impactful retail and consumption components that even further contribute to the harm food has on our environment. Crippa et al (2021) shares that 3.1 billion tonnes of CO2-eq are attributable to the supply chain (food processing, transport, packaging, and retail) and another 2.1 billion tonnes of CO2-eq are attributable to post-retail phases (cooking and waste).

Other analytical components to elevate and add greater detail to this analysis were considered, but constraints on resources and time prevented us from exploring these. For future work, including per capita analyses into the global impacts of each commodity would add another important perspective to the study, and give more insight into the reasoning behind the dominating environmentally impactful countries. Additionally, a focus on waste, as it is the largest of the post farm-to-gate food processes that contribute to GHG emissions (1.6 billion tonnes CO2-eq) would help to highlight the biggest contributing factors to this process and shed light on ways to reduce food waste (Crippa et al., 2021). There is not a lot of information available by country in terms of where food waste ends up, and the stages of the food supply chain where the most amount of waste is being generated. Noting the share of waste that is being produced from packaging, for example, per commodity, would be quite useful, and is something LCA methodology is geared towards achieving.

Equity

Some of the mitigation strategies we researched have high costs of implementation, highlighting possible equity issues. For example, anaerobic digesters can provide a profitable treatment to methane emissions and transform them into an energy source, but are generally not affordable for most developing countries. Not all farms will be able to access expensive production process technology, which may prove to be inaccessible particularly to smaller operations. For this reason we also tried to provide inexpensive agricultural practices that have been shown to create increased productivity while reducing environmental footprint, such as intercropping as a way to produce higher yields and reducing the use of fertilizers. Crop rotation has also been associated with pest control and soil fertility (Perfecto, 2009). Alternatives to the current highly chemically intensive industrial agriculture include, “traditional or indigenous systems,... extant organic and agroecological farms,...natural systems agriculture,” (Perfecto, 2009). Some studies have shown there is some debate on whether organic farming or highly efficient technologically advanced agricultural systems are more environmentally friendly. Additionally, while mitigation strategies may offer alternative strategies for cultivation, there may be a cultural component to traditional cultivation practices that would require sensitivity and consideration. Improving access to contribution and mitigation analyses for farm operations of all-sizes is an important equity gap in promoting sustainable practices regardless of the food product, production type, or locality.

Results from this research show that LUC is one of the two most significant impact categories for emissions. Recent studies have shown that indigenous land repatriation is a viable way to combat climate change, and address LUC. A UN backed report by conservation experts called the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) finds that, “nature on indigenous peoples’ lands is degrading less quickly than in other areas…the world should not only draw lessons from those and other local communities’ environmental stewardship but that scientists and policy makers need to support and partner with them in order to stem the tide of biodiversity loss,” (Sneed, 2019). However slight, “21% of global land is intact due to the conservation practices of Indigenous Peoples, compared to 14% protected and conserved by countries,” (Sneed, 2019). This is in part attributed to Traditional Ecological Knowledge (TEK), which is a term used in literature since the 1960s to refer to the deep understanding of land stewardship by indigenous people. While indigenous peoples and knowledge are highly diverse, collectively these techniques for land management are now scientifically proven to, “reduce nuisance diseases and pests, generate stems…, stimulate flowering for pollinators, enhance nut quality and abundance, enhance browse and forage for game animals, increase hunting efficiency, and reduce risks of severe fire” (Long et al., 2021).

Conclusions

With the expediency of climate change, lowering emissions from agricultural production is a front-line issue to preserve existing resources and ensure the viability of common practices in food production. Interventions to reduce emissions require different strategies depending on the location, production type, and size of operation. However, improving sustainability and lowering emissions should be prioritized and incentivized across all production systems. Country-level contribution analyses across the production process identify the areas where mitigation efforts could make significant progress. Most of the environmental impact across all categories comes from a short list of high producing countries: less than 10 of the 194 in the FAOSTAT food production database. Rankings in this research project confirm that commodities with the largest production quantities do not necessarily have the highest environmental impacts, i.e. sugar cane. Hotspots show areas where improvements in the food production process would benefit the most for effective climate resiliency strategy.

Information on mitigation strategies should be readily available to stakeholders, practitioners, and policy makers. LCA and LCT play a crucial role, as producers, consumers, and policymakers alike depend on accurate and standardized data regarding the environmental effects of various food products, production methods, or stages within the supply chain to inform their choices. Incentives for improving emissions outcomes have already been seen in federal reforms such as the Common Agricultural Policy (CAP) of the EU and the US national legislation of Agricultural Improvement Act of 2018. UNEP is expanding life cycle initiatives within their operations, and these results and assessments help show a wider audience the usefulness and applicability of LCA thinking and results in the context of agriculture and environmental footprints of food production. As novel environmental strategies for agricultural climate adaptation are researched, LCT will remain an integral tool to measure emission outcomes. This report can benefit from ongoing research and efforts to harmonize LCT with higher level studies and further develop LCA approaches.

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