Title: Global Environmental Benefits of Plant-Based Diets: A Multi-Regional Input Output Analysis

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ABSTRACT

The global food system, especially animal husbandry, is a major driver of negative environmental impacts. This paper investigates the potential of adopting more plant-based diets (vegan, vegetarian, no beef) to reduce greenhouse gas (GHG) emissions, land use and related biodiversity loss, and water stress within global food supply chains. This is achieved by combining Multi-regional Input Output (MRIO) data from EXIOBASE3 with nutritional data from FAOSTAT for 49 regions covering the globe and comparing the results to planetary boundaries. We find that a shift to a vegan diet has the potential to reduce GHG emissions by up to 61%, land use by 60%, and related biodiversity loss by 49%. The vegetarian and no beef scenarios have around half of those reduction potentials, while water stress is nearly constant for all scenarios. Adopting a more plant-based diet would allow to meet the food-specific 1.5° C climate target on a global scale but still exceed the planetary boundary for the biodiversity goal. Moreover, many high-income regions cannot reach an equitable level of emissions aligned with climate targets. Overall, transitioning towards more plant-based diets

provides great levers to alleviate environmental stress and create a more sustainable and equitable food system, but further policy actions are imperative to meet biodiversity targets and ensure equity.

Keywords: Sustainable food systems, sustainable food consumption, planetary boundaries, equitable food system, plant-based diets

1. Introduction

The global food system has become a major driver of environmental damage and the cause of millions of premature deaths due to undernourishment but also unhealthy diets. Modern human behavior and consumption have detrimental effects on our world, and with growing atmospheric greenhouse gas (GHG) concentrations, increasing land use, decreasing biodiversity, and unsustainable water use, anthropogenic impacts have to be reduced in order to prevent irreversible damage[1–3]. Especially meat and dairy are problematic, as they provide just 18% of calories and 37% of protein of the average diet, but use 83% of farmland and cause most GHG emissions within the food sector[4]. For a sustainable diet, a major change in food choices and a transformation of the food system itself are needed[5]. However, a global systemic analysis of the regionalized food system impacts across supply chains is still lacking.

Many environmental impacts can be tackled simultaneously through dietary choices like a more vegan or vegetarian diet[6]. Previous studies have shown that vegan diets or diets with substantially lower meat consumption would reduce GHG emissions[7,6,8–13], biodiversity loss[9,11,12] energy demand[6], land use[6,10–12] and freshwater use[11]. Given the high environmental impact of animal-based food consumption, positive consumer sentiment about reducing their individual impact[14,15] and even potential monetary savings[16], it is important to understand what are the greatest levers in the food supply chain. Furthermore, it is vital to understand how policies can work from the production and consumption side. In fact, for affluent regions, food policies are found to be most effective on the consumption side[17]. Thus, understanding the best options to tackle impact reduction from an individual diet perspective is needed and highly relevant for effective policy design.

It is important to consider that food supply chains are globally interlinked, thus food is often grown in one country, processed in another, and ultimately consumed in yet another, making the tracking and assigning of impacts to specific regions and sectors important but difficult[18]. Spatially-resolved, and product- and service-disaggregated data are needed, which are captured by Multi-Regional Input Output (MRIO) analysis. MRIO databases contain monetary flows between regions' major economic sectors and can thus be used to track the flow of goods and services around the world[19]. Adding environmental extensions allows to assign impacts, such as GHG emissions, biodiversity loss and water stress, to these financial flows disaggregated by region and sector[20]. In MRIO analysis, these impacts can be assessed from a production perspective, referring to a region's domestic impacts, and from a consumption-based perspective, which includes the impacts induced abroad due to imports.

This paper investigates the potential of adopting more plant-based diets (vegan, vegetarian, no beef) to reduce GHG emissions, land use and related biodiversity loss, and water stress within global food supply chains. This is achieved by combining MRIO data from EXIOBASE3 with nutritional data from FAOSTAT for 49 regions covering the globe and comparing the results to planetary boundaries for GHG emissions and biodiversity loss. We begin by analyzing the potential of reducing environmental impacts through sustainable dietary shifts (Section 3.1). We then compare these reductions with planetary boundaries using both an equal per-capita and an equity-based approach (Section 3.2).

2. Materials and Methods

2.1 EE-MRIO

The underlying data for the MRIO analysis in this paper is EXIOBASE3 version 3.8.2[21,22], which provides monetary flows between 163 sectors and 49 regions (44 individual countries and 5 aggregated regions covering the whole globe) with regionalized environmental impacts and socio-economic indicators, thus providing environmentally extended MRIO (EE-MRIO) tables. Food sectors in EXIOBASE can be grouped into 13 categories (wheat; rice; other cereals and grains; oil seeds; fruits, vegetables & nuts; milk; fish; meat; beef; pork; poultry; other meat animals; and other animal products (see details in SI Table A.2).

EXIOBASE3 data includes the industry matrix T, showing which region-sector combination receives input from which sector-region combination, the final demand matrix Y, which contains information on which regions demand how much of which region-sector combination and the satellite matrix (containing the extensions), which gives information on environmental and social impacts of each region-sector combination. The system boundary includes crop cultivation, animal farming, further processing of food products, and related upstream activities, such as electricity and transportation (cradle-to-gate perspective)[20,23]. Accounting for all supply chain impacts and avoiding double-counting are essential in accurately estimating impacts from food production, as they are otherwise systematically underestimated in MRIO analysis[24]. A discussion of the limitations of this method and database is included in Section 4.2 and a more detailed description is provided in SI Section B.1.

2.2 Impact categories

Environmental impacts were calculated according to UNEP-SETAC[25] methods following the procedure by Cabernard et al.[26] which is consistent with methods in the Global Resource Outlook[2].

Climate change is measured in CO_2-equivalent emissions in metric tons and defined as the sum of CO_2 emissions and other greenhouse gases multiplied by appropriate conversion factors according to their heating potential, i.e. 28 for methane and 265 for nitrous oxide. Additionally, CO_2-equivalent emissions for hydrofluorocarbons and perfluorocarbons are included. All emissions data is contained within the extensions in EXIOBASE.

Land use is measured in km^2 and includes cropland, permanent pastures, forest area, and infrastructure land[21]. Land-use-related biodiversity loss is defined as the loss of different taxa (plants, mammals, birds, amphibians, and reptiles) due to anthropogenic land use. It is calculated using the countryside species area relationship (SAR) model and taxa-specific vulnerability scores (VS) and measured in global potentially disappeared fractions (global PDF) due to land use. Land use data is contained within EXIOBASE, while sector-region-specific impact factors are adapted from UNEP SETAC[27] and Chaudhary et al.[28] .

Water stress measures the blue water (surface and groundwater readily available for human use) consumption weighed by the water scarcity of water resources. It is measured in m^3 of H_2O equivalent and calculated using the AWARE method by weighing total blue water consumption given in EXIOBASE with sector-region-specific impact factors based on work by Boulay et al.[29].

2.3 Dietary change model

For the analysis, three diet scenarios are considered:

- **Vegan**: Veganism advocates for a food system devoid of unnecessary harm to animals and is thus often understood more as a philosophy than a diet[30,31]. This diet eliminates all animal-based products including meat, eggs, dairy, fish, and any derived products like gelatin.

- **Vegetarian**: In a vegetarian diet, all meat products are excluded, and this usually includes fish and meat byproducts like gelatin. However, dairy products and eggs are still consumed in this diet.
- **No Beef**: Red meat is shown to have a much larger environmental impact than other types of meat[4,32]. This diet excludes all meat and products derived from cattle but still includes other meats meat like goat, pork and poultry, and animal food products and animal food products.

The developed model converts the monetary flows from the industry matrix T and the final demand matrix Y in the MRIO data into calories (kcal) and protein content (g protein) of animal food products. It then replaces these with vegetarian or vegan products according to pre-determined allocations (see Table 1) keeping calories constant while also tracking protein. Its geographic scope is global, using regional-based caloric, protein and monetary data as well as modeling the adoption of different diets throughout the whole economy. Substitution patterns are chosen to prioritize protein-rich food, especially oil seeds like soya as they already represent a high percentage of plant-based diets across the world[33]. In addition to oil seeds, legumes likes beans and lentils are vital for sustainable diets in the future[5], but they are not explicit sectors in EXIOBASE.

The data for the caloric and protein content was mainly taken from the FAOSTAT Food Balances Sheet (FBS) for 2017[34] as the sectoral and regional data coverage is the highest in that year. This dataset gives average nutritional information on many food categories, including yearly food intake in grams, daily caloric intake in kcal, and daily protein intake in grams. As FBS does not give explicit data on processed dairy products like cheese and yogurt, the dataset is complemented by values calculated from the FAO Individual Food Survey for Brazil 2013-

2014[35] to preserve methodological consistency. This data was chosen as otherwise caloric and protein content of dairy is underestimated, the survey year is close to that of the EXIOBASE3 data, and the data was surveyed nationally with a high sample size ($n = 71971$). Finally, data was aggregated into the 49 regions and 13 food categories corresponding to regions and sectors covered in EXIOBASE (see SI Figure A.1 and Section A.1-A.4).

In a two-stage process, the model first alters the industry matrix T to change how sectors are composed and, secondly, the final demand Y to change how much of each sector is eventually demanded. For this, the matrices are translated into physical flows by dividing by a price vector that defines conversion factors for each sector-region combination. This price vector is based on calculations for 2011 by Cabernard et al[23]. The developed model introduces a "penetration rate" p where $p = 0$ means that none of the calories of animal-based calories will be replaced, and $p = 1$ means that 100% of the calories from animal-based foods will be replaced. For a full description of the model see SI Section B.2.

Scenario:	**Vegan**	**Vegetarian**	**No Beef**
Rice	5%	5%	5%
Wheat	20%	15%	10%
Other cereals & grains	10%	10%	10%
Oil seeds	65%	30%	40%
Other animal products (e.g. eggs)	0%	30%	25%
Dairy	0%	10%	10%

Table 1: Overview table with the caloric re-allocation for each scenario. A value of e.g. 5% means that in the respective scenario, 5% of the animal-based calories will be replaced by this sector. The values are chosen to favor high-protein sectors (oil seeds, other animal products) to keep protein constant as similar as possible (cf. Figure A.1 in the SI).

2.4 Planetary boundaries, equal-per-capita and equity-based approach

The concept of planetary boundaries is defined as limits of impact levels under which humanity can still develop safely on Earth[36]. Here, an equal-per-capita approach is chosen to disaggregate the planetary boundaries for climate and land-related biodiversity loss impacts to the respective regions. The approach is based on a global reduction goal that is then allocated to each region based on its population size in relation to the global population. The equal per-capita approach for GHG emissions was chosen to prioritize intergenerational and intragenerational equity, aligning with the IPCC's emphasis on fair allocation principles[37]. Population data is taken from the United Nations Department of Economic and Social Affairs Population Division[38] (2015 data) and then aggregated to the 49 regions covered by EXIOBASE.

Taking the finding from the UNEP Emissions Gap Report 2021[39], the 1.5°C goal would require a reduction to around 25Gt CO_2-equivalents emissions by 2030 (with even higher reduction in the following decades), meaning that global per-capita emissions would have to be 2.9t CO_2-equivalents, given a population of around 8.6 billion. Assuming that food accounts for roughly one-quarter of global emissions[4,5], this would transform into per-capita emissions of around 0.7t CO_2-equivalents, meaning a 39% reduction compared to 2015 food-related per-capita emission levels. Only one study could be identified[40] that quantifies a sustainable level of biodiversity loss for the planet, based on the work of Steffen et al.[41], which examines historical biodiversity conditions prior to significant human influence. This study was also referenced in the Global Resources Outlook 2024[2] and suggests a sustainable, food-specific target of approximately 1.6×10^{-12} global PDF per capita.

The equal-per-capita approach tacitly assumes that the adoption of an alternative diet would be uniform across all regions. However, reducing the impact of the food system should also include equity considerations that take regional circumstances into account[42,43]. Within the dietary change model, this can be analyzed by replacing the global penetration rate p with a region-specific penetration rate p_r and optimizing the value set $(p_1, \dots, p_{49})$ such that for each region the consumption-based per capita impact ϵ_r is as close as possible to the global per-capita target ϵ_g (see SI Section B.3 for a detailed description). The resulting scenario shows how much each region must reduce its consumption of animal foods to achieve a scenario that is compatible with a sustainable level of with the defined sustainable level of 0.7t CO_2-equivalents. As there is research consensus and political will for the 1.5°C goal, this equity-based approach focuses only on GHG emissions.

These two methods are applied to all 49 regions, without considering potential issues related to historical impacts, trade dependencies, land-use constraints, financial and political capacity, food availability and malnourishment.

2.5 Sensitivity Analysis

To evaluate the robustness of the dietary change model and the scenarios developed here, it is important to understand how sensitive they are to perturbations in the sector allocations. For this, a sensitivity analysis is conducted where the values in Table 1 are decreased or increased by 5% (in absolute terms, i.e. total coverage will be 95% and 105%). All impact categories are recalculated and the percentage change from the initial value is recorded. A detailed description is given in SI Section B.4.

3. Results

3.1 Reduction potential through dietary shift

Results for all scenarios are summarized in Figure 1. Globally, a shift towards a more vegan diet has the greatest potential to mitigate greenhouse gas emissions (-61%), land-use-related biodiversity loss (-49%) and land use (-60%). Water stress is slightly reduced (-2%). The large reduction in GHG emissions is in a large part due to the high GHG (especially methane) emissions associated with beef and dairy, as well as the elimination of the emissions associated with growing feed like maize and soy. The protein content in the vegan scenario is also nearly identical to the status quo (see SI Section C.1-2). This is robust with regard to the choice of foods that animal food products are replaced by, as long as they are plant-based and not too reliant on grains and cereals (see sensitivity analysis in Section 3.4).

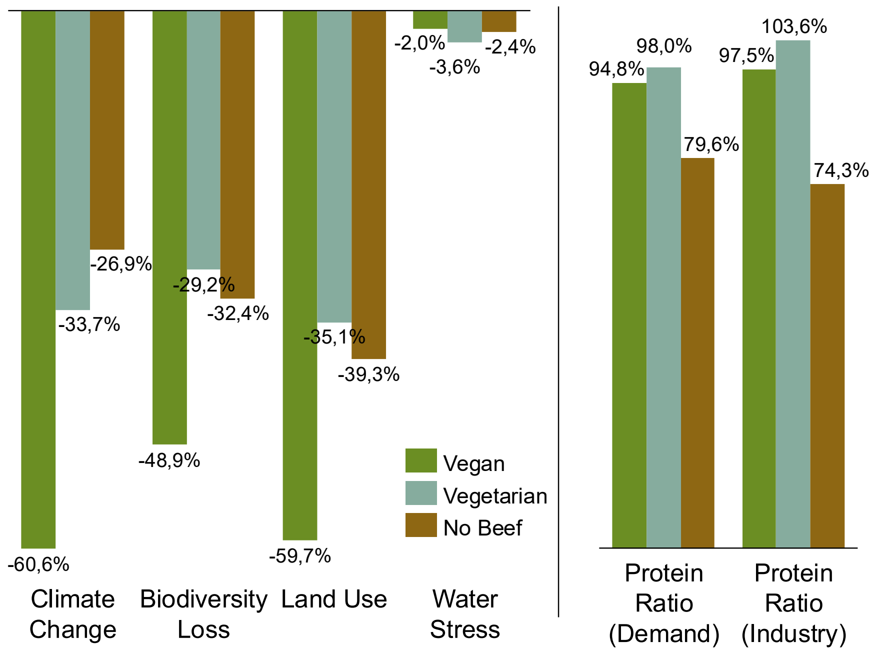

Figure 1: Reduction in impacts for all considered scenarios. A penetration rate of p = 1 is always assumed. Protein replacement ratio is given for the industry matrix T (right), and the demand matrix Y (left). For the protein ratiothe bars on the left give the replacement ration for the demand matrix, the one on the right the ration for the industry matrix, disaggregated by scenario. Ideally, the protein ratio should be higher than 100% to account for the lower digestibility of plant-based protein (see Section 4). The protein ratio is calculated in respect to the replaced foodstuff and not the whole food system.

When considering a less restrictive diet, the reduction potential is lower. While a vegetarian scenario would allow to decrease climate impacts by a third, it is still only around half the reduction potential of a vegan diet. However, the reductions in biodiversity loss (-29%) and land use (-35%) are smaller than the scenario without red meat (-32% and -39%, respectively). Similar to the vegan scenario, water stress barely changes for the vegetarian scenario (-4%)

and the no beef scenario (-2%). While the protein content in the vegan and vegetarian scenarios is comparable to the status quo, the one in the no beef scenario is about one-quarter less.

In Figure 2, the results for GHG emissions and land-based biodiversity loss are disaggregated by food sector. Even if a high number of calories from animal products are replaced by plant-based products, the corresponding impacts increase only marginally, highlighting the efficient conversion of crops, that would otherwise be used for animal feed, into direct human food consumption. Noteworthy is also the large remaining impact of dairy in the vegetarian and no beef scenarios, indicating high impacts from this sector. Additional graphs for land use and water stress are included in SI Section C.3.

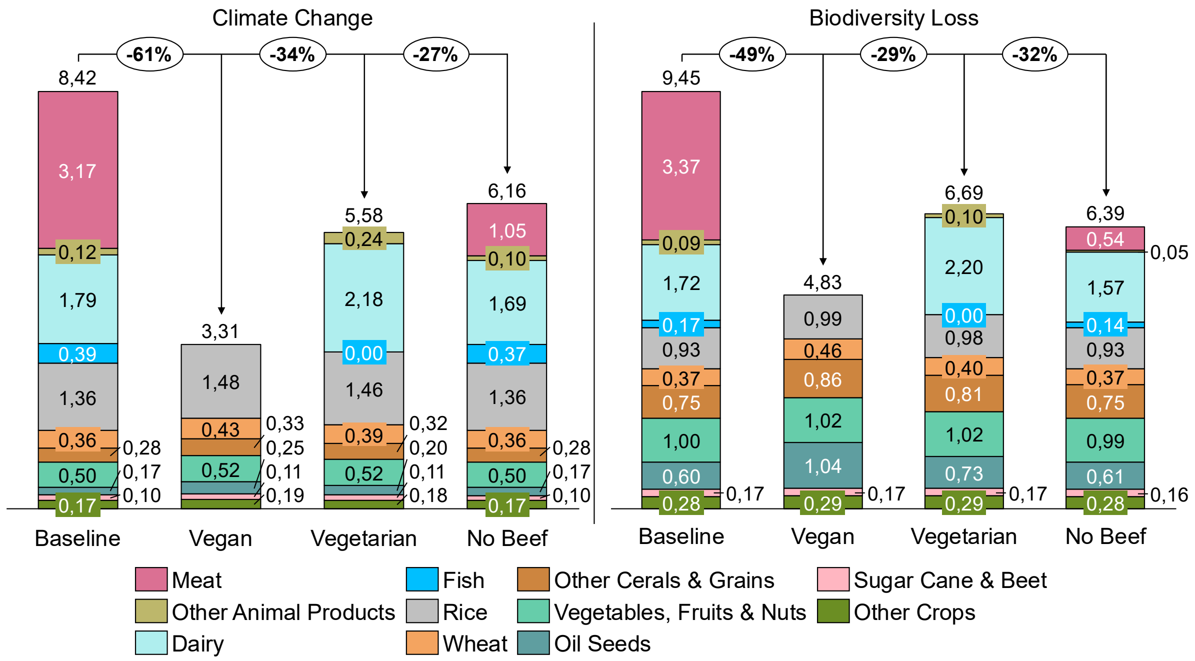

Figure 2: All scenarios with their respective climate change impacts in Gt CO2-equivalent emissions (left) and land-use-related biodiversity loss measured in 10^{-2} global PDF (right), disaggregated by food sector.

3.2 Equal-per-capita approach

As can be seen in Figure 3, the food-specific climate target is exceeded in the baseline scenario both globally (36%) and in any of the aggregated regions (13-452%). In particular, high-income regions, such as Australia, Europe and the USA, but also Brazil surpass the food-specific climate target manifold. This can be attributed to high consumption of animal products (see SI Figure C.5). Conversely, only the vegan diet allows to meet the food-specific climate target globally, for all regions except Australia[44,45]. Globally, in a vegan scenario, a reduction of 61% is possible, surpassing the global goal. In fact, a penetration rate of 57% would also suffice to reach this level as impacts scale linearly with the penetration rate (see SI Figure C.10).

The global food-specific land-use-related biodiversity target is exceeded globally (688%) and also for every region (345-2804%). Highest per-capita impacts are observed in Australia, which is in accordance with previous findings[45]. Even in the vegan scenario, none of the plotted aggregated regions can reach this sustainable level, highlighting the urgent need for enhanced land use management (see Section 4).

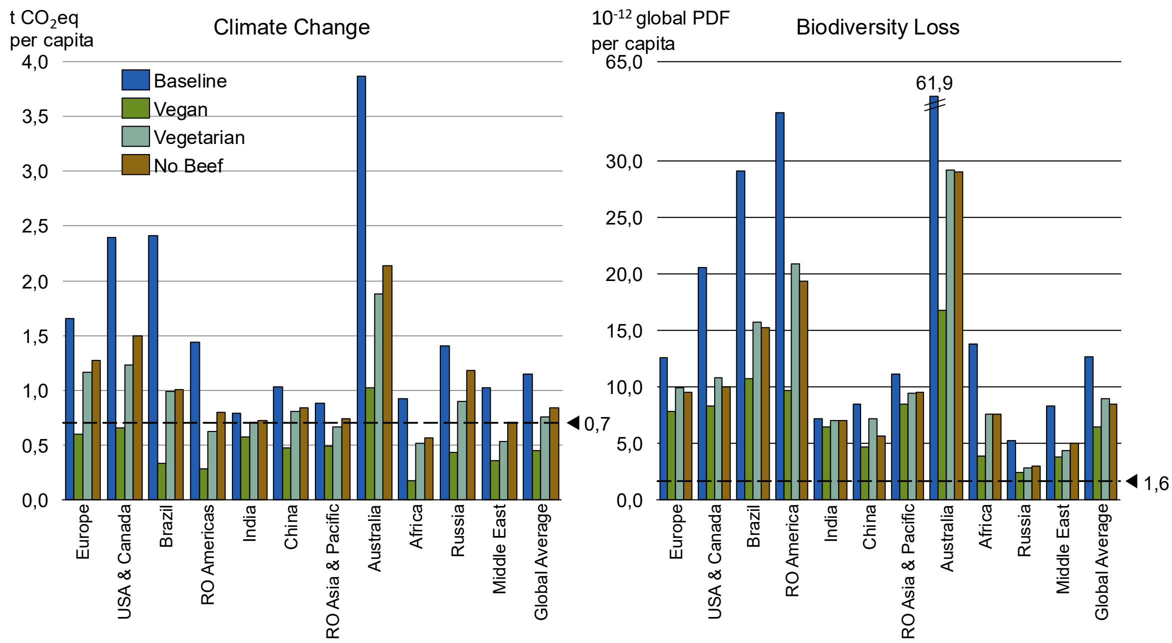

Figure 3: GHG emissions per capita (left) and land-use-based biodiversity loss per capita (right) disaggregated by region. The respective sustainable targets are indicated with dashed lines. While some regions can reach the GHG emissions target in the vegan or vegetarian scenario, none can reach the biodiversity goal in any scenario.

The regional differences persist even in the more plant-based scenario as high impacts not only stem from meat, dairy and fish consumption, but also from high-impact and luxury food items, long transport, storage, food waste and loss, and other regional variations in production and consumption[4,46,47]. For example, in our vegan scenario, Europe's per-capita GHG emissions are 103% and its biodiversity loss 243% higher than those of Africa, respectively.

3.3 Equity-based approach

As can be seen from Figure 3, not all countries – foremost industrialized high-income countries – will be able to reach parity with the equitable level of per capita emissions. Figure 4 further shows that while some regions reach this level with a low penetration rate, others are still far above it, even under a penetration rate of 100%, i.e. a fully vegan scenario. For example, India and Africa (excl. South Africa) can reach the target with penetration rates of 40% and 28%, respectively, meaning that only those percentages of animal products have to be substituted. On the other hand, Norway and Switzerland exceed the target even in the vegan scenario by 70% and 39%, respectively. This points to further need for addressing the high impact from the food system beyond dietary choices like over-consumption and food waste (see Section 4).

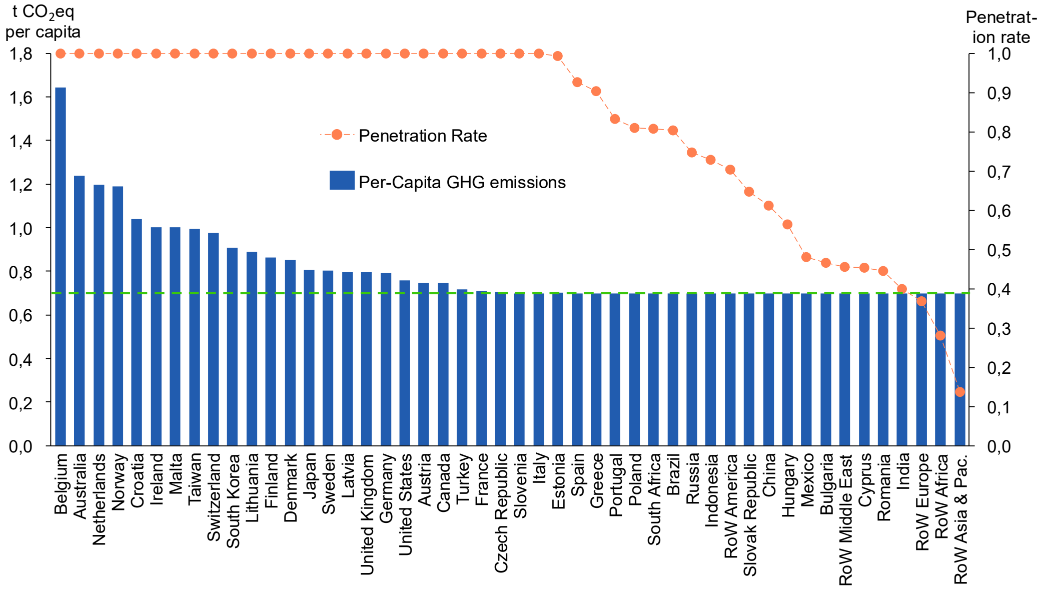

Figure 4: Regional per-capita CO2-equivalent emissions from a consumption perspective in an equity-based scenario. The green dashed line gives the equitable per-capita GHG emissions level. While most regions can reach this level with varying penetration rates (orange dots), many others cannot -- even in a fully vegan scenario. All countries/regions with a population of over 1 million people were considered.

3.4 Sensitivity analysis

Overall, the vegan scenario shows little sensitivity to all food sector allocations (see Table 1) compared to the vegetarian one (SI Figure C.13-14) when varying allocations by $\pm 5\%$ in absolute terms. For the vegan scenario, grains and cereals show the highest effect on water stress, with wheat having the biggest potential impact ($\pm 0.9\%$). Rice displays the greatest possible effect on climate change ($\pm 0.7\%$). This can most likely be explained by the high emissions of methane (CH_4) that occur during rice cultivation due to the flooding of rice paddies[49]. Wheat and oil seeds show relatively large effects on land use ($\pm 0.7 - 0.8\%$).

For the vegetarian scenario, the effect of food sector allocations is mostly dominated by animal food products. Changing the allocation of dairy products has a comparatively large effect on land use ($\pm 6.9\%$). Its influence on land-use-related biodiversity loss ($\pm 5.0\%$) and climate change ($\pm 4.5\%$) is also large compared to other food sectors. A detailed description of the sensitivity analysis and visualized results are included in SI Section C.4.

4. Discussion

4.1 Comparison with literature

The method in this paper extends the work by Wood et al.[50] and Vita et al.[51], who also employ MRIO analysis in the context of the food supply chain to look at diet scenarios. However, it expands on these works by widening the regional scope to the global supply chain, considering region-specific nutritional data (FAOSTAT), mapping the full supply chain impacts of the global food system[26,52] including a regionalized impact assessment for water stress and land-related biodiversity loss[25,28,29], and comparing the results to planetary boundaries.

Many studies have quantified the reduction potential in the food system, but differences exist in the methodologies and regional scopes which can affect the results. In two systematic reviews[53,54], the greenhouse gas emissions reduction potential of a vegan diet is found to range between 23-72% with medians of 45% and 50% (compared to 61% in our study), while for a vegetarian diet, this ranges from 25-58% with both medians of 31% (compared to 34% in our study). For land use, reduction potentials range from 40-86% (medians 55% and 59%) for a vegan diet and 28-84% (medians 51% and 50%) for a vegetarian diet (compared to 60% in a vegan and 35% in a vegetarian scenario in our study). Therefore, the results of our study are in the range of previous studies. For land-use-related biodiversity loss and water stress, no relevant studies that quantify the global reduction potential could be found, so this paper contributes to filling this research gap.

4.2 Limitations and Outlook

One limitation of this study is the limited sectoral and regional resolution. Important crops like legumes (lentils, chickpeas, peas, soybeans) and nuts, which are particularly important for a vegan diet[33], do not have their own explicit sectors in EXIOBASE. On the other hand, limited regional resolution of only 49 regions – 44 explicit countries and 5 Rest-of World (RoW) regions – does not allow to properly assign and trace impacts to those countries aggregated as RoW. Especially the under-representation of South American, Asian, and African countries, as well as island nations, presents a problem when discussing global inequity and inequality in the food system, as many of the environmental effects are felt in those regions.

Another inherent limitation is the design of the dietary change model. When removing specific food groups, the supply chains pertaining to the substitution sectors are scaled to make up for the calories lost. This tacitly assumes that existing supply chain structures are kept constant, and others will not arise. It also does not consider if those scaled supply chains can be realized or would exceed regional capacity and available resources. The somewhat paradoxical scenario of having a fully vegetarian scenario with high consumption of dairy and eggs but no use of the animal meat resulting from this cannot be properly addressed within this model. Moreover, whether in every context an animal product can be substituted (e.g. in medicine, additives etc.) is not considered. Switching to a plant-based diet can either increase or decrease household income depending on the foods chosen. Cheaper staples like beans may free up income, while pricier alternatives like vegan meats can reduce savings. At the same time, plant-based production requires less labor and processing than animal agriculture, reducing value added across the food system. The potential rebound effects[51,55] from freed-up income and their impact on other spending were not considered in this analysis.

While the analyses consider calories and implicitly protein, protein quality and other micro- and macronutrients are not integrated into the model. Hunger and malnourishment affect around 10% of the population[56], thus considering vitamins, fats, minerals, and amino acid profiles, i.e. lower digestibility of plant protein sources[57–59], is important. This could be improved by integrating methods used in nutritional life cycle analysis (n-LCA), where the nutritional quality of foodstuff is taken into account[60,61].

For the equity and equal-per-capita based approaches the targets assume that food will always contribute 25% to GHG emissions and 2/3 to biodiversity loss. This is of course a simplification and through decarbonization and other technological improvements the contributions could even be higher in the future. With these approaches we focus on per-capita impacts and allocating planetary boundaries based on population size. This disregards potential issues related to historical responsibilities, trade dependencies, land-use constraints, financial and political capacity, food availability and malnourishment. Thus, results do not necessarily reflect a fair or practical policy strategy and require more regionalized considerations.

4.3 Policy implications

This study shows that a vegan scenario has the greatest potential to mitigate detrimental effects of diets on the environment. It primarily aims to quantify the environmental potential of dietary shifts rather than predict or analyze their immediate feasibility in specific regions. Rather than propose a complete dietary shift, we want to understand the maximum range of environmental impact reductions. As the model is linear, this can then be used to induce more modest policy-induced changes, e.g. replacing 20% of animal-based products reduces GHG emissions by around 12%.

For a sustainable food system measures are needed including actively promoting plant-based diets; discouraging consumption of high-impact foods like meat and dairy; aligning subsidies, incentives and taxes with sustainability goals and external costs[62–65]; improvements in technologies and management; and minimizing food waste and loss[2,11]. The comparison with planetary boundaries for GHG emissions and biodiversity loss, however, shows that even a completely vegan scenario does not suffice to reach a sustainable level on a regional level. Other measures, like reducing food loss and choosing sustainable foodstuffs, are also needed. Finally, when employing an equity-based approach, the need to address the disparity between high-impact and low-impact countries becomes apparent. In high-income countries, food losses and food waste are huge problems[46,47] and over-consumption further adds to climate change impact. For example, daily caloric consumption per person in Europe is around 30% higher than in Africa[48].

A path towards a more sustainable and plant-based diet faces several hurdles: tradition and social norms[66,67]; sunk investments into animal husbandry infrastructure; existing supply chains; non-arable land; food intolerances and allergies or other food-related conditions; and generally a low social acceptance rate of a vegan diet[68–70]. Furthermore, political factors like influential meat and dairy lobbies, subsidies for animal food products and conservative policies currently put plant-based alternatives at a market disadvantage[71,72].

By taking the entire food supply chain into account, this study also highlights the importance of going beyond production-based policies that involve regulating national production and national animal husbandry. While regulations on animal treatment for national farms, waste treatment, farm run-offs into soil and waterways, soil preservation, emissions standards etc. are important to create a legal framework for national production standards, these policies usually only address production-based impacts, while not addressing the imported emissions, e.g. when buying coffee imported from Colombia or feeding soy grown in Brazil to Swiss pigs. This would avoid unwanted leakage of environmental impacts into foreign countries with more lax environmental regulations and weaker governance[73–75]. Especially areas of high ecosystem value like tropical regions have seen an increase in land-use-related biodiversity loss in recent decades due to land conversion for human use (soy, maize, cattle etc.) which needs urgent addressing[2].

By broadening the legislative scope to consumption-based policies, the environmental lever is much higher. These policies can take on myriad forms: aligning subsidies with environmental goals, pollution taxes, stricter import laws, investments by consumers into production regions, advertisement regulations against e.g. greenwashing, information campaigns, nudging and so on. For international politics, targeting the sustainability of the food sector could address other social and environmental issues simultaneously and promote global cooperation, as food is intrinsically connected with poverty, inequality, health and well-being, clean water access, energy, education, ecosystem health on land as well as underwater, and sustainable economic growth[76–78].

Data: The MRIO data from EXIOBASE is publicly available here. The aggregated nutritional data, population data and code are available here.

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Global Environmental Benefits of Plant-Based Diets: A Multi-Regional Input Output Analysis (Supplementary Information)

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4th January 2026

A Data

A.1 Regions

Region (EXIOBASE)	Countries/Territories
Europe	EU-27, Iceland, Liechtenstein, Norway, United Kingdom, Switzerland, Türkiye
USA & Canada	United States, Canada
Brazil	Brazil
RO Americas	Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Greenland, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela, Mexico
India	India
China	China (mainland)
RO Asia & Pacific	Afghanistan, Armenia, Azerbaijan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, Democratic People's Republic of Korea (North Korea), Fiji, French Polynesia, Georgia, Hong Kong, Japan, Kazakhstan, Kiribati, Kyrgyz Republic, Lao People's Democratic Republic, Macao, Malaysia, Maldives, Marshall Islands, Micronesia, Mongolia, Myanmar, Nepal, New Caledonia, New Zealand, Pakistan, Palau, Papua New Guinea, Philippines, Republic of Korea (South Korea), Samoa, Singapore, Solomon Islands, Sri Lanka, Taiwan, Tajikistan, Thailand, Timor-Leste, Tonga, Turkmenistan, Tuvalu, Uzbekistan, Vanuatu, Vietnam
Australia	Australia
Africa	Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon,Cabo Verde (Cape Verde), Central African Republic, Chad, Comoros, Democratic Republic of Congo, Republic of Congo, Côte d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, South Africa, Sudan, Swaziland (Eswatini), Tanzania, Togo, Tunisia, Uganda, Zambia, Zimbabwe
Russia	Russia
Middle East	Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen

Table A.1: Aggregated regions

A.2 FAOSTAT Food Groups

Sectors (cf. Figure A.1)	Sectors from FAOSTAT FBS [1]
Wheat	Wheat
Rice	Rice
Other Cereals & Grains	Barley and products, Maize and products, Rye and products, Oats, Millet and products, Sorghum and products, Cereals (Other)
Oil Crops	Soyabeans, Rape and Mustardseed, Sunflower seed, Cottonseed, Palm kernels, Oilcrops (Other)
Fruits, Vegetables & Nuts	Potatoes and products, Sweet potatoes, Beans, Peas, Pulses (Other) and products, Nuts and products, Groundnuts, Coconuts (Incl Copra), Sesame seed, Olives (including preserved), Tomatoes and products, Onions, Vegetables (other), Oranges, Mandarins, Lemons, Limes and products, Grapefruit and products, Citrus (Other), Bananas, Plantains, Apples and products, Pineapples and products, Dates, Grapes and products (excluding wine), Fruits (other), Coffee and products, Cocoa Beans and products, Cassava and products, Roots (Other), Yams
Beef	Bovine Meat
Fish	Fish, Seafood
Meat	Meat
Milk	Milk (excluding Butter)
Other Animal Products	Eggs
Other Meat Animals	Mutton & Goat Meat, Meat (Other), Offals (Edible)
Pork	Pigmeat
Poultry	Poultry Meat

Table A.2: Aggregated food sectors

A.3 Sector Allocations

The actual matching of the allocations to sectors in EXIOBASE is based on global physical flows, i.e. if a food group from Table 1 in the paper corresponds to two sectors in EXIOBASE and their allocation is 10% then their eventual sector-level allocation will match the ratio of their physical flows. If sector A1 has a physical flow of 4 kt and sector A2 a physical flow of 6 kt, then sector A1 will be allocated $4/10 \hat{=} 40\%$ and thus in total 4% and sector A2 $6/10 \hat{=} 60\%$ and thus in total 6%. As the sector chosen in this thesis are limited, this is only relevant for two sectors (rice and dairy) and summarized in Table 1 in the paper.

In the specific case of dairy, the sector "Raw Milk" is mapped to "Milk (excluding Butter") of the FBS, while "Processing of dairy products" is mapped to "Dairy" of the FAO Individual Food Survey for Brazil 2013-2014.

Strictly speaking, this is not necessary, as sector allocation could be formulated on a more granular level. However, doing this removes two extra variables that would further complicate the model without giving a lot of benefit in model or result quality. Other sector that could make use of this allocation are fish, beef,

Food group	Sectors (EXIOBASE)	Share
Dairy	'Raw milk' (14)	53.1%
	'Processing of dairy products' (40)	46.9%
Rice	'Cultivation of paddy rice' (1)	21.9%
	'Processed rice'(41)	78.1%

Table A.3: Allocation for sectors in the model for assigning the percentages from the allocation table.

poultry, and pork, but as they are replaced this is not necessary.

A.4 Nutritional data

The data for the caloric and protein content was mainly taken from the FAOSTAT Food Balances Sheet (FBS) for 2017 [1] as the sectoral and regional data coverage is the highest in that year. This dataset gives average nutritional information on many food categories, including yearly food intake in grams, daily caloric intake in kcal, and daily protein intake in grams. As FBS does not give explicit data on processed dairy products like cheese and yogurt, the dataset is complemented by values calculated from the FAO Individual Food Survey for Brazil in 2013-2014 [2] to preserve methodological consistency.

Then, data is aggregated into the 49 regions covered in EXIOBASE and 13 food categories corresponding to sectors covered in EXIOBASE. Figure A.1 shows box plots of caloric, protein, and protein per calorie data for all 13 food sectors that could be matched. Some outliers due to low data precision and low daily intake were replaced by global averages. This is particularly prevalent for oil seeds, where many European countries record low daily consumption, and combined with the low numerical precision in the FBS database, this leads to many outliers.

B Method Description

B.1 Environmentally-extended Multi-regional Input Output analysis

Environmentally-extended Multi-regional Input Output (EE-MRIO) analysis [3, 4] is a tool to quantify global economic flows of goods and services and their associated environmental, economic and social impacts. The underlying data contains financial flows between countries' economic sectors and connects them to various impacts like energy use, greenhouse gas emissions and water use through so-called extensions.

The "heart" of this method are two matrices: the **industry matrix**, showing which region-sector combination receives input from which sector-region combination, and the **final demand matrix**, which contains information on which regions demands how much of which region-sector combination. Together with the satellite matrix (containing the extensions), which gives information on environmental and social impacts of these transactions, EE-MRIO analysis can be used to investigate global patterns in impact

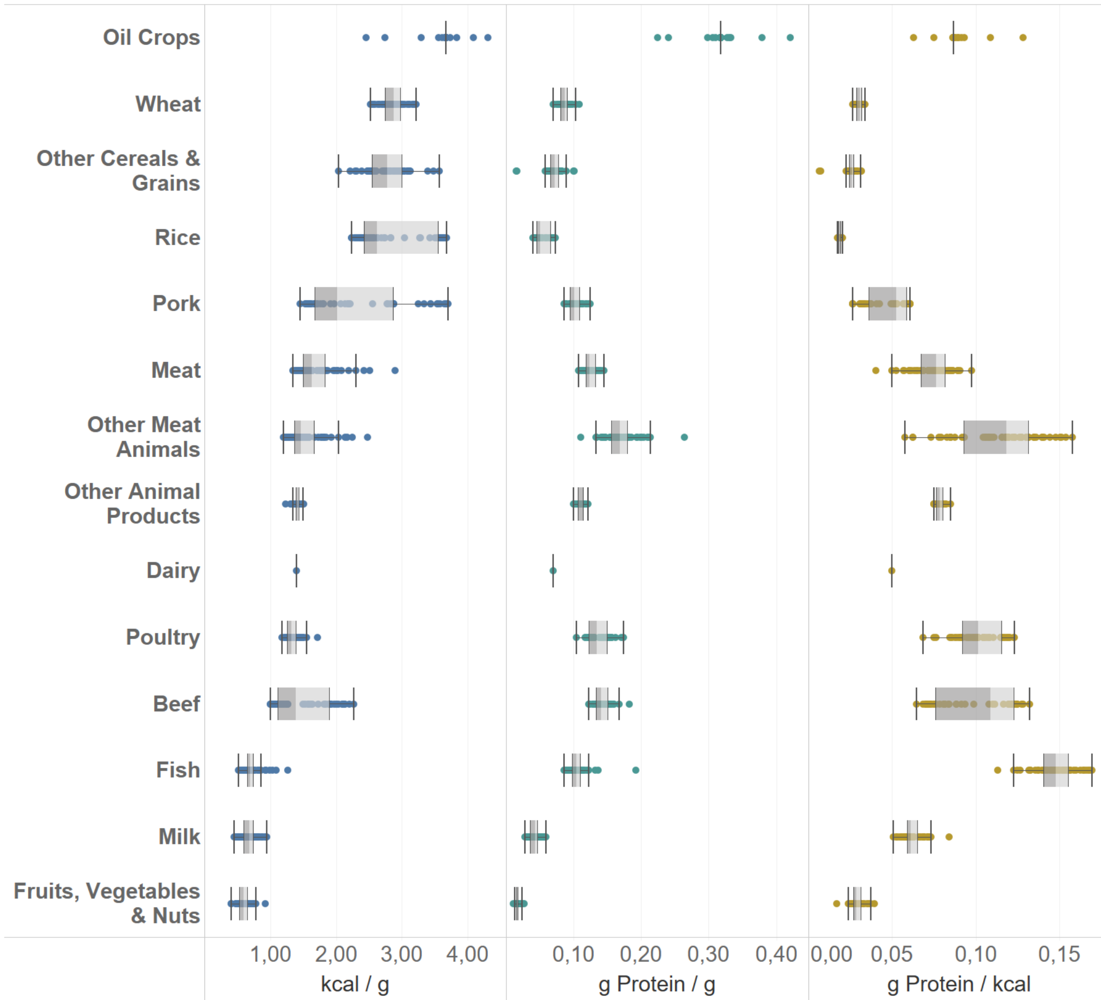

Figure A.1: Aggregated nutritional data for different food sectors covered in EXIOBASE. The box plots visualize the nutritional data for the 49 regions covered. Values are calculated based on food supply, caloric intake and protein intake data taken from FAOSTAT Food Balances 2017 and supplemented by FAOSTAT Individual food consumption data for Brazil. The nutritional values of food groups differ for the regions, sometimes quite significantly, making it important to incorporate this into the diet scenarios.

distribution.

The mathematical form of basic MRIO analysis is given in Equations (1)-(3), which describe the general Leontief model [6]. By selecting specific sectors and regions as "targets", the impacts of specific broad sectors like the Swiss food sector can be isolated and analyzed. The index "T" signifies all target sector-region combinations, "O" all the remaining combinations, and "All" means all combinations (49 regions × 163 sectors = 7987 total sector-region combinations[1]).

$E^i_{\mathrm{T}} \in \mathbb{R}^{7987}$ is the impact vector containing the impact of all sector-region combinations regarding an

[1]The numbers and dimensions from here on are based on the resolution of the underlying database used called EXIOBASE, thus they would be different when substituting for another MRIO database.

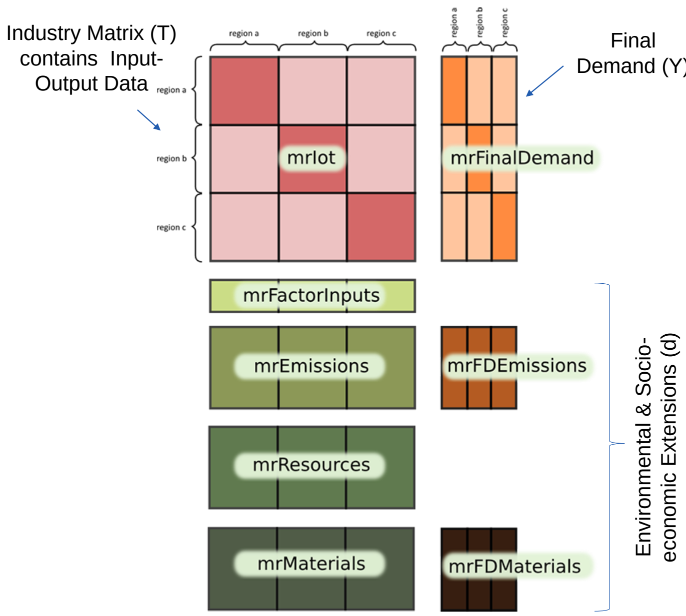

Figure B.2: Overview of the data structure behind MRIO analysis, adapted from [5].

impact category i; $d_i \in \mathbb{R}^{7987}$ is the vector with impact coefficients related to a specific impact category i; $A \in \mathbb{R}^{7987\times7987}$ is the direct input coefficient matrix which defines the input of each sector-region combination $(49 \cdot 163)$ per monetary output of each sector–region combination $(49 \cdot 163)$; $Y \in \mathbb{R}^{49\times7987}$ is the final demand matrix, namely the direct demand from each region (49) of the output of every sector-region combination $(49 \cdot 163)$[2]; and $\mathbb{1}$ is identity matrix. $L \in \mathbb{R}^{7987\times7987}$ is the so-called Leontief inverse, which gives information on the cumulated input per output from one sector-region combination into the other. $Z \in \mathbb{R}^{49\times7987}$ is the total monetary output and $T \in \mathbb{R}^{7987\times7987}$ is the industry matrix which represents the gross output of each sector region combination into another sector-region combination.

$$E_{\mathrm{T}}^{i} := \mathrm{diag}(d_i) \cdot L_{\text{All-T}} \cdot Y_{\text{T-All}} \tag{1}$$

$$L := (\mathbb{1} - A)^{-1} \tag{2}$$

$$T := A \times [z, \dots, z]^{\intercal}, \quad z := \sum_{i=1}^{49} Z_{ij} \tag{3}$$

The operator $\cdot$ is to be understood as a matrix multiplication, and $\times$ as the scalar product. $L_{\text{All}-\text{T}}$ denotes the sub-matrix of Leontief inverse L containing the cumulated input of all sector-regions into target-sector-regions, $Y_{\text{T}-\text{All}}$ is the part of the final demand matrix containing entries for the demand of all target sector-region combinations.

[2]To be exact, for each region there are 7 demand categories. However, in this thesis they are not considered separately but combined into one final demand.

However, the general Leontief model does not allow assessing full supply chain impacts of intermediate sectors like the food industry. This is improved by considering a total supply chain impact model [7, 8]:

$$E^i_{\mathrm{T}} = \mathrm{diag}(d_i) \cdot L_{\mathrm{All-T}} \cdot \mathrm{diag}\left(Y_{\mathrm{T-All}} + A_{\mathrm{T-O}} \cdot L^{\mathsf{T}}_{\mathrm{O-O}} \cdot Y_{\mathrm{O-All}}\right). \tag{4}$$

$A_{\mathrm{T-O}}$ means the sub-matrix of A going from all target sector-region combinations into the rest of the economy, $L^{\mathsf{T}}_{\mathrm{O-O}}$ means the part L describing flows within the rest of the economy, and $Y_{\mathrm{O-All}}$ is the sub-matrix of Y describing the flows from the rest of the economy into all sector-region combinations. The last term can be understood as a correction term to avoid double-counting impacts. This method to avoid double-counting impacts was first proposed by Dente et al. [9] and further developed by Cabernard [10] and applied in the field of plastics [8] and other material resources [11].

By modifying Equation (4) the different perspectives and linkages between those perspectives can be calculated [10]. These perspectives are:

- A **production** perspective, where impacts are allocated to the sectors or regions that produce that impact, e.g. the cultivation of soy in Brazil is allocated fully to Brazil even though much of it is exported for animal feed in other countries.
- A **target** perspective where impacts are attributed to the target-sectors-regions that are supplied [12]. For example, the impacts caused by growing feed for dairy cattle and electricity used for processing dairy, both used for dairy products, are attributed to dairy.
- A **consumption** (or final demand) perspective, where impacts are allocated to the sector or region that finally request a product or service, e.g. if Austria imports meat that was produced in Germany with feed imported from Brazil, the impacts will be allocated to Austria. This thesis uses mostly this perspective when talking about regional impacts, as it represents the most fair allocation of impacts in light of policy implications [13].).

Accounting for all scope 3 impacts[3] and avoiding double-counting are essential in accurately estimating consumption and production-based impacts, as they are otherwise systematically underestimated [10]. In the global food sector specifically, greenhouse gas emissions, water stress and land-use-related biodiversity loss are underestimated by over 20% from a consumption perspective. Also, from a production perspective, GHG emissions are underestimated by around 20%, and land-use-related biodiversity loss by around 10% [10].

[3] Scope 3 impacts include all cumulated upstream and production impacts [14],

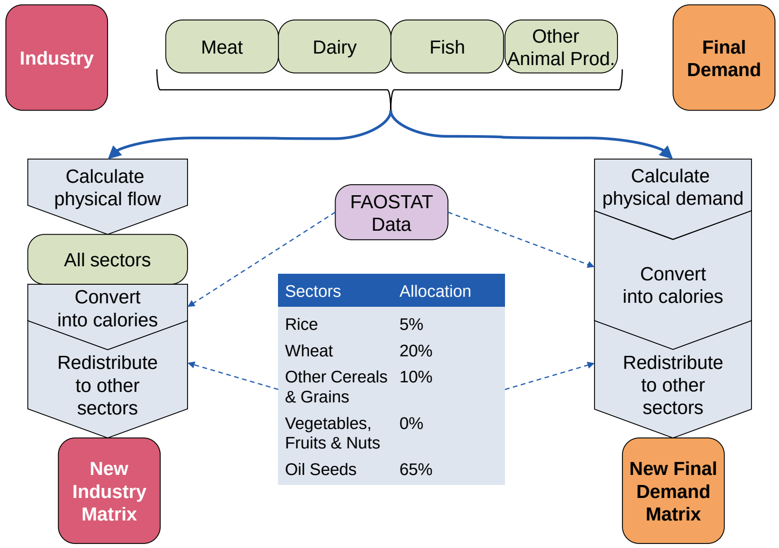

Figure B.3: Graphical representation of the model developed for this thesis. This diagram represents the steps in the vegan scenario where all animal food products are replaced. Depending on the penetration rate p either 100% or only a part of animal food is replaced.

B.2 Linking EE-MRIO with food consumption scenarios

The model developed within this thesis calculates the calories (measured in kcal) of animal food products and replaces these calories with vegetarian or vegan products according to pre-determined allocations, summarized in Table 1 in the paper. The concept of this model is based on previous work by Wood et al. [15] and Vita et al. [16]. However, it expands on these approaches by widening the geographic scope from Europe to the whole globe, using regional-based caloric, protein and monetary data as well as modelling the adoption of different diets throughout the whole economy.

Figure B.3 offers a crude graphical representation of the model steps for the case of a vegan scenario. The developed model also introduces a "penetration rate" $p \in [0,1]$ where $p = 0$ means that none of the calories of animal-based calories will be replaced, and $p = 1$ means that 100% of the calories from animal-based foods will be replaced. The model otherwise leaves inherent input-output structures in place and merely scales them, i.e. if one country would increase rice consumption by 5%, all existing import streams of rice to that country would also increase by 5% each.

In a two-stage process, the model first alters the industry matrix T to change how sectors are composed and, secondly, the final demand Y to change how much of each sector is eventually demanded. For this, the matrices are translated into physical flows T_{phys} and Y_{phys} through dividing by a price vector that defines conversion factors for each sector-region combination. This price vector is based on calculations for 2011 by Cabernard [8].

Let $m = \{m_j\}$ be the set of animal food product sectors that are to be (partially) replaced (e.g. beef, fish etc.) by a set of other food product sectors $l = \{l_i\}$ (e.g. wheat, oil seeds, dairy, etc.). The degree of replacement is given by the penetration rate p.

First, the industry matrix T is altered. For this, the monetary values in T are converted to physical values

$$T_{\text{phys}} = T \oslash v := \left(T_{ij}/v_i\right) \tag{5}$$

where $v \in \mathbb{R}^{7987}$ is a price vector giving conversion values for all sector-regions combinations. For this thesis, the only relevant unit for food products is kilotons (kt).

Let (r, n) with $r \in \{1, \ldots, 49\}$ and $n \in \{1, \ldots, 163\}$ be a sector-region couple. The physical input of the sectors in m into this combination

$$\sum_{1 \le j \le |m|} T_{\text{phys}}(m_j; r, n) \tag{6}$$

is converted into calories by using data from FAOSTAT (see Figure A.1) and subsequently replaced by calories of sectors in l according to the allocation table (see Table 1 in the paper). This is done by calculating the physical flow of the sectors in l into this specific sector-region combination (r, n),

$$T_{\text{phys}}(l_i; r, n) \tag{7}$$

converting it into calories and scaling the economic flow so that the new physical flow corresponds to the old one plus the additional one corresponding to the calories dictated by the allocation table. The region- and sector-specific caloric content of m_j and l_i in region r shall be denoted by $\text{kcal}(r, m_j)$ and $\text{kcal}(r, l_i)$, respectively, and the penetration rate is p.

$$\underbrace{p \times \sum_{1 \le j \le |m|} T_{\text{phys}}(m_j; r, n) \times \text{kcal}(r, m_j)}_{:= K(m; r, n)} \stackrel{!}{=} \sum_{1 \le i \le |l|} \alpha_i \times T_{\text{phys}}(l_i; r, n) \times \text{kcal}(r, l_i) \tag{8}$$

$$\alpha_i := \frac{\gamma_i \times K(m; r, n)}{T_{\text{phys}}(l_i; r, n) \times \text{kcal}(r, l_i)} \tag{9}$$

$$T^{\text{new}}(l_i; r, n) := (1 + \alpha_i) \times T(l_i; r, n) \quad \forall l_i \in l \tag{10}$$

$$T^{\text{new}}(m_j; r, n) := (1 - p) \times T(m_j; r, n) \quad \forall m_j \in m \tag{11}$$

where γ_i are the allocation values from the allocation table such that

$$\sum_{1 \le i \le |l|} \gamma_i = 1. \tag{12}$$

Finally, the input into the animal food product sectors m_j is reduced

$$T^{\text{new}}(\circ; r, m_j) := (1-p) \times T(\circ; r, m_j) \quad \forall m_j \in m \tag{13}$$

where $\circ$ represents all 163 sectors.

For the final demand matrix, first, the monetary demand Y is also converted into physical units

$$Y_{\text{phys}} = Y \oslash v := \left(Y_{ij} / v_i\right). \tag{14}$$

The model then iterates through all 49 regions, calculates how much physical flow is demanded by sectors in m

$$\sum_{1 \le j \le |m|} Y_{\text{phys}}(m_j; r) \tag{15}$$

and replaces them with calories from sectors in l. This is also done by first calculating the physical demand of a sector in l

$$Y_{\text{phys}}(l_i; r), \tag{16}$$

scaling the demand of the economic flow so that the physical one corresponds to the old one plus the additional one corresponding to the calories dictated by Table 1 in the paper:

$$\underbrace{p \times \sum_{1 \le j \le |m|} Y_{\text{phys}}(m_j; r) \times \text{kcal}(r, m_j)}_{:=O(m;r)} \stackrel{!}{=} \sum_{1 \le i \le |l|} \beta_i \times Y_{\text{phys}}(l_i; r) \times \text{kcal}(r, l_i) \tag{17}$$

$$\beta_i := \frac{\gamma_i \times O(m; r)}{Y_{\text{phys}}(l_i; r) \times \text{kcal}(r, l_i)} \tag{18}$$

$$Y^{\text{new}}(l_i; r) := (1 + \beta_i) \times Y(l_i; r) \quad \forall l_i \in l \tag{19}$$

$$Y^{\text{new}}(m_j; r) := (1-p) \times Y(m_j; r) \quad \forall m_j \in m \tag{20}$$

where again γ_i are the allocation values from the allocation table.

These calculations are repeated for each (r, n)-couple for the industry matrix T and each r for the final demand matrix Y.

During these replacement processes, the amount of protein being removed (e.g. protein in beef) and the one being added (e.g. protein in wheat) for both matrices Y and T are tracked. The ratio of these two numbers, respectively, is also reported to better judge the nutritional value of the scenarios.

B.3 Equal-per-capita and equity-based approach

The model described in Section B.2 reduces the demand for animal foods equally in each region, which can be considered somewhat unfair, as large regional differences in impacts are present [17], and many regions already have low consumption of animal food and low impacts. Thus, in this section, a method to reduce animal food consumption based on a regional equal-per-capita goal is described. The approach is based on a global reduction goal that is then allocated to each region based on its population size in relation to the global population. This is done solely for climate change impacts in this thesis, but could be extended to other impact categories, where planetary boundaries or other science-based targets exist [18].

A fair and sustainable scenario would be one in which regional consumption-based per-capita greenhouse gas emissions are compatible with a specific goal, not exceeding global carbon sinks and uniform across the globe. Research on this level of sustainable emissions has not reached a consensus, as sources differ on the specific goal, timeline (e.g. keeping within the 1.5 °C limit by 2100 [19]) and how quickly carbon-negative technology can be ramped up. A truly long-term sustainable level would be one where net carbon emissions are zero, i.e. a fully decarbonized world [20].

Within the model described in Sector B.2, this can be investigated by replacing the global penetration rate p by a region specific penetration rate p_r and optimizing the value set $(p_1, \dots, p_{49})$ such that for each region the consumption-based per capita impact ϵ_r is as close as possible to the global per-capita impact ϵ_g in the reduction scenario.

The scenario and its climate change impact are calculated within the EE-MRIO analyis, and the set $(p_1, \dots, p_{49})$ is iteratively changed according to the optimization problem

$$\min_{p_r} \quad \sum_{r=0}^{49} \left| \epsilon_r(p_r) - \epsilon_g \right| \quad \text{s.t.} \quad 0 \le p_r \le 1. \tag{21}$$

This is done by an algorithm that evaluates the regional per-capita impact of the scenario and then changes all p_r according to

$$p_r^{\text{new}} = \begin{cases} \min\left(p_r^{\text{old}} + \delta, 1\right), & \text{if } \epsilon_r(p_r) - \epsilon_g \ge 0 \\ \max\left(p_r^{\text{old}} - \delta, 0\right), & \text{otherwise} \end{cases} \qquad \forall r \in \{1, \dots, 49\}. \tag{22}$$

The new optimization step is then used as a basis for changing the underlying monetary data in EXIOBASE according to the model proposed in Sector B.2, and new values for $\epsilon_r(p_r)$ can be computed. The value of δ determines how fast and precise the optimization is performed. For this thesis, a value of $\delta = 5 \times 10^{-4}$ was chosen. As p_r cannot be lower than 0 or higher than 1, the min() and max() functions are necessary. The optimization is stopped once a plateau for all $\epsilon_r(p_r)$ is reached, even if the overall reduction goal is not achieved.

The resulting scenario shows how much each region has to reduce its consumption of animal foods to achieve a scenario that is compliant with the 1.5 °C goal. For example, a value of $p_r = 0.5$ would mean that this region would need to reduce animal-based food consumption by 50%. But it also shows which regions cannot achieve this model.

B.4 Sensitivity analysis

To evaluate the robustness of the model and the scenarios developed here, it is important to understand how sensitive they are to perturbations in the sector allocations (see Table 1 in the paper).

For this, the allocation values are decreased or increased by 5% (in total terms). All impact categories are recalculated and the percentage change from the initial value is recorded. For example, for the vegan scenario the allocation to wheat is 20%. Now all the impacts (climate change, water stress, land-use-related biodiversity loss, land use, value added, work force) are recalculated using allocation values of 15% and then 25% ceteris paribus, i.e. all other parameters are kept the same. This also means that the resulting scenarios will replace 95% and 105% of the removed calories, which might sound somewhat counterintuitive at first. However, this sensitivity analysis wants to investigate only the effect of increasing or decreasing the contribution of a single isolated sector l_i, so that the resulting change δE in the impact category E is only a function of the change in allocation

$$\delta E = \delta E(\Delta l_i)\,, \tag{23}$$

where $\Delta l_i = \pm 5\%$ is the change in the allocation of sector l_i. As MRIO analysis is linear, the resulting deviations are symmetrical

$$\delta E(\Delta l_i = -5\%) = -\delta E(\Delta l_i = +5\%)\,. \tag{24}$$

The sensitivity of the impact categories to the considered parameters is then visualized as the relative change to the initial impact of the scenario, i.e. $\pm\delta E/E$.

If the sensitivity analysis was constructed by limiting the scenario to 100% caloric replacement, the resulting change δE would be a function of the (somewhat arbitrary) choice of initial allocation percentages, and the increases and decreases of the other allocation percentages to maintain a 100% calorie replacement. Thus, this would not allow for an isolated analysis of the parameters in the model.

C Additional results

C.1 Status quo

Here we assess the 2015 status of the food system to better understand the magnitude that animal husbandry and production of animal food products have in the global food system.

Animal-based foods make up the majority of climate change impacts (65%), land-use-related biodiversity loss (57%) and land use (67%), as can be seen in Figure 1. In these categories, meat also constitutes the largest single-sector share (see Figure C.4). The exception in the four considered impact categories is water stress (12%). Water stress specifically only refers to blue water consumption (lakes, rivers and aquifers) which are mostly used for crop production38,39, especially wheat (29%) and vegetables, fruits and nuts (19%).

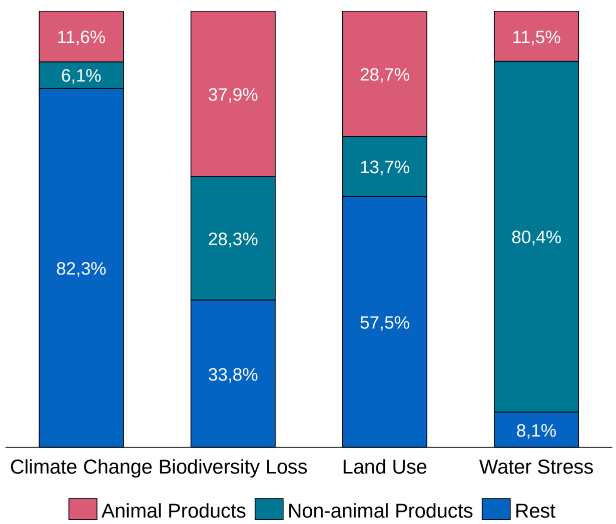

Figure C.4: Share of impacts attributed to animal food products, non-animal based products, and the rest of the global economy. Animal foods include meat, fish, dairy, eggs and all derived products including wool and leather. Impacts related to animal food products are calculated setting all animal food-related sectors in EXIOBASE as targets, impacts related to non-animal food products are calculated as the difference between overall impacts minus animal food-related impacts.

Figure C.5 shows that animal food products make up for nearly two thirds of greenhouse gas emissions (65%) of which again meat constitutes the largest share (38%), followed by dairy (21%). Another observation is the regional differences between the production-based impacts (left side in Figure C.5) and the consumption-based impacts (right side in Figure C.5). Generally, wealthier regions have lower production-based than consumption-based impacts, while lower-income regions like Brazil show the opposite trend. For example, in Europe consumption-based climate change impacts are 22% higher than from a production perspective.

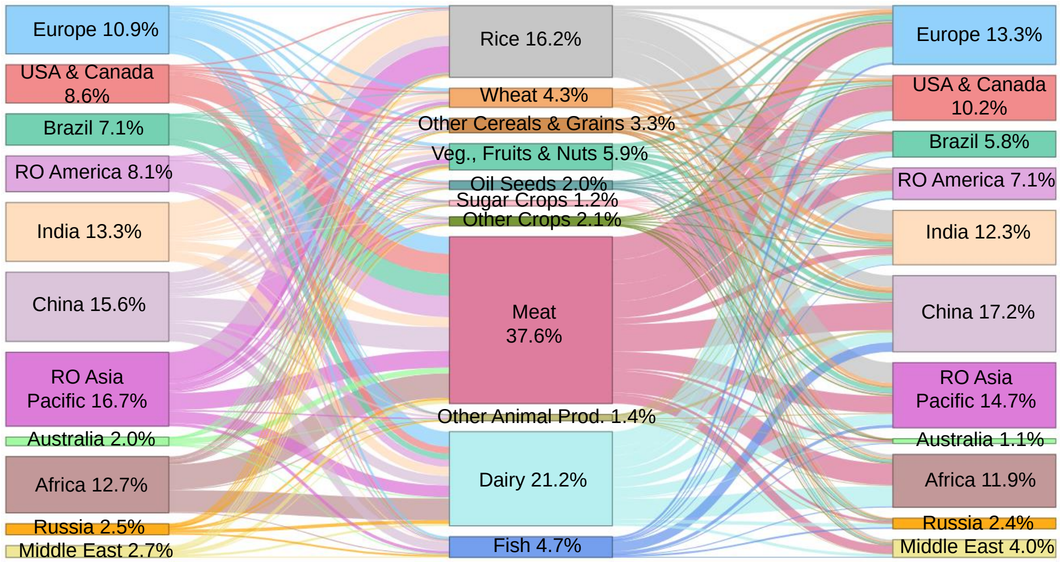

Figure C.5: Climate change flow between production region (left), target sectors (middle), and final demand region (right). The total flow of GHG emissions is 8.42 Gt.

C.2 Status quo (additional graphs)

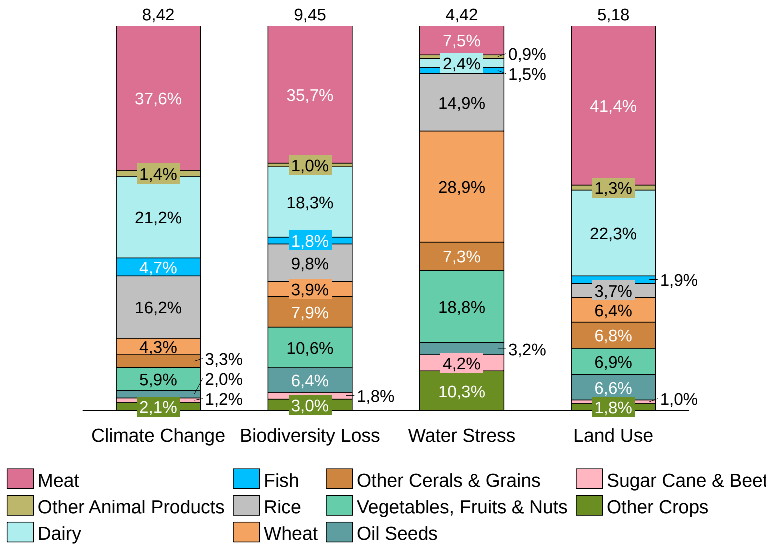

Figure C.6: Overview of impacts for the baseline, disaggregated by food sector. Animal food make up the majority of the contribution to climate change, biodiversity loss, and land use. Units: Gt (climate change), 10^{-2} global PDF (land-use-related biodiversity loss), 10^7 m^3 (water stress), 10^7 m^3 (land use).

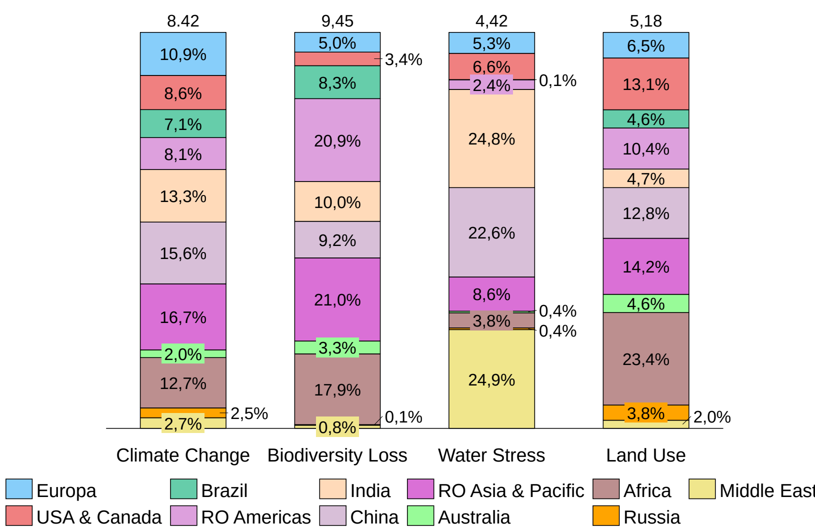

Figure C.7: Impact overview from a production perspective, disaggregated by region. Units: Gt (climate change), 10^{-2} global PDF (land-use-related biodiversity loss), 10^7 m^3 (water stress), 10^7 m^3 (land use).

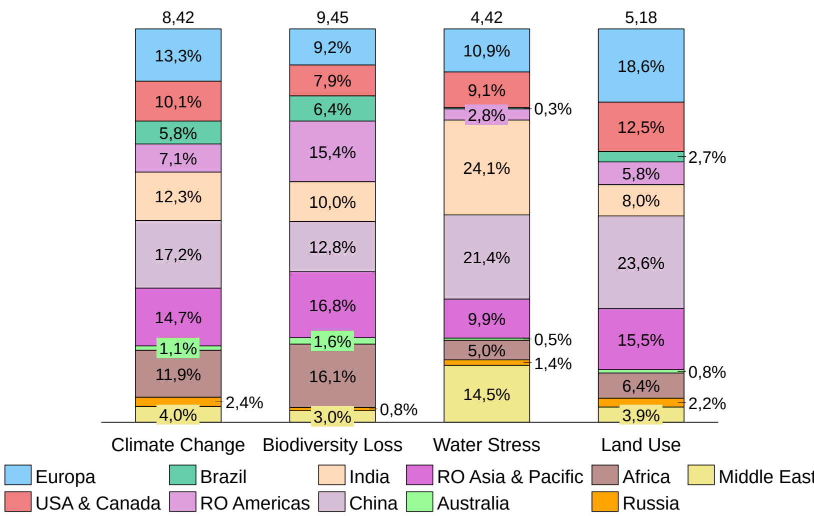

Figure C.8: Impact overview from a production perspective, disaggregated by region. Units: Gt (climate change), 10^{-2} global PDF (land-use-related biodiversity loss), 10^7 m^3 (water stress), 10^7 m^3 (land use).

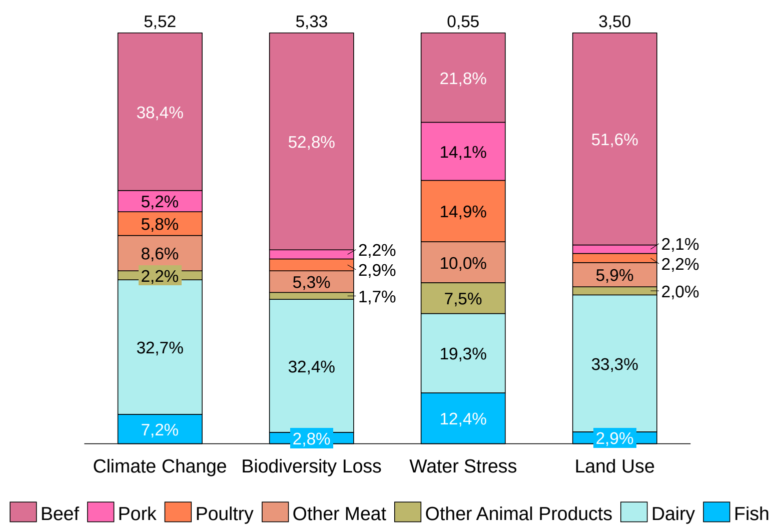

Figure C.9: Overview of impacts for the animal sectors in the baseline, disaggregated by food sector. Dairy and beef make up the majority of the contribution to climate change, biodiversity loss, and water stress. Units: Gt (climate change), 10^{-2} global PDF (land-use-related biodiversity loss), 10^7 m^3 (water stress), 10^7 m^3 (land use), 10^6 Billion Euro (value added), 10^9 FTE (work force)

C.3 Diet scenarios (additional graphs)

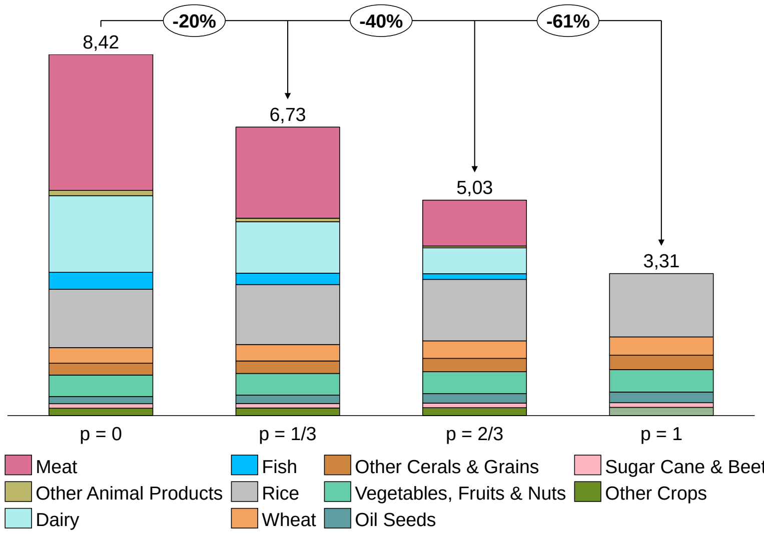

Figure C.10: Different penetration rates and their effect on GHG emissions in the vegan scenario. Unit: Gt.

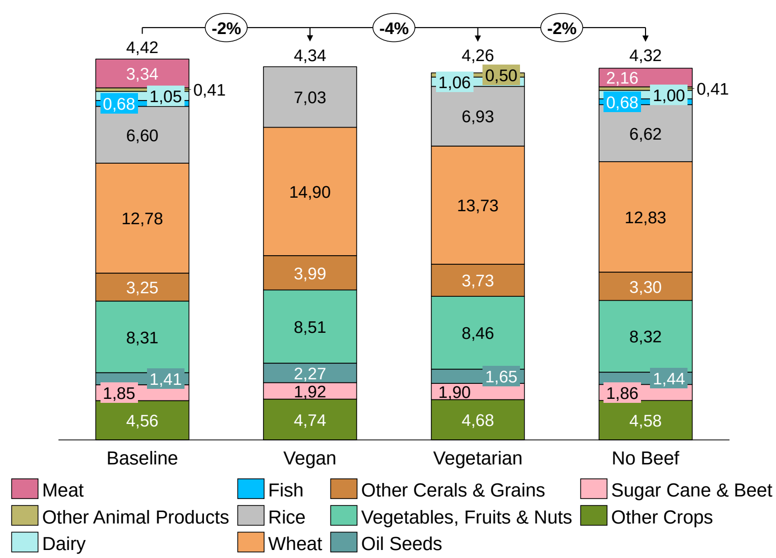

Figure C.11: All scenarios with their respective water stress in 10^7 m^3, disaggregated by food sector.

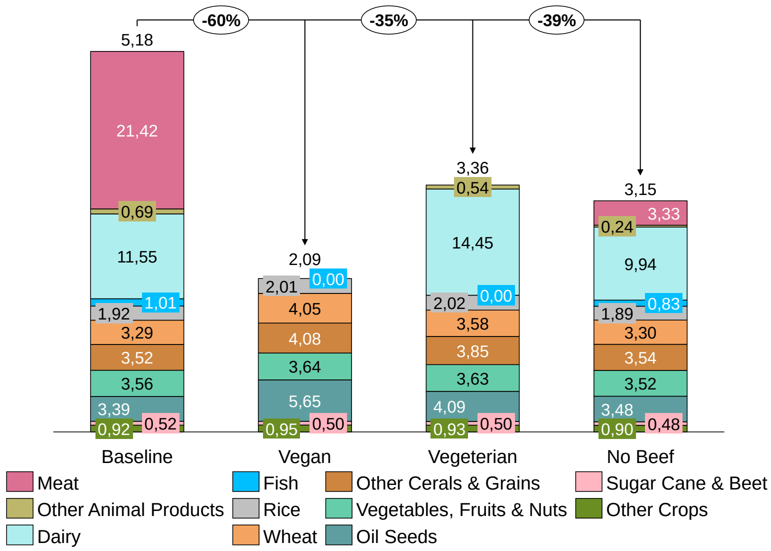

Figure C.12: All scenarios with their respective land use in 10^7 m^3, disaggregated by food sector.

C.4 Sensitivity analysis

The sector allocations in Table 1 in the paper are constructed mostly according to protein content per gram, but are still somewhat arbitrary. Thus, it is important to analyze how influential the choice of a particular parameter is within this model and which sectors affect the resulting impact categories the most. The results in this section are global numbers, and are not a continuation of the previous section on the Swiss food system.

Figures C.13 and C.14 give information on how sensitive the sector allocations are in the vegan and vegetarian scenarios, respectively. As the "reduced meat" scenario uses the same allocations as the vegan one, and the "no beef" scenario uses the same allocations as the vegetarian one, these scenarios are omitted as results would be exactly the same, just scaled according to the initial value of the impact categories (see Sector B.4).

It is important to state that Figures C.13 and C.14 represent the effect of reducing or increasing the allocation of a particular food sector *within the context of existing supply chain data in EXIOBASE*, and not the isolated impacts from the respective food sector as would be normally reported in bottom-up life cycle analysis (LCA).

Overall, the vegan scenario shows little sensitivity to all allocations compared to the vegetarian one (see the different scales in both figures). Grains and cereals show the highest effect on water stress, with wheat having the biggest potential impact (±0.9%). Rice displays the greatest possible effect on climate change (±0.7%). This can most likely be explained by the high emissions of methane (CH_4) that occur during rice cultivation due to the flooding of rice paddies [21]. Wheat and oil seeds also show relatively large effects on land use (±0.7 – 0.8%).

For the vegetarian scenario, the effect of food sector allocations is mostly dominated by animal food products. Changing the allocation of dairy products has a disproportionately large effect on land use (±6.9%). Its influence on land-use-related biodiversity loss (±5.0%), climate change (±4.5%) and work force (±1.8%) is also large compared to other food sectors.

The values for "Other Animal Products" are relatively high for value added and work force. It is not immediately clear why this might be, but it could be due to what EXIOBASE is aggregating to "Other Animal Products". In this thesis, it was initially assumed that this is largely eggs, but this category could also include food groups not considered previously.

This sensitivity analysis suggests that, when setting parameters for the diet scenarios, the resulting impacts for climate change, land-use-related biodiversity loss and land use are rather insensitive to all food sectors considered except for dairy, where those impacts are up to ten times more sensitive. Water stress is most sensitive to the wheat sector, while work force and value added are most sensitive to other animal food products and dairy. These findings suggest that the exact composition of the scenario is not as important, as long as calories from meat and fish are not replaced by a high amount of dairy (in the scenarios dairy is allocated 10% in the vegetarian and "no beef" scenarios) and the allocations to wheat and rice are kept rather low (in the scenarios, wheat is allocated between 10-20%, rice is allocated 5%).

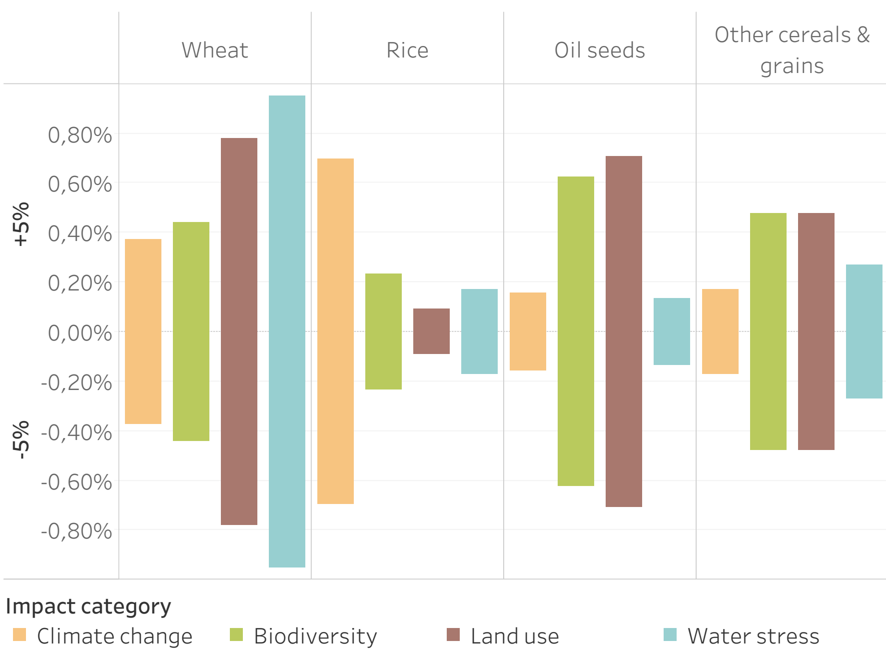

Figure C.13: Sensitivity analysis for the vegan scenario. In each column, the percentage according to Table 1 in the paper is increased by 5% (upper values) or decreased by 5% (lower values).

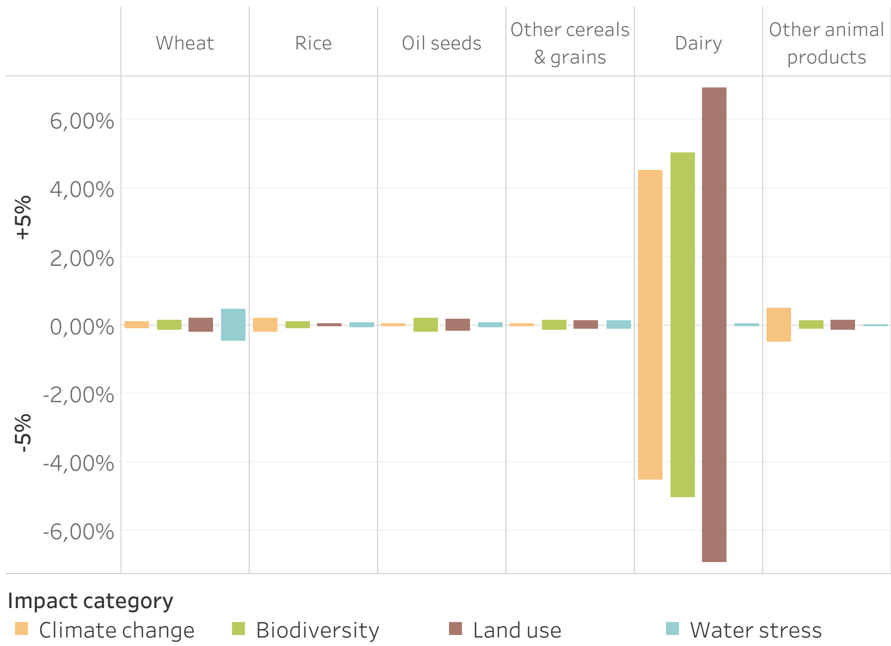

Figure C.14: Sensitivity analysis for the vegetarian scenario. In each column, the percentage according to Table 1 in the paper is increased by 5% (upper values) or decreased by 5% (lower values).

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