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Shifting towards sustainable and healthier dietary patterns in the Rhine-Ruhr Metropolis, Germany

An extended One Health Life Cycle Assessment

Dissertation

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Summary

The current state of global food systems threatens the environment and public health due to unhealthy dietary patterns and animal welfare concerns. Addressing these complex issues requires a transdisciplinary approach. To promote sustainable development, it is vital to encourage healthier dietary patterns within planetary boundaries. While using Life Cycle Assessment (LCA) as a standard method to evaluate environmental impact is expected, further research is needed to incorporate a more comprehensive sustainability assessment that aligns with major societal goals. This study adopted the One Health approach, which integrates human, animal, and environmental dimensions into the LCA perspective. The One Health approach seeks to achieve balanced health for all three dimensions. This thesis explores the transition towards healthier and more sustainable diets using an extended LCA with integrated One Health indicators. It suggests more sustainable alternatives from a One Health perspective while accounting for current dietary habits. Furthermore, this research examined how the COVID-19 pandemic has impacted dietary habits and lifestyle changes in different regions and rethinks ways to reshape post-pandemic food systems.

In Chapter 3, the importance of promoting sustainability in food production and consumption is discussed in the context of Western diets in the German federal state of North Rhine-Westphalia. The study took a One Health approach, incorporating human and animal health aspects into LCA to evaluate the sustainability of diets. The study found that men's reference diet had a greater impact than women's due to men consuming more unhealthy foods. Both diets were linked to an increased risk of non-communicable diseases. Honey, seafood, and fish were the primary food items that contributed to the loss of animal welfare. Overall, alternative diets improve sustainability, but the choice of protein is critical in sustainability from a One Health perspective.

In Chapter 4, an extended LCA framework was applied to assess the impacts of food consumption in the Rhine-Ruhr Metropolis in Germany, using data collected from an online survey. The study revealed that meat has the highest overall environmental impact, while fish consumption results in the greatest loss of animal welfare. Furthermore, the study identified sodium intake as the most significant risk factor for life minutes lost. The findings suggest that shifting towards vegetarian and flexitarian diets can significantly reduce greenhouse gas emissions, improve human health, and reduce animal welfare loss. The findings underscore the importance of making only a few dietary changes to enhance sustainability.

Chapter 5 highlights the impact of COVID-19 on eating habits and lifestyle. A survey conducted in 2020 in Brazil and Germany showed that physical activity levels and diet quality varied between the two countries. In Germany, indoor and outdoor activities increased, while in Brazil, physical activity levels decreased. Some regions in Brazil reported increased awareness of healthy and sustainable eating habits, but in Germany, there was a rise in convenience food consumption. Participants also reported discomfort while purchasing food due to hygiene measures and avoided going to supermarkets during the lockdown period. By conducting a real-time assessment of self-reported changes in eating habits and lifestyle during the COVID-19 lockdown, valuable insights can be obtained to develop strategies to improve conditions in the post-pandemic era and prepare for future pandemics.

This doctoral thesis highlights the importance of multi-dimensional approaches, specifically the One Health approach, in evaluating food production and consumption sustainability. Accordingly, making dietary changes is crucial to improving the overall health and sustainability of Western diets. The shift towards healthier, ethical, and environmentally sustainable diets is one of the major challenges that humanity faces today. It is a part of the sustainable transition from regional to global food systems, which makes them more resilient in dealing with the ongoing challenges of climate change, future pandemics and conflicts.

Zusammenfassung

Der derzeitige Zustand der globalen Lebensmittelsysteme bedroht die Umwelt und die öffentliche Gesundheit aufgrund ungesunder Ernährungsgewohnheiten und Bedenken hinsichtlich des Tierschutzes. Die Behandlung dieser komplexen Probleme erfordert einen transdisziplinären Ansatz. Um eine nachhaltige Entwicklung zu erreichen, ist es wichtig, gesündere Ernährungsgewohnheiten innerhalb der planetarischen Grenzen zu unterstützen. Zwar wird erwartet, dass die Methode der Ökobilanzierung (Life Cycle Assessment, LCA) als Standardmethode zur Auswertung der Umweltauswirkungen eingesetzt wird, jedoch sind weitere Studien erforderlich, um eine breitere Nachhaltigkeitsbewertung einzubeziehen, die mit den primären gesellschaftlichen Zielen in Einklang steht. In dieser Studie wird der One-Health-Ansatz verfolgt, der die Dimensionen Mensch, Tier und Umwelt in die LCA-Perspektive integriert. Der One-Health-Ansatz zielt darauf ab, eine ausgewogene Gesundheit für alle drei Dimensionen zu erreichen. In dieser Arbeit wird der Übergang zu einer gesünderen und nachhaltigeren Ernährungsweise anhand einer erweiterten Ökobilanz mit integrierten One-Health-Indikatoren untersucht. Sie schlägt nachhaltigere Alternativen aus der One-Health-Perspektive vor und berücksichtigt dabei die derzeitigen Ernährungsgewohnheiten. Darüber hinaus wurde untersucht, wie sich die COVID-19-Pandemie auf die Ernährungsgewohnheiten und den Lebensstil in verschiedenen Regionen ausgewirkt hat, und diskutiert wie die Lebensmittelsysteme nach der Pandemie aussehen könnten.

In Kapitel 3 wird die Notwendigkeit der Nachhaltigkeit in der Lebensmittelproduktion und im Lebensmittelkonsum im Zusammenhang mit einer westlichen Ernährung in Nordrhein-Westfalen eruiert. Die Studie verfolgte einen One-Health-Ansatz, der Aspekte der menschlichen und tierischen Gesundheit in die Ökobilanz einbezieht, um die Nachhaltigkeit der Ernährungsweise zu bewerten. Die Studie zeigte, dass die Referenzernährung von Männern einen größeren Einfluss hat als die von Frauen, da Männer mehr ungesunde Lebensmittel konsumieren. Beide Ernährungsweisen wurden mit einem erhöhten Risiko für chronische Krankheiten in Verbindung gebracht. Honig, Meeresfrüchte und Fisch waren die wichtigsten Lebensmittel, die zur Beeinträchtigung des Tierschutzes beitrugen. Insgesamt verbessern alternative Ernährungsformen die Nachhaltigkeit, aber die Wahl des Proteins ist aus Sicht von One Health entscheidend für die Nachhaltigkeit.

In Kapitel 4 wurde ein erweiterter LCA-Rahmen genutzt, um die Auswirkungen des Lebensmittelkonsums in der deutschen Metropolregion Rhein-Ruhr zu bewerten, indem Daten aus einer Online-Umfrage verwendet wurden. Die Studie ergab, dass Fleisch die

höchsten Gesamtumweltauswirkungen hat, während der Fischkonsum die größte Beeinträchtigung des Tierwohls mit sich bringt. Darüber hinaus wurde in der Studie die Natriumaufnahme als wichtigster Risikofaktor für verlorene Lebensminuten ermittelt. Die Ergebnisse deuten darauf hin, dass eine Umstellung auf eine vegetarische und flexible Ernährung die Emissionen von Klimagasen erheblich reduzieren, die menschliche Gesundheit verbessern und das Wohlbefinden der Tiere verbessern kann. Die Ergebnisse unterstreichen, dass nur wenige Umstellungen in der Ernährung schon eine Verbesserung der Nachhaltigkeit bewirken können.

Kapitel 5 zeigt die Auswirkungen von COVID-19 auf Essgewohnheiten und Lebensstil auf. Eine im Jahr 2020 in Brasilien und Deutschland durchgeführte Umfrage zeigte, dass das Niveau der körperlichen Aktivität und die Qualität der Ernährung in den beiden Ländern unterschiedlich sind. In Deutschland stiegen die Aktivitäten im Haus und im Freien, während in Brasilien hingegen körperliche Aktivitäten abnahmen. Einige Regionen in Brasilien berichteten über ein gesteigertes Bewusstsein für gesunde und nachhaltige Ernährungsgewohnheiten, während dagegen in Deutschland der Konsum von Fertiggerichten zunahm. Die Teilnehmer berichteten auch über Beschwerden beim Lebensmitteleinkauf aufgrund von COVID-bedingter Hygienemaßnahmen und vermieden es, während der Lockdown einkaufen zu gehen. Durch eine Echtzeitbewertung der von den Teilnehmern selbst angegebenen Veränderungen der Essgewohnheiten und des Lebensstils während des COVID-19-Lockdowns können wertvolle Erkenntnisse gewonnen werden, um Strategien zur Verbesserung der Bedingungen in der Zeit nach der Pandemie zu entwickeln und um sich besser auf künftige Pandemien vorzubereiten.

Die Doktorarbeit unterstreicht die Notwendigkeit eines mehrdimensionalen Ansatzes, insbesondere des One-Health-Ansatzes, bei der Analyse der Nachhaltigkeit von Lebensmittelproduktion und -konsum. Diesem Ansatz entsprechend ist eine Umstellung der Ernährung von entscheidender Bedeutung für die Verbesserung der allgemeinen Gesundheit von Menschen, Tieren und der Umwelt und allgemein der Nachhaltigkeit der westlichen Ernährungsweise. Die Umstellung auf eine gesündere, ethische und ökologisch nachhaltige Ernährung ist eine der größten Herausforderungen, vor denen die Menschheit heute steht. Sie ist Teil des nachhaltigen Übergangs von regionalen zu globalen Lebensmittelsystemen, der diese belastbarer macht für die aktuellen Herausforderungen des Klimawandels, künftiger Pandemien und Konflikte.

List of Acronyms and Abbreviations

µDALYs	Micro Disability-Adjusted Life Years
AL	Loss of Animal Lives
ALYS	Animal Life Years Suffered
AMR	Antimicrobial resistance
BLE	German Federal Agency for Agriculture and Food (in German *Bundesanstalt für Landwirtschaft und Ernährung*)
BMEL	German Federal Ministry of Food and Agriculture (in German *Bundesministerium für Ernährung und Landwirtschaft*)
BUND	German Federation for the Environment and Nature Conservation (in German *Bund für Umwelt und Naturschutz Deutschland*)
CO2	Carbon Dioxide
COVID-19	Coronavirus disease 2019
DALYs	Disability-Adjusted Life Years
DGE	German Nutrition Society (in German *Deutsche Gesellschaft für Ernährung*)
DIfE	German Institute of Human Nutrition Potsdam-Rehbrücke (in German *Deutsche Institut für Ernährungsforschung Potsdam-Rehbrücke*)
DRFs	Dietary Risk Factors
DW	Deutsche Welle
E%	Energy percent of total caloric intake
EFSA	European Food and Safety Authority
ELCD	European Reference Life Cycle Database
EPIC II	European Prospective Investigation into Cancer and Nutrition II
EQ	Encephalisation quotient
EU	European Union
Eurostat	Statistical Office of the European Union
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
FFQ	Food Frequency Questionnaire
FU	Functional Unit
g	Gram
GBD	Global Burden of Disease
GDP	Gross Domestic Product

GHG	Greenhouse gases
GHGE	Greenhouse gases emission
HEI	Healthy Eating Index
HENI	Health Nutritional Index
IBGE	Brazilian Institute of Geography and Statistics (in Portuguese *Instituto Brasileiro de Geografia e Estatística*; IBGE)
IES	Institute of Environment and Sustainability
IKM	Initiative Group European Metropolitan Regions in Germany (in German *Initiativkreises Europäische Metropolregionen in Deutschland*)
Int$	International dollars
IPAQ	International Physical Activity Questionnaire
ISN	Interest group of the German Pig Farmers' Association (in German *Interessengemeinschaft der Schweinehalter Deutschlands e.V.*)
ISO	International Organization for Standardization
IT.NRW	State Organisation IT.NRW - Statistics and IT Services (in German *Landesbetrieb IT.NRW - Statistik und IT-Dienstleistungen*)
JRC	Joint Research Centre
kcal	Kilocalories
kg	Kilogram
kg CO_2-eq	Kilograms of CO_2 equivalent
kg N-eq	Kilogram nitrogen oxide equivalent
kg oil-eq	Kilogram oil equivalent
kg P-eq	Kilogram phosphorus equivalent
kg $PM_{2.5}$-eq	Kilogram fine particulate matter (inhalable particles ≤ μ2.5 diameter size) equivalent
kg SO_2-eq	Kilogram sulphur dioxide equivalent
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LUC	Land Use Change/ Land Use Conversion
m^2 of crop eq	Square meter crop equivalent
m^3	Cubic meter
MAL	Loss of Morally Adjusted Animal Lives
MDS	Mediterranean Diet Score
METs	Metabolic Equivalents of Tasks

mg	Milligram
NCDs	Non-Communicable Diseases
NHANES	American National Health and Nutrition Examination Survey
NRW	North Rhine-Westphalia
NVS II	German National Nutrition Survey II (in German *Nationalverzehr Studie ii*)
OECD	Organisation for Economic Co-operation and Development
OHHLEP	One Health High-Level Expert Panel
PAL	Physical Activity Level
PEF	Product Environmental Footprint
PPP	Purchasing Power Parity
PUFA	Polyunsaturated Fatty Acids
ReCiPe	A harmonised life cycle impact assessment method at the midpoint and endpoint level
RIVM	Dutch National Institute for Public Health and the Environment (in Dutch *Rijksinstituut voor Volksgezondheid en Milieu*)
SARS-CoV-2	Severe acute respiratory syndrome coronavirus type 2
SDGs	Sustainable Development Goals
UN	United Nations
WBAE	German Scientific Advisory Board for Agricultural Policy, Food and Consumer Health Protection (in German *Wissenschaftliche Beirat für Agrarpolitik, Ernährung und gesundheitlichen Verbraucherschutz*)
WFP	World Food Programme

1 Introduction

1.1 Background

The main objectives of food systems are to promote healthy nutrition and protect the health of our planet (Pinstrup-Andersen et al., 2012; Whitmee et al., 2015). Unfortunately, our current global food systems often exceed planetary boundaries, leading to unprecedented environmental damage and contributing to the global health burden (Willett et al., 2019). In fact, food production and consumption are responsible for nearly 30% of the world's total environmental impact (Poore & Nemecek, 2018), resulting in ecosystem damage and a decline in biodiversity (Crenna et al., 2019). Unhealthy dietary patterns also contribute to the rise in non-communicable diseases that cause death and are strongly linked to the shift towards Western diets (Swinburn et al., 2011; Waterlander et al., 2017). Furthermore, the COVID-19 pandemic has revealed the weaknesses of food systems, emphasising the need for more resilient and healthier food systems (Benton, 2020; Bisoffi et al., 2021).

The transformation of food systems is a global concern that requires a transdisciplinary approach to solve complex challenges (von Braun et al., 2023; Willett et al., 2019). Modern food systems face various issues, including climate change, pandemics, and wars, making it challenging to meet the demands of the growing world population (Abbasi, 2022; Hendriks et al., 2022). By 2050, the world must find a way to feed 9-10 billion people, which is the biggest challenge facing humankind (UN, 2021b). The UN Food System Summit has identified the necessary actions to progress towards the Sustainable Development Goals (SDGs), which depend on creating healthier and more sustainable food systems (UN, 2021a). One way to achieve this is by changing diets and promoting healthier eating patterns within the planetary boundaries (Alders, 2017). However, changing dietary intake in populations is complex and requires paradigm shifts through collective learning and socio-cultural, political and economic changes (O'Riordan & Stoll-Kleemann, 2015).

The Life Cycle Assessment approach (LCA) is the standard framework for evaluating the environmental impact of product processes, including food products of diets, integrating the disciplines of nutrition, environment, and societal issues (Castellani et al., 2017; Heller et al., 2013; Roy et al., 2009). It is an internationally recognised and standardised method that evaluates the resources and emissions throughout a product's lifecycle (ISO, 2006a), estimating the impacts on both human health and the environment (JRC et al., 2010). While the methodology has been adjusted and adapted over time (Heijungs & Guiné, 2012), it remains highly flexible for various applications (ISO, 2006a). Life Cycle Assessment trends lean towards more comprehensive assessments encompassing more dimensions and other holistic approaches (Nemecek et al., 2016). This study employs the One Health approach for sustainability assessment, integrating the dimensions of One Health (human, animal, and environment) into the LCA method.

One Health is an approach that aims to optimise and sustainably balance the health of people, animals, and ecosystems (OHHLEP et al., 2022). It links various issues related to humans, animals, and ecosystems holistically and integrated (Davis et al., 2017; Lebov et al., 2017; Rüegg et al., 2017). The One Health approach is inclusive, meeting the challenges of a growing and complex global food system (Angelos et al., 2016; 2017; AVMA, 2008). Despite extensive research, the interconnection between human, animal, and environmental health within the food systems still needs more investigation. One Health continues to broaden and integrate more critical aspects, such as human health, livestock production, and ecological environments, to address food security and environmental sustainability (Brown, 2007; de Castañeda et al., 2023; Zinsstag et al., 2011).

In One Health's view, sustainable dietary practices consider the three dimensions of humans, animals, and the environment. The environmental dimension departed from the Planetary Health concept, which contemplates the impact of human activities on the natural environment. Food production and consumption have multiple ecological impacts, such as land-use changes, biodiversity loss, and freshwater degradation (Clark et al., 2022; Notarnicola et al., 2017; Tukker et al., 2011). Human health is also a key concern regarding nutrition and health in sustainable diets. This dimension focuses on the human health burden resulting from the westernisation of diets, which contribute to the leading causes of death worldwide, such as cardiovascular diseases, certain types of cancer and diabetes (GBD 2019, 2020). By addressing these issues, the risk factors contributing to Disability-Adjusted Life Years (DALYs) associated with unbalanced diets can be reduced. DALYs is a metric used to quantify the burden of a particular disease by measuring the number of years lost due to either premature death or disability caused by the disease (Kirch, 2008). Animal health is a critical component of One Health research, which traditionally focuses on zoonotic diseases. However, sustainability assessments have often overlooked animal welfare despite its contribution to increasing public discussions and policy initiatives. Measuring animal welfare entails determining an animal’s physical health and well-being, and substantial efforts are still needed to achieve a scientific consensus on the matter (de Boer & Aiking, 2022; de la Torre García, 2017; Nicks & Vandenheede, 2014).

This thesis delves into exploring the transition towards healthier and more sustainable diets to contribute to healthier food systems during COVID-19. The study adopts the One Health approach and aims to evaluate and optimise the sustainability of diets across the human, animal, and environmental spheres through a comprehensive food life cycle perspective from production to consumption. The human health aspect of the study investigates non-communicable diseases influenced by food consumption, considering the interconnectedness of food, nutrition, and health. Animal welfare criteria are integrated to capture the neglected issues related to livestock production and how food consumption indirectly affects the well-being of livestock. The environmental sphere is represented by several ecological outcomes arising from food production and consumption. The study suggests optimised alternatives to more sustainable and healthier dietary options. Diet optimisation aims to improve sustainability performance without diverging from current dietary behaviour, thus increasing adherence by the population.

Furthermore, this research was conducted during the COVID-19 pandemic, which likely triggered additional changes in eating behaviour and lifestyles. During the lockdown, it was important to evaluate how dietary patterns and lifestyle had changed, comparing the Rhine-Ruhr Metropolis to metropolitan regions in Brazil. The sociocultural differences between a high-income and a middle-income country bring distinct experiences concerning self-reported changes in eating habits to rethink current consumption patterns and reshape them for post-COVID-19.

1.2 NRW Forschungskolleg “One Health and Urban Transformation”

This doctoral thesis was part of the “One Health and Urban Transformation – identifying risks and developing sustainable solutions” program under the North Rhine-Westphalia (NRW) “Forschungskolleg”, funded by the Ministry of Culture and Science of the German Federal State of North Rhine-Westphalia. This Graduate school is part of a consortium between the Centre for Development Research (ZEF) and other institutions of the University of Bonn, the International Centre for Sustainable Development (IZNE) of the Bonn Rhein-Sieg University of Applied Science (HBRS), and the United Nations University – Institute for Environment and Human Security (UNU-EHS).

This Forschungskolleg aims to understand the interactions between human animals and the environment and develop sustainable solutions in the context of urban transformations and confluent health risks. The program focuses on four research areas: Brazil (São Paulo), Ghana (Accra), India (Ahmedabad), and Germany (Ruhr Metropolis).

This thesis was carried out at the Centre for Development Research (ZEF) in cooperation with the Institute for Nutrition and Food Science (IEL), the Institute for Food and Resource Economics (ILR) at the University of Bonn, and the Food and Research Centre (FoRC) at the University of São Paulo.

1.3 Scope of the thesis

This study aims to improve sustainable and healthier diets in the Rhine-Ruhr Metropolis amid the COVID-19 pandemic. With a specific focus on the initial year of the pandemic (2020), it was crucial to investigate the impact of dietary patterns on human, animal, and environmental health, as well as changes in eating habits and associated lifestyle behaviours. The study also intends to identify ways of improving diets through dietary shifts across human-animal-environment dimensions.

Scientists agree that reducing animal-based food consumption and increasing plant-based options is necessary for high-income countries to achieve a sustainable and nutritious diet that aligns with planetary limits. In Europe, food production and consumption account for 27% of anthropogenic environmental impacts, with animal-based products being the primary contributors to ecosystem damage (Castellani et al., 2019; Notarnicola et al., 2017; Tukker et al., 2011). Germany, known for its high consumption of meat, dairy and energy-dense foods, has taken steps to improve agricultural sustainability, including reducing greenhouse gas emissions and promoting sustainable nutrition (BMEL, 2020a; Meier & Christen, 2013; Treu et al., 2017). Despite these efforts, per capita meat consumption remains high, with the state of North-Rhine-Westphalia (NRW), a leading meat producer, contributing to environmental pressures and animal welfare concerns (Deblitz et al., 2022; Deutscher Ethikrat, 2020). In densely populated urban areas like the Rhine-Ruhr metropolitan region, the demand for food must be met with consideration for health and sustainability, which may require alternative food systems that prioritise these values (Alemu & Grebitus, 2020; Vieira, 2023).

During the COVID-19 pandemic, urban areas experienced higher infection rates, leading to the implementation of stricter hygiene and confinement measures (Sharifi & Khavarian-Garmsir, 2020). The pandemic also caused several societal changes that disrupted the food systems, revealing their vulnerabilities (Benton, 2020). Consequently, people's eating habits and lifestyle behaviours changed, with an increase in unhealthy eating behaviour and a decrease in physical activity noted in several high-income and middle-income countries (Ammar et al., 2020; González-Monroy et al., 2021; Lamy et al., 2022). The COVID-19 pandemic also enhanced the awareness of the population that infectious diseases, such as SARS-CoV-2, have a zoonotic origin, stressing the link between animals in livestock production systems and consumption patterns and, consequently, the associated sustainability outcomes (Attwood & Hajat, 2020; Schneider & Götte, 2022).

1.4 Study objectives

This study seeks to evaluate the impact of diets on the health of humans, animals, and the environment during the COVID-19 pandemic. It aims to propose optimised diets that represent more sustainable alternatives in terms of One Health dimensions, using the Life Cycle perspective. Additionally, the study seeks to investigate observed changes in dietary behaviour and lifestyle that may have occurred during the COVID-19 pandemic. To achieve these objectives, the study has set out the following goals and important steps in the research process:

Main objectives:

1. Create a framework integrating the One Health into the Life Cycle perspective.
2. Assess the sustainability of diets in the Rhine-Ruhr Metropolis using indicators that represent the One Health approach.
3. Based on the assessment outcomes, propose optimised diets for better health performance for humans, animals, and the environment.
4. Evaluate changes in eating habits and lifestyle during the first year of the pandemic by comparing the Rhine-Ruhr Metropolis to metropolitan regions in Brazil.

Steps in the research process:

1. Characterise and validate the proposed extended LCA Framework with indicators representing the One Health dimensions.
2. Apply the extended LCA to assess the sustainability of primary data on food consumption collected via survey in the Rhine-Ruhr Metropolis.
3. Propose optimisation scenarios with better sustainability performance closest to the current dietary behaviour and within nutritional requirements, considering trade-offs among One Health dimensions.
4. Evaluate self-reported changes in eating habits and other lifestyle behaviours (such as physical activity) by comparing the Rhine-Ruhr Metropolis to other metropolitan regions in Brazil representing different socio-cultural contexts.

1.5 Structure of the thesis

The thesis structure was carefully crafted to address the primary research questions using empirical evidence from qualitative research. The framework utilises an extended LCA, incorporating One Health indicators, to evaluate the sustainability of food consumption and suggest sustainable dietary changes. A literature review was conducted to establish the LCA framework, and the research was adapted to the pandemic's unique circumstances. As a result of the COVID-related restrictions, an online survey was disseminated to gather data during the lockdown period in 2020 throughout the Ruhr region and other areas in the Rhineland. The survey's content was also modified to include variables that reflect changes in eating habits, food supply, and lifestyle, such as physical activity, directly impacting food consumption data. **Figure 1** provides a detailed outline of the final structure of each research step.

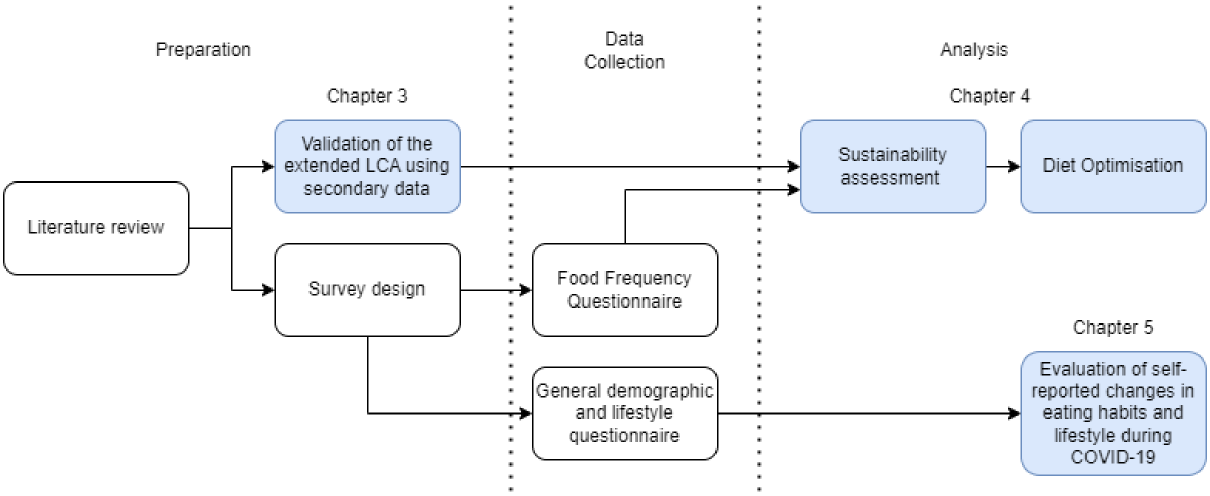

Figure 1. Structure of the dissertation: Steps in the research process.

Note: LCA: Life Cycle Assessment.

Chapter 2 elucidates the conceptual and methodological approaches applied, research areas and study design. Chapters 3 and 4 explore the sustainability assessment of food consumption using the One Health dimensions and propose sustainable dietary shifts while considering the trade-offs among One Health indicators. Chapter 3 serves as the methodological chapter, where the extended LCA was created and applied to secondary data on food consumption in NRW to characterise and validate the added indicators into LCA. In this chapter, NRW diets were optimised by gender using existing sustainable dietary patterns from the literature. On the other hand, Chapter 4 applies the framework to primary data collected via survey in the Rhine-Ruhr Metropolis. Methodological improvements were made to overcome challenges in estimating human health indicators, as identified in Chapter 3. The optimisation considered the inherent characteristics of each observed diet. It used criteria representing the One Health dimensions to seek sustainability improvement and obtain feasible solutions that the study population could eventually adopt.

Chapter 5 evaluates the effects of COVID-19 on eating habits and lifestyle based on self-reported changes in the Rhine-Ruhr Metropolis compared to several metropolitan regions in Brazil. This chapter provides evidence of some reported changes that might have influenced food consumption during the pandemic and its further implications for the sustainability assessment. Chapter 6 concludes the overall conducted work, highlighting essential findings and synthesising the main outcomes. Finally, Chapter 7 provides a final outlook for future research.

2 Methodical Approach

2.1 Integrating One Health into the sustainability assessment of diets

The concept of One Health has gained significant relevance in the pursuit of sustainable food systems due to its ability to integrate multiple disciplines and coordinate actions. Numerous international institutions have adopted the One Health approach as part of their sustainability agenda, seeking to "optimise the health of people, animals, and ecosystems"; One Health "recognises the interdependence of the health of humans, domestic and wild animals, plants, and the wider environment, including ecosystems" (OHHLEP et al., 2022). While One Health research has traditionally focused on zoonotic diseases and the animal-human interface, it also interrelates with the concept of Planetary Health (Falkenberg & Schmiege, 2023). Planetary Health is concerned with "the health of human civilisation and the natural systems on which it depends", including the concept of a "planetary healthy diet", emphasising the impact of food production and consumption on human and ecosystem health (The Lancet Planetary Health, 2017, 2019; Whitmee et al., 2015). While Planetary Health is relevant to this research topic, One Health offers a more comprehensive perspective by addressing crucial dimensions of the human-animal-environment nexus.

A comprehensive approach, such as LCA, is needed to understand the impact of food production and consumption. Life Cycle Assessment is a well-established, science-based method that evaluates the environmental impact of a product or system throughout its entire life cycle, using a functional unit as the basis for comparison (Klöpffer, 2014). The LCA framework consists of four key components: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation of Results, as outlined by ISO 14040 (ISO, 2006a, 2006b). Goal and Scope Definition establishes the purpose, functional unit, system boundaries, data quality, multifunctionality, and allocation procedures (Silva, 2021). Life Cycle Inventory involves data collection, calculation, and allocation of flows and emissions (Arvidsson & Ciroth, 2021). Life Cycle Impact Assessment categorises inventory data (e.g., emissions, resource use) into impact categories using standard comparison units (Klöpffer, 2014; Sala et al., 2016). Finally, the Interpretation Phase ensures the completeness of results, conducts sensitivity analysis and consistency checks, and addresses uncertainties related to the findings (Sala et al., 2016).

The proposed conceptual framework for this research aims to combine the life cycle perspective with the One Health approach to evaluate the sustainability of food production and consumption at the diet level. Three LCA concepts were utilised to create an extended LCA framework based on the One Health approach. The first step consisted of incorporating nutritional aspects into the traditional environmental LCA, linking nutrition to health as described by Heller et al. (2013), Ridoutt (2021) and Stylianou et al. (2021). Next, an animal welfare LCA framework developed by Scherer et al. (2018), which considers livestock production conditions representative of animal welfare, was integrated. Combining those frameworks resulted in an extended One Health LCA framework applied in this research.

The extended One Health LCA framework was utilised to determine the sustainability of food consumption, taking the total intake per person per day as a functional unit. Each food item was evaluated throughout its life cycle, from *farm-to-fork*. Life Cycle Inventory data specific to the European context was used to characterise environmental impact categories. Additionally, animal welfare criteria at the national level were considered to estimate impacts on animal welfare. Nutritional aspects representing dietary risk factors were also analysed using epidemiological studies at the national level to measure the health burden associated with several non-communicable diseases (NCDs) related to dietary intake. **Figure 2** provides a visual representation of this methodological framework.

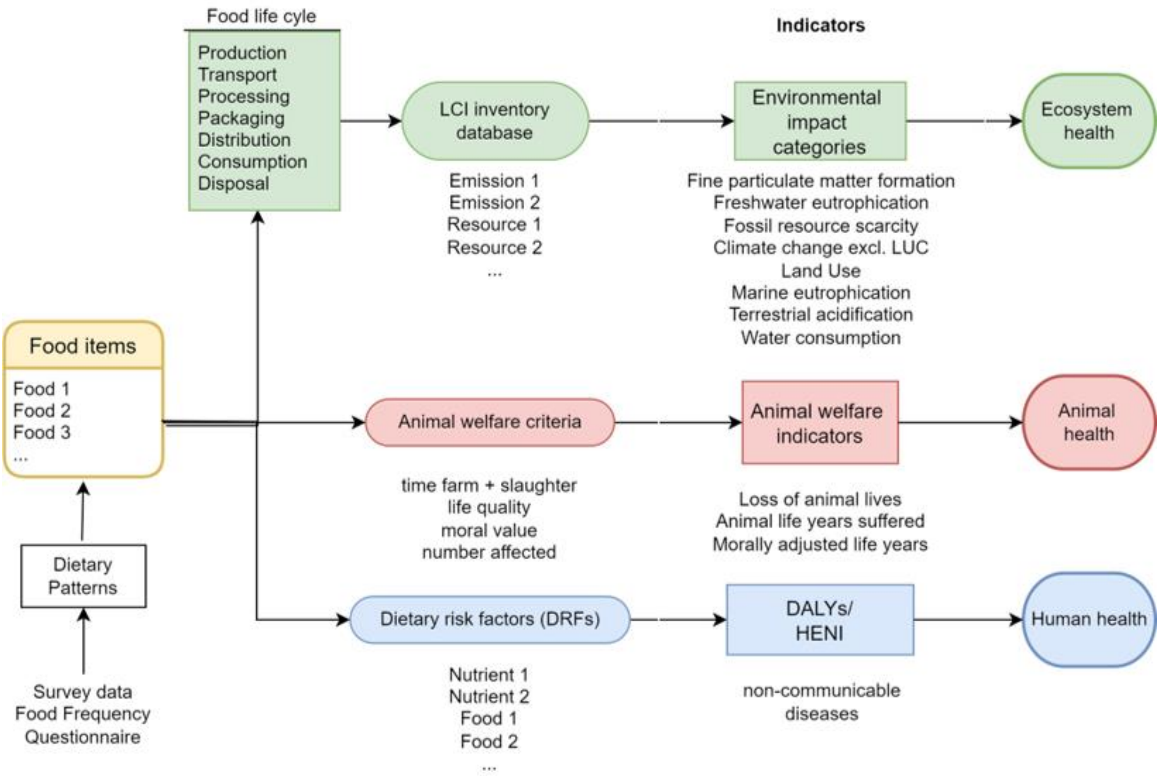

Figure 2. Extended One Health Life Cycle Assessment Framework.

Note: HENI stands for Health Nutritional Index, LCI stands for Life Cycle Inventory, LUC stands for Land Use Change, and NCDs stands for non-communicable diseases.

2.2 Research areas

This research focuses on two countries of the four research areas of the “One Health and Urban Transformation graduate school: Germany and Brazil. The study concentrated on metropolitan regions, including the Rhine-Ruhr Metropolis in NRW and several Brazilian metropolitan areas. Considering transdisciplinary approaches aimed at sustainable solutions for a One Health approach and urban transformations within metropolitan regions, it is reasonable to select the Rhine-Ruhr Metropolis and Brazilian metropolitan areas as study areas in the scope of this dissertation.

With a population of approximately 12.8 million, the Rhine-Ruhr Metropolis is one of Europe’s largest and most densely populated areas, consisting of 21 cities (*kreisfreie Städte*) and 15 districts (*Kreise*) (IKM, 2021), as displayed in **Figure 3**. The region has undergone structural transformations with economic, social, and ecological consequences, resulting in ecological modernisation and revitalisation of industrial areas towards more sustainable and greener practices (Goess et al., 2016; IKM, 2021). Additionally, the sustainability strategy of NRW aims to promote sustainable production and consumption, health and well-being, and environmental and biodiversity protection (Die Landesregierung Nordrhein-Westfalen, 2020). This study contributes to the region's ongoing urban transformation and sustainability goals.

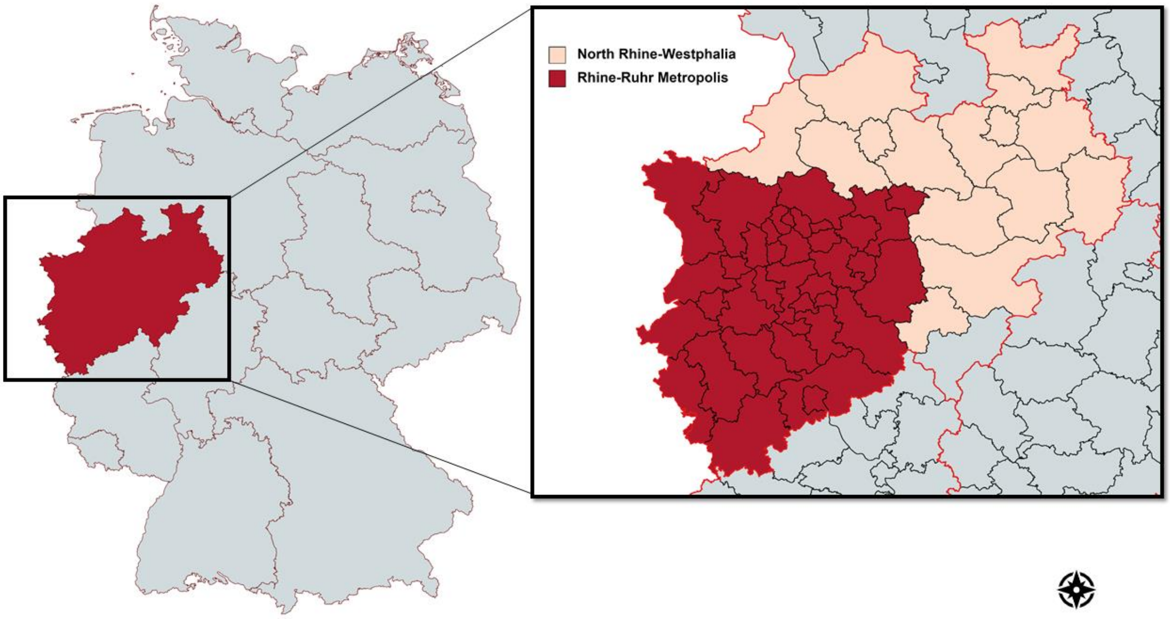

Figure 3. Research area: Rhine-Ruhr Metropolis.

Data source from IKM (2021).

The inclusion of metropolitan research areas in Brazil came at a later stage of the research. This decision was motivated by the opportunity to partner with the FoRC at the University of São Paulo (USP). Brazil was one of the focus areas for the program's research, and a comparative study was designed to explore the similarities and differences between Brazilian metropolitan regions and the German Rhine-Ruhr Metropolis concerning self-reported changes in eating habits and lifestyle behaviours during the pandemic. Cross-regional empirical research provides valuable insights into the unique challenges and opportunities faced by different regions across the globe when tackling similar issues (Köllner et al., 2018). The research areas, listed in order of sample size, included Greater São Paulo, other Brazilian metropolitan regions, other metropolitan regions in São Paulo state, and other urban areas within metropolitan regions.

2.3 Study design

This cross-sectional study used survey data collected between June 2020 and January 2021. An online survey was developed to enable data collection during the lockdown period. The survey included general information on demographics, lifestyle questionnaires, and a food frequency questionnaire available in German, English, and Portuguese. Only participants 18 years or older were recruited, and those under 18 were directed to the end of the survey page, and their data was not collected. Before participation in the survey, informed consent was provided digitally. While both Brazilian and German surveys were similar, the Brazilian survey was adapted to fit socio-cultural circumstances. The food frequency questionnaire in the Brazilian study was simplified to provide a snapshot of food consumption using Brazilian nutrition guidelines (Brasil, 2014). The study was disseminated via partnership (FoRC-USP) channels, using extensive digital social media, broadcast interviews and WhatsApp chains.

In Germany, an additional aim was to conduct a sustainability assessment and diet optimisation, which required detailed food frequency data. Therefore, participants were asked to complete a validated detailed food frequency questionnaire, EPIC II (Nöthlings et al., 2007), developed by the German Institute of Human Nutrition Potsdam-Rehbrücke (DIfE) (Harttig, 2021). We recruited participants using a convenience sampling strategy via digital means, including social media, community digital networks, associations, and university channels (Figure 4). We distributed postcards with QR codes to advertise the survey in commercial and residential areas within the Rhine-Ruhr Metropolis, which was limited due to lockdown measures.

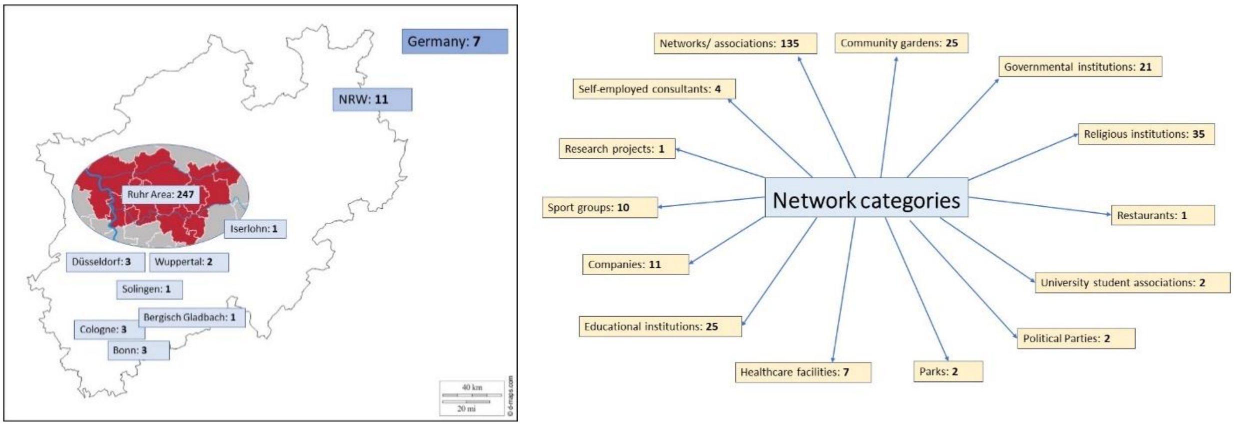

Figure 4. Survey outreach in the Rhine-Ruhr Metropolis using digital networks.

Figures by Christine Heinzel.

3 Changing dietary patterns is necessary to improve the sustainability of Western diets from a One Health perspective

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3.1 Abstract

Western diets are associated with multiple environmental impacts and risks to human health. European countries have gradually acted towards the "farm-to-fork strategy", embracing a Life Cycle Assessment (LCA) perspective to promote the sustainability of food production and consumption in the European Union. Although LCA enables the assessment of several environmental impacts simultaneously, diet-related human health and animal welfare impacts are underrepresented in life cycle impact assessment methods. This study proposes integrating additional indicators into LCA to evaluate the sustainability of diets under the One Health (OH) approach, which holistically considers interlinked complex health issues between humans, animals and the environment. Human health loss is estimated according to risk factors for non-communicable diseases (NCDs); while animal welfare is measured as *animal life years suffered*, *loss of animal lives* and *loss of morally adjusted animal lives*. The extended LCA framework is applied to men's and women's reference diets in the German federal state of North Rhine-Westphalia (NRW), compared to three optimised dietary scenarios: a) national dietary guidelines (DD); b) vegan diet (VD) and c) Mediterranean diet (MD). Men's reference diet causes greater impacts than women's across OH dimensions due to the higher food consumption, especially of ready-to-eat meals, sausages, meat and beverages. Both men's and women's reference diets are associated with several risk factors for cardiovascular diseases, diabetes, stroke and neoplasms due to high-risk exposure to dietary factors. Besides meat, consuming honey, fish, and seafood has the greatest impact on animal welfare because of the large number of animals involved. Alternative diets improve the sustainability of food consumption in NRW, although trade-offs arise: MD worsens animal suffering due to the higher fish intake; water consumption increases in both VD and MD due to a higher intake of nuts and vegetables. Results highlight the importance of including

animal welfare and human health indicators into LCA to better elucidate the potential impacts of diets characterised by high intake of animal products from the OH perspective.

3.2 Introduction

The path towards more sustainable and healthier diets constitutes one of humankind's most significant challenges, considering the need to feed a growing world population under the effects of climate change, which currently threatens ecosystems, agriculture and global health (IPCC, 2021; Pörtner et al., 2021; Springmann et al., 2018; Willett et al., 2019). Over the past decades, high-income countries have shifted consumption patterns towards energy-intensive and animal-based foods, unfolding significant environmental damage and the rising prevalence of obesity and non-communicable diseases (NCDs) (Swinburn et al., 2011; Westhoek et al., 2014). On a global level, food consumption represents more than a quarter of anthropogenic greenhouse gas (GHG) emissions – including those from Land Use Change (LUC) – and is a major cause of other environmental impacts, e.g., terrestrial acidification and freshwater (marine) eutrophication (Crippa et al., 2021; Poore & Nemecek, 2018). Moreover, industrial agriculture is directly linked to unbalanced biogeochemical nutrient cycles, natural resource depletion and biodiversity loss in both aquatic and terrestrial ecosystems (Chaudhary & Kastner, 2016; Springmann et al., 2018).

In the European Union (EU), about 950 kg of food are consumed per capita and year; associated with around 27% of the overall EU consumption-based environmental footprints, with animal-based products accounting for a large share (Beylot et al., 2019; Notarnicola, Tassielli, et al., 2017; Sala, et al., 2019; Tukker et al., 2011). EU food consumption additionally contributes to global GHG emissions, deforestation and biodiversity loss through agricultural imports and international trade (Castellani et al., 2017; Crenna et al., 2019; Sanyé-Mengual et al., 2019). The environmental impacts of food consumption in the EU may have already transgressed global planetary boundaries in climate change and land use (Sala et al., 2020). In 2020, the Farm to Fork Strategy introduced new targets to achieve sustainable food systems as central points of the EU Green Deal (European Commission, 2020). As a Member State, Germany adopted these strategies as national agricultural policy objectives, including nutrition and animal welfare labelling actions, which require impact assessments along the entire supply chain (BMEL, 2020b). Nevertheless, Western diets are predominant in Germany, negatively affecting human health and the environment (Helander et al., 2021; Meier et al., 2014). The prevalence of overweight and obesity in the country is about 60% among men and 43% among women (Stehle, 2014). German diets are linked to several diet-related risk factors contributing to cardiovascular diseases, stroke, diabetes and cancer, which are among the top causes of death in the country (GBD 2019, 2020).

Despite the growing environmental, social and ethical concerns about meat consumption in Germany, the country still has one of the largest per-capita meat consumption in the EU, at 59.5 kg per capita and year (BLE & BZL, 2020; BMEL, 2019; Sanyé-Mengual et al., 2019). In the last 20 years, Germany's livestock production has become highly intensive, partly driven by increasing international demand, especially from China (Destatis, 2021a; Heinrich Böll Stiftung & BUND, 2016). Around 30% of Germany's total meat production is located in the state of North Rhine-Westphalia (NRW) (DW, 2020). NRW is one of the most intensive livestock-producing regions in the EU, with an output of 1,768,289 tonnes of pigs, 212,668 tonnes of cattle and 56,862 tonnes of poultry slaughtered in 2019 (ISN, 2021; IT.NRW, 2020). The intensification of livestock production systems has significant implications for animal health and welfare (Bonnet et al., 2020). Although new animal welfare legislation provides minimum animal protection, there are still complex ethical questions, hurdles and potential trade-offs to overcome (Deutscher Ethikrat, 2020). For instance, the COVID-19 pandemic has worsened animal conditions and made social and health problems in the meat industry more evident (Marchant-Forde & Boyle, 2020). There is a growing consensus that a significant reduction of animal-based products is necessary to promote human health and mitigate environmental impacts, especially in Western diets across high-income countries (Bonnet et al., 2020; Westhoek et al., 2014).

One way to assess the sustainability of diets is through Life Cycle Assessment (LCA), a standardised method to evaluate impacts from all food supply chain stages (i.e., *cradle-to-grave*), allowing for extensions and flexibilities (Muralikrishna & Manickam, 2017; Roy et al., 2009). LCA studies emphasise the need to consider other impacts besides climate change to evaluate alternative dietary scenarios (Meier & Christen, 2013; Poore & Nemecek, 2018). Integrating nutritional aspects is particularly important in agri-food systems (Heller et al., 2013; McAuliffe et al., 2020). For instance, Ribal et al. (2016) include environmental, economic, and nutritional indicators to assess the sustainability of school meals and mitigate trade-offs. Stylianou et al. (2016) combine environmental LCA with epidemiology-based nutritional indicators on human health to simultaneously evaluate the environmental and health impacts of foods. Chapa et al. (2020) compare the environmental impacts of different American diets by defining alternative Functional Units (FUs) that capture the provision of nutrition and satiety as essential functions of food intake. Batlle-Bayer et al. (2020) recently proposed a FU that combines nutritional and socio-economic data to measure food affordability in LCA. Still, Life Cycle Impact

Assessment (LCIA) methods often overlook human health impacts from food consumption and further implications for animals.

LCA could benefit from more comprehensive and integrative approaches to improve the overall sustainability of food systems at different geographical scales (Colonius & Earley, 2013; Zinsstag et al., 2011). The One Health (OH) approach can serve as an overarching framework when rethinking sustainability strategies for shaping future dietary patterns. OH is defined as "a collaborative, multi-sectoral and transdisciplinary approach to achieve optimal health outcomes recognising the interconnection between people, animals, plants and the environment" (AVMA, 2008). As such, the OH approach can be applied to study complex health issues transecting the human-animal-environment spheres as integral parts of the food system at the local, regional, national, and global levels (Davis et al., 2017; Lebov et al., 2017). Classical OH research has mainly focused on the transmission of zoonotic pathogens in the food supply chain (Angelos et al., 2016; Klous et al., 2016). However, food consumption is associated with several non-communicable diseases (NCDs), the effects of which warrant further investigation (Afshin et al., 2019; Willett et al., 2019).

Integrating the OH domains into traditional LCA approaches is far from straightforward. LCIA methods estimate pollution and environmental degradation impacts on human health as Disability-Adjusted Life Years (DALYs). Although several metrics related to both nutrient quantity and quality exist, the role of nutrition in LCA is commonly assessed through the definition of the FU as mass, energy or single nutrient contents (Green et al., 2020; Weidema & Stylianou, 2020). Applying nutritional epidemiological concepts can help assess the relationship between dietary patterns and the risk of developing particular chronic diseases (Heller et al., 2013). Moreover, animal welfare issues are commonly disregarded in LCA and remain subject to consumers' preferences when proposing integrated sustainability actions (van der Weele et al., 2019). Only a few studies propose animal welfare indicators consistent with the LCA framework and comparable across several food items (Scherer et al., 2018, 2019).

This study aims to implement the OH approach into LCA to assess the sustainability of food consumption by considering additional indicators on human health and animal welfare from a life cycle perspective. The extended LCA framework is applied to evaluate the impacts of reference diets for both men and women in NRW based on data for observed food consumption at the regional level. NRW is one of the most populated areas in Europe and a typical example of Western dietary habits, i.e., characterised by high calorie and animal product intake. Alternatives to the reference NRW diets are also evaluated with the ultimate goal of providing recommendations for more sustainable dietary patterns across environmental-human-animal health dimensions.

3.3 Methods

The study departs from the LCA methodology, consisting of the following steps according to the ISO14040/44:2006 standards (ISO, 2006a, 2006b).

3.3.1 Goal and scope

The enhanced LCA is applied to the German federal state of NRW, located in the North-Western part of the country, to estimate the sustainability of the reference diet under the OH approach. With approximately 17.5 million inhabitants, NRW is one of the most populated regions in Germany, including the Rhine-Ruhr metropolitan area, the largest conurbation in Europe (Destatis, 2021b). NRW is also next to other densely populated countries in Western Europe, such as Belgium and the Netherlands (Eurostat, 2020). The FU is defined as the average food consumption per capita and day for the year 2008, based on the "National Nutrition Survey II" (NVS II) (Max Rubner Institut, 2008). Although there are more recent surveys at the national level (BMEL, 2021), the NVS II is the most recent and representative data at the regional level, available for the federal state of NRW. Most NVS II participants were women (53.9%) with an average age of ~46 years and low physical activity (Max Rubner Institut, 2008). Two different mass-based FUs are considered to differentiate impacts by gender since this factor influences the predisposition to chronic diseases (e.g., cardiovascular diseases). Hence, the FU is estimated at 4.147 kg and 3.663 kg per capita and day for men and women, respectively. Three other dietary scenarios are examined as possible alternatives to the reference diet (RD) in NRW. These diets were designed by quadratic optimisation to represent other consumers' choices while delivering approximately the same FUs and similar nutritional properties (see **section 3.3.2.1**).

Impacts are quantified from farm-to-fork (i.e., cradle-to-plate). The system boundaries include the following sub-stages, as shown in **Figure 5**: a) agricultural production (crop production and animal husbandry), b) transport of raw materials, c) processing into food products, d) packaging, e) distribution of food products, f) retail and g) consumption (food preparation in households, including packaging disposal). Food losses and waste are considered at the retail and consumption sub-stages. Other downstream impacts from food waste management and disposal are excluded. All sub-stages comprise the production and transportation (distribution) of the respective inputs – including energy –

except for capital goods. When multiple co-products are obtained from some of the sub-stages mentioned above, partitioning is generally applied by considering their relative economic value, which aligns with the Product Environmental Footprint (PEF) (European Commission, 2018). The only exception is dairy production, in which physical allocation is applied among co-products of milk production (meat and feed) and processing of dairy products (skimmed milk powder, cream, milk fat derivates, etc.). Although this is not fully compliant with the PEF guidance, it follows the International Dairy Federation guide (Broekema et al., 2019; International Dairy Federation, 2016). This also avoids the need to gather economic data for such products, for which prices are highly variable and not always available. Additionally, cut-off criteria are applied to exclude the impacts of a few co-products, namely dried citrus pulp, brewer grain, animal manure, and nutshells, given their relatively low market value (Broekema et al., 2019). Agricultural production includes land use (as area occupation) but excludes land conversion (or LUC), often implying additional CO_2 emissions from carbon stock changes besides other ecological alterations.

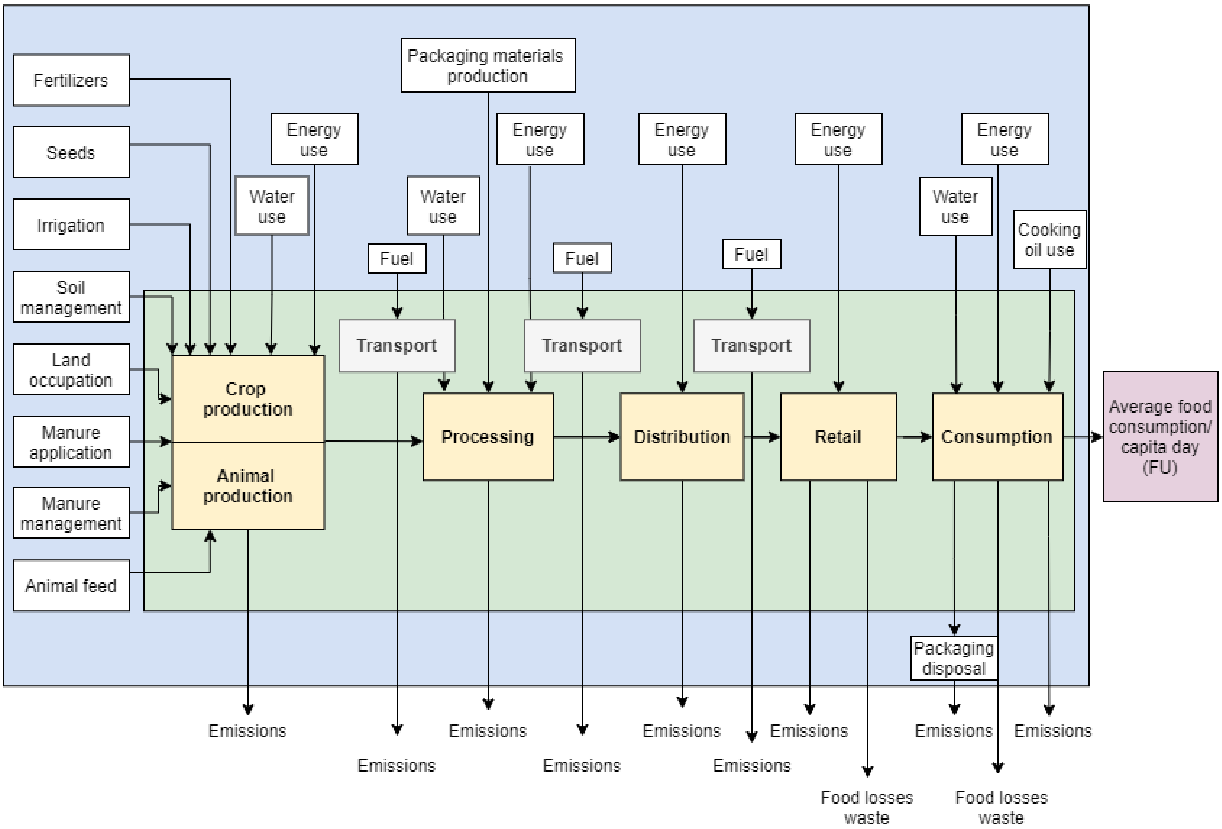

Figure 5. System boundaries from farm-to-fork to estimate the impacts of average diets in North Rhine-Westphalia.

The system includes one-life-cycle per 100 grams of food product and respective quantity per functional unit.

3.3.2 Life Cycle Inventory (LCI)

3.3.2.1 Food consumption in the reference diet and alternative dietary scenarios

The quantities of each food item consumed per FU were estimated using the regional NVS II data (Max Rubner Institut, 2008). Since these data sources only provided quantities per food category, additional assumptions were needed to identify specific food items in each category and associated quantities. National-level data from (Treu et al., 2017), also based on the NVS II, were used with this aim. The list of food items was further rearranged and renamed according to the product dataset in Optimeal® (Broekema et al., 2019), consistent with the EFSA Comprehensive European Food Consumption Database (EFSA, 2018b). All food items were selected based on representativeness within each food category. Food items accounting for less than 1% of the total weight and for which no equivalent category could be identified were reallocated into the most representative or similar food item category based on the physical similarity (e.g., offal redefined as “meat products”; *sauerkraut* redefined as “head cabbage”). Only five food items were excluded, representing less than 0.0006% of the overall food consumed in 2008 (in weight) (see **Chapter 3 Appendices, Tables S1** and **S2** for further information). The two reference diets include 100 food items plus 17 beverages grouped into 16 major food categories, as shown in **Table 1**.

Table 1. Reference diet in North Rhine-Westphalia in grams per day by gender.

Food Categories	Food items	Women	Men
Alcoholic beverages	Beer, regular	31.20	175.20
	Wine, red	23.46	25.53
	Wine, white	10.54	11.47
	Beer and beer-like beverages	7.80	43.80
	Spirits	1.30	3.70
	Cider	0.99	1.07
Animal and vegetable fats and oils	Butter	7.85	12.32
	Margarine, normal fat	5.88	8.89
	Vegetable oil	3.27	4.79
Ready-to-eat meals	Ready-to-eat soups	71.00	92.00
	Vegetable-based meals	57.20	53.56
	Prepared mixed vegetable salad	52.80	49.44

	Pasta, cooked	36.00	47.00
	Meatballs	13.02	25.20
	Meat-based meals	9.92	19.20
	Meat stew	8.06	15.60
	Egg-based meal	5.00	4.00
	Potato based dishes	5.00	8.00
	Pizza and pizza-like pies	3.56	6.39
Drinking water	Tap water	692.79	710.91
	Bottled water	340.66	349.57
	Still mineral water	113.55	116.52
Eggs and egg products	Chicken egg	13.00	18.00
Fish and other seafood	Fish products	10.73	13.84
	Salmon and trout	8.44	9.73
	Herring	2.96	3.42
	Shrimps	0.87	1.01
Fruit and fruit products	Apple	104.49	93.26
	Bananas	35.78	29.52
	Strawberries	33.10	21.76
	Peaches	21.75	13.60
	Oranges	19.67	15.32
	Pear	18.44	16.46
	Mandarins	10.59	8.25
	Fruit compote	7.57	6.35
	Kiwi	4.88	4.03
	Jam	0.95	0.91
Fruit and vegetable juices	Juice, apple	81.12	92.66
	Juice, orange	69.29	79.14
	Fruit juice	18.59	21.23
	Fruit and vegetable juices	16.24	18.55
	Fruit nectar	9.40	10.74
	Juice, tomato	2.35	2.68
	Wheat bread and rolls	85.12	112.00

Grains and grain-based products	Pastries and cakes	25.60	36.80
	Mixed wheat and rye bread and rolls	18.62	24.50
	Rye bread and rolls	17.29	22.75
	Multigrain bread and rolls	11.97	15.75
	Pasta, wheat flour, without eggs	11.20	12.60
	Cereal flakes	9.60	10.80
	Wheat milling products	9.54	10.73
	Biscuits	1.95	2.81
	Rice	1.66	1.87
Legumes, nuts and oilseeds	Tree nuts	3.78	4.53
	Peas, green, without pods	3.30	3.57
	Beans	2.16	2.33
	Beans, green, without pods	1.28	1.39
	Lentils	1.05	1.14
Meat and meat products	Cooked smoked sausage	9.38	18.40
	Chicken meat	6.67	8.89
	Fresh and lightly cooked sausage	6.26	12.26
	Pork/piglet meat	6.23	13.02
	Dry sausage	5.74	11.24
	Beef meat	5.56	11.64
	Sausages	4.69	9.20
	Mixed beef and pork meat	4.42	7.32
	Turkey meat	1.18	1.57
	Veal meat	0.79	1.66
	Ham, pork	0.74	0.71
	Meat and meat products	0.60	0.74
	Mutton/lamb meat	0.56	1.16
	Bacon	0.20	0.19
Milk and dairy products	Cow milk	101.65	126.12
	Yoghurt, cow milk, plain	42.20	37.19
	Fermented milk products	30.14	26.57
	Quark	14.70	15.38

	Cheese	14.15	14.81
	Buttermilk	13.78	12.14
	Cheese, Gouda	7.08	7.41
	Flavoured milk	6.35	7.88
	Cheese, Edam	3.27	3.42
	Evaporated milk	2.40	2.58
	Cheese, Camembert	2.18	2.28
	Cheese, processed spreadable	1.63	1.71
	Cream	0.48	0.52
Non-alcoholic beverages	Coffee	552.00	628.00
	Herbal tea, infusion	209.44	99.33
	Black tea, infusion	62.56	29.67
	Soft drink, flavoured	42.32	107.64
	Cola beverages, caffeine	27.60	70.20
	Soft drink, fruit content	22.78	57.46
Snacks, desserts, and other foods	Starchy pudding	22.38	23.03
	Ice cream, milk-based	10.40	12.40
	Custard	6.50	7.75
	Ices and desserts	5.72	6.82
	Snack food	5.28	7.92
	Pretzels	0.72	1.08
Starchy roots and tubers	Potato boiled	36.92	46.80
	Potatoes and potato products	17.75	22.50
	French fries	9.23	11.70
	Main-crop potatoes	7.10	9.00
Sugar and confectionery	Chocolate (Cocoa) products	8.65	8.65
	White sugar	8.48	8.48
	Confectionery (non-chocolate)	4.75	4.75
	Molasses and other syrups	1.85	1.85
	Honey	1.28	1.28
Vegetables and vegetable products	Carrots	24.96	21.09
	Tomatoes	23.86	19.06

	Head cabbage	13.51	12.19
	Tomato purée	11.43	10.78
	Leafy vegetables	9.87	8.91
	Cucumbers	9.77	7.97
	Leek	5.20	4.69
	Onions, bulb	5.20	5.63
	Peppers, paprika	4.30	3.44
	Spinach (fresh)	2.08	1.88
	Cultivated mushroom	1.04	0.94
Total		3,663	4,147

*Data source: (EFSA, 2018a; Max Rubner Institut, 2008; Treu et al., 2017).

Three alternative dietary scenarios were designed to represent more recent nutritional shifts in Germany, following the same approach as Kramer et al. (2017) and Tyszler et al. (2016). This consists of applying quadratic optimisation in Optimeal® (Broekema et al., 2019; 2020; te Pas et al., 2021) to generate diets that are similar to the RD in terms of the overall quantities of food items consumed and associated nutritional properties after replacing or excluding specific food items according to the consumers' choices the alternative diets aim to capture, under nutritional constraints. The quadratic optimisation is carried out to deliver approximately the same amount of overall food consumed (kg per capita and day) as in the Reference diet (RD) to have comparable FUs for both men and women, respectively, i.e., 3.787 and 3.897 kg in DGE diet (DD); 4.029 and 4.207 kg in Vegan diet (VD); and 3.536 and 3.399 kg in Mediterranean diet (MD). All food items selected were available in the EFSA dataset (EFSA, 2018) in Optimeal®. Nutritional constraints were defined as upper and lower values for macro- and micronutrient intake in line with EFSA (EFSA, 2018a, 2019a), considering men and women with low physical activity (PAL 1.4), the same as in NVS II. Specific dietary considerations and product selection criteria applied for defining the three alternative diets are as follows:

a. ***German Nutrition Society (DGE) diet (DD)***: this diet is designed according to the official dietary recommendations of the DGE for daily intake within seven food groups following a descending orientation circle (DGE, 2021). DD characterises a health-oriented and nutritionally balanced food selection, primarily based on whole foods, minimising ultra-processed foods, and including almost three times the amount of vegetables as the RD.

b. ***Vegan diet (VD)***: this is a 100% plant-based diet, excluding all animal-based products (e.g., meat, dairy, eggs, fish, and honey), following recommendations of the DGE (Richter et al., 2016). Due to many dietary constraints applied, only tolerable upper nutrient intake levels (EFSA, 2018a) were considered as nutrient constraints that avoid adverse health risks. At the product level, plant-based food items replace milk and dairy, meat products, and eggs. In particular, the consumption of grains, nuts, legumes, and pulses has substantially increased relative to RD.

c. ***Mediterranean diet (MD)***: This diet is characterised by the high intake of plant-based and fish products, according to the pyramid and meal plan from (Bach-Faig et al., 2011) and (Fidanza and Alberti, 2005). The MD entails a significant increase in consumption of fruits and vegetables relative to RD and three times the amount of fish. Food items were selected to represent a preference for regional products, based on statistics of overall food supply in NRW (IT.NRW, 2020; Verbraucherzentrale NRW, 2015) and food imports at the country level (Eurostat, 2021; FAOSTAT, 2021). Yet, a large share of this diet (~38%) is covered by imports, i.e., fish, nuts and seeds, olive oil, part of fruit and vegetables and wine.

More specific information on the food items, quantities consumed, and nutritional properties per day of the alternative dietary scenarios can be found in (See **Section S1 Table S3; Table S4** and **Section 4, Table S13** and **Table S14** in **Chapter 3 Appendices**). As a result of the optimisation, the above-described diets provide between 1,800 to 1,830 kcal per day for women and between 2,230 to 2,280 kcal for men, which is slightly less kcal than the RD – i.e., 1,999 and 2,643 kcal per person and day, for women and men, respectively. This is still in line with the dietary reference values for EU adults with low physical activity – between 1,800 and 1,820 kcal for women and between 2,230 and 2,280 kcal for men. Uncertainty analysis of the scenarios above was conducted through 100-run Monte Carlo simulations in Optimeal® to assess variability in food item composition, associated nutrients, and impacts resulting from the optimisation.

3.3.2.2 LCI of the respective food products

The software Optimeal® (Broekema et al., 2019) and its underlying dataset were used to estimate aggregated impact values per 100 g of food product along its life cycle, i.e., from *cradle-to-plate*. Impacts were estimated by multiplying impact values and the quantities consumed by each food item per FU (see **Figure 5**). Optimeal® follows the methodological recommendations of the PEF Guidance 6.3 in terms of the LCI from *processing-to-mouth* for various products (European Commission, 2018). This refers to energy use, water consumption, food losses and cooking methods (Broekema et al., 2019). There are a few exceptions to the dairy production process. LCI modelling in Optimeal® is carried out with SimaPro, based on specific data sources and methodological assumptions, as detailed below (see **Section S2** of the **Chapter 3 Appendices** for further details**):**

a. ***Agricultural production***: Optimeal® determines agricultural production's origin by considering an average mix of major producer/exporter countries and associated shares based on FAOSTAT data for the period 2009-2013 (FAOSTAT, 2013) combined with additional trade statistics (Broekema et al., 2019). Impacts from crop production arise from land occupation, soil management, irrigation, manure application, seeds, fertilisers and energy and water consumption in agricultural operations, excluding pesticides whose LCI data is not available for all food products in the analysed diets. Livestock production includes impacts from animal feed, as well as emissions from enteric fermentation and manure management (Broekema et al., 2019). Emissions to air, soil and water are modelled considering the characteristics of each production system. Cultivation of crops (as well as animal feed) uses country-level data from major sourcing regions. As for animal farming, most processes are modelled based on regional data that is representative of intensive production systems in Western Europe (mainly the Netherlands and Irland), i.e., dairy, pig, poultry (i.e., eggs and broiler) and beef farms (Durlinger et al., 2017b). Other animal production systems, i.e., fisheries, aquaculture, and beekeeping, also include the production of materials, energy, fish meals, and the management of beehives (Arena et al., 2014; Broekema et al., 2015). LCI data are modelled according to the Agri-footprint 4.0 methodology, compliant with the PEF guidance, covering more crops and countries and specific cultivations, allocation of co-products and calculation of emissions in cattle processes (Durlinger et al., 2017a). Food losses from agricultural production are not considered.

b. ***Transport of raw materials***: Transport of outputs and inputs across sub-stages is included by assuming the average distance of travel per transport modality (road, rail, water, air), the relative tonnage load capacity of the vehicles used, and their respective load factor, type of fuel, and emission intensity, according to the Agri-footprint 4.0 method (Durlinger et al., 2017b).

c. ***Processing into food products***: Optimeal® includes milling, parboiling, extraction, refining, and meat processing using the Agri-footprint 4.0 method (Durlinger et al., 2017b). Energy and water consumption are estimated according to the PEF Guidance (European Commission, 2018). Additional data sources used for other specific processes are described in **Table S5** in **Chapter 3 Appendices**.

d. ***Packaging***: The production of packaging materials is included using the Ecoinvent 3 database (Wernet et al., 2016), which comprises the most common food packaging materials. Only aluminium production is modelled based on the ELCD database (JCR-IES, 2012). Transport of packaging materials is included by considering the average distance covered by truck, ship, and train, based on the PEF Guidance (European Commission, 2018).

e. ***Distribution of food products****:* Cooling, freezing, lighting, and heating are included, considering the storage time and product density, according to the PEF Guidance (European Commission, 2018).

f. ***Retail****:* Retail activities are modelled by taking default parameters from the PEF Guidance (European Commission, 2018). This includes energy use during retail storage (i.e., cooling, freezing, and lighting, excluding heating), food losses at the retail facility, travel distances and means of transport.

g. ***Consumption****:* Optimeal® estimates energy use for cooking, frying, boiling, baking, microwaving, chilling, and freezing, considering the preparation time per food product and a *raw-to-cooked ratio*. Production of additional inputs (e.g., oil for frying, water for brewing) and food losses at the household are calculated based on the PEF Guidance (European Commission, 2018). Consumption also includes the disposal of food packaging, according to Ecoinvent 3.4. (Wernet et al., 2016), assuming average disposal scenarios in the European context (see **Table S5** in **Chapter 3 Appendices**).

3.3.3 Life cycle impact assessment (LCIA)

The LCIA considers environmental impact indicators at the midpoint level and human health and animal welfare loss as additional indicators. It must be noted that animal welfare impacts are associated with animal production up to the processing sub-stage, i.e., animal husbandry to slaughtering, aquaculture/fisheries to cleaning/degutting, and beehive management to honey extraction. The impacts on human health are generated only through food consumption (see **Figure 5**).

3.3.3.1 Environmental impact indicators

The environmental dimension is assessed through the ReCiPe 2016 characterisation method (Huijbregts et al., 2017) at the midpoint level to provide details on the sources of environmental degradation. Specifically, the following impact categories are considered: a) climate change (as kg CO_2-eq.), b) fine particulate matter (as kg $PM_{2.5}$-eq), c) terrestrial acidification (as kg SO_2-eq), e) freshwater eutrophication (as kg P-eq), f) marine eutrophication (as kg N-eq), g) land occupation (as m^2 of crop equivalent), h) water consumption (as m^3) and i) fossil resource scarcity (as kg oil-eq). These include the most relevant impact categories identified by the PEF Guidance (European Commission, 2018). The same LCIA methods are applied regardless of the country of origin of the products consumed, as these are defined globally. It should be noted that toxicity-related impacts are excluded, as estimating them requires quantifying emissions arising from pesticide use, which are excluded from the LCI due to data limitations. This aligns with the study's goal of assessing human health impacts associated with dietary risk factors for NCDs.

3.3.3.2 Animal welfare indicators

Animal welfare indicators are defined according to the methodology proposed by Scherer et al. (2018), which covers the impacts from farm to slaughter. Specifically, three indicators are considered to assess animal welfare loss, expressed in a) "Animal Life Years Suffered (ALYS)", b) "loss of Animal Lives (AL)", and c) "loss of Morally Adjusted Animal Lives (MAL)". These correspond to midpoint-level indicators and are quantified by applying the equations below (**Eq. 1-7**).

$$ALYS = NAf \times ([Ld - Sd] \times [1 - Q] + Sd) \qquad [1]$$

$$AL = LL + LD \qquad [2]$$

$$MAL = NAf \times (1 - Lf) \times mv \qquad [3]$$

$$NAf = \frac{1}{(Lw \times Pf)} \qquad [4]$$

$$LL = NAf \times (1 - Lf) \qquad [5]$$

$$LD = NAf \times ([Lf - Sf] \times [1 - Q]) + Sf \qquad [6]$$

$$Lf = \frac{Ld}{L_{exp}} ; Sf = \frac{Sd}{L_{exp}} \qquad [7]$$

Where:

NAf: "number of animals affected"; Q: "quality of life"; Ld: "life duration"; Sd: "slaughter duration"; LL: "lives lost"; LD: "lives with disability"; Lf: "life fraction"; Sf: "slaughtering fraction"; L_{exp}: "Life expectancy"; mv: "moral value"; Lw: "live weight"; Pf: "food product fraction". Source: (Scherer et al., 2018).

ALYS measures the loss of life quality due to farm conditions, defined by the space allowance (or stocking density) throughout the animal lifetime for the different animal husbandry systems (e.g., cattle, swine, poultry, fish and shrimp aquaculture, beekeeping). *Quality of life* is calculated differently for each animal, following regression equations retrieved from (Scherer et al., 2018) and it was adapted to the standards or minimum requirements established by official German animal welfare protection laws (see **Section S3 Table S6** in **Chapter 3 Appendices**). The *number of animals affected* is the number of animals involved in the FU. It is given by the food product fraction, defined as the average slaughter yield (in kg/animal) ratio to the live animal weight (kg/animal).

AL measures the number of *lives lost* (LL) and *lives with a disability* (LD), similar to human DALYs. The indicator considers the premature death imposed on animals through slaughtering for production purposes and the distress caused during their farm life and slaughter, measured as time fractions of suffering through a lifetime. Both life and slaughter fractions are calculated in relation to the animal's life expectancy and the respective durations in years. The slaughter fraction entails catching animals at the farm, transporting them to the slaughterhouse and keeping them until the moment of their death. The time suffered through milking during their entire lifetime is also considered for dairy cows. **Chapter 3 Appendices (Section S3, Table S7)** describes the LCI data sources, assumptions and calculations for each criterion in detail.

MAL measures the degree of animal awareness by establishing a *moral value* (mv), which depends on the animal's self-awareness and intelligence based on the neuron count and brain mass. This captures each animal's intrinsic value based on its sense of awareness and emotions related to its experiences (Phillips & Kluss, 2018). The *mv* is calculated by dividing the animals' biological values by the corresponding human's value (Scherer et al., 2018). When available, the *mv* includes the number of cortical neurons and the total number of neurons to predict intelligence between species, as suggested by (Herculano-Houzel, 2012). Since data are not always available, the *encephalisation quotient* (EQ) was additionally considered, often used as a proxy to compare intelligence across species, considering the *brain-to-body weight ratio* (Jerison, 1975) as shown in **Eq. 8-9**. The Appendices of Chapter 3 (Section S3, Table S8) provide further information related to calculation steps and assumptions.

$$EQ = brain\,weight\,(0.12 \times body\,weight^{0.67}) \qquad [8]$$

$$mv = \left((CNa/CNh) + (TNa/TNh) + (EQa/EQh)\right)/3 \qquad [9]$$

Where:

CNa: animal number of cortical neurons; CNh: human number of cortical neurons; TNa: animal total number of neurons; TNh: human total number of neurons; EQa: animal encephalisation quotient; EQh: human encephalisation quotient. Source: (Jerison, 1975; Scherer et al., 2018).

After deriving ALYS, AL, and MAL values per gram of animal product, these were used as input for calculating impacts derived from processed food items, such as meat and dairy products, and more sophisticated food preparations at the household level. Major data sources and assumptions for this conversion and associated intermediate impact values are detailed in the **Chapter 3 Appendices (Section S3, Table S9)**. “Other meat” refers to meat not elsewhere classified, i.e., veal, mutton and lamb. It was assumed that these animals have similar welfare conditions as sheep due to lack of data (Scherer et al., 2019).

3.3.3.3 Human health indicators

Human health indicators are based on nutritional quality indices using epidemiological studies proposed by Heller et al. (2013). These comprise a framework for health assessment on a diet level integrated into LCA by relating risk factors to underlying causes of death. The link between food intake in the LCI data and dietary risk factors was established similarly to Stylianou et al. (2016). Epidemiological data from the Global Burden of Disease (GBD) database were used as characterisation factors for human health impacts, expressed as %DALYs, i.e., the proportion of DALYs attributed exclusively to the dietary risk factors for each NCD (GBD 2019, 2020). DALYs are a measure of the years of life lost due to death or disability caused by a specific disease (Kirch, 2008). The GBD database provides country-level DALY values related to fifteen dietary risk factors for several diseases by gender (GBD 2019, 2020).

NCDs were assessed as indicators for food-consumption-related impacts on human health. Drawing from the GDB database (GBD 2019, 2020), the attributable percent of DALYs associated with each selected NCD by gender was estimated for Germany in 2019. In this study, only DALYs attributed to dietary risk factors were considered to represent the disease burden associated with dietary choices, while other risk factors (behavioural, metabolic) were not considered. The extracted data was filtered so that only risk factors that contribute more than 5% of the total disease burden of the particular disease were selected. As a result, the following NCDs were selected to indicate the human health impact of diet: a) cardiovascular diseases (ischemic heart disease and hypertensive heart disease); b) diabetes and kidney diseases (including diabetes mellitus type I and II); c) stroke and d) neoplasms (including colon, rectum, stomach, oesophageal and breast cancers).

Nutrients contained in the respective food products in Optimeal® are based on the European Food Composition Database (EFSA, 2019b). These data comprise 60 nutrients in total, including macronutrients and micronutrients, e.g., fibre and vitamin A, for over 2,500 food products, considering multiple preparation methods commonly practised in ten European countries (Broekema et al., 2019). Nutritional indices derived from food items consumed within the diets were qualified as dietary risk factor exposure to estimate the underlying diseases affecting human health, using optimal intake levels available in the GBD database. The optimal daily intake level and the reference diet intake values for both men and women are shown in **Table 2** (see **Table S10** in **Chapter 3 Appendices** for further details**)**.

Table 2. Dietary risk factor exposure optimal levels of daily intake and reference diet intake values for both genders in North Rhine-Westphalia

Dietary risk factor exposure	Optimal level of daily intake	Reference diet daily intake values	
		Women	Men
Diet high in processed meat (g/day)	< 0g/day	27.00 (-)	52.00 (-)
Diet high in red meat (g/day)	< 16.2g/day	49.15 (-)	95.55 (-)
Diet high in sodium (mg/day)	< 1000 mg	2608.73 (-)	3369.30 (-)
Diet high in sugar-sweetened beverages (kcal)	< 50 kcal	38.12 (+)	89.91 (-)
Diet high in trans-fatty-acids (E%)	< 0.5%	0.71 (-)	0.75 (-)
Diet low in polyunsaturated fatty acid (PUFA) (E%)	> 12%	6.13 (-)	6.12 (-)
Diet low in seafood omega-3 fatty acids (mg/day)	> 250 mg	708.68 (+)	841.18 (+)
Diet low in vegetables (g/day)	> 397 g/day	111.22 (-)	96.57 (-)
Diet low in legumes (g/day)	> 50 g/day	7.79 (-)	8.44 (-)
Diet low in fruits (g/day)	>312 g/day	257.22 (-)	209.46 (-)
Diet low in whole grains (g/day)	>113.4 g/day	57.48 (-)	73.80 (-)
Diet low in fibre (g/day)	> 30g/day	24.51 (-)	27.46 (-)
Diet low in nuts and seeds (g/day)	> 16.2 g/day	3.78 (-)	4.53 (-)
Diet low in calcium (mg/day)	> 1200 mg	945.10 (-)	1073.91 (-)
Diet low in milk (g/day)	> 490g/day	108.00 (-)	134.00 (-)

Note: Symbols (-) indicate the reference diet intake values are not within the optimal intake levels and constitute a risk exposure factor. Symbols (+) indicate the reference diet intake values are within the optimal intake levels, not constituting a factor for risk exposure (Afshin et al., 2019; GBD 2019, 2020).

3.4 Results

3.4.1 Impact results from the reference diets in NRW

The overall impacts resulting from the RD in NRW relate to the quantity of food consumed and the underlying food product choices. Men's diet shows higher impact values than women's because of the greater quantity of food consumed per FU and the larger share of high-impact food items. Notably, men consume 98 g/day of animal protein (i.e., meat and sausages), almost twice the amount observed in the women's reference diet (53 g/day). Moreover, men's consumption of beverages is relatively higher than women's; e.g., men consume almost six times the amount of beer (and similar beverages) consumed by women and 2.5 times the amount of sweetened soft drinks. In contrast, women consume much more milk, dairy, and fruits and vegetables than men, i.e., respectively, accounting for 7% and 10% of the total food consumed vs. 6% and 7%. Total animal-based or animal-containing products represent around 10-12% of the FU in both RDs while contributing to 27-29% of total energy intake in kcal. As described below, these products significantly contribute to environmental impacts, animal welfare loss and human health impacts.

Environmental impacts per FU are shown in **Figure 6**. Animal-based products (e.g., beef, sausages), ready-to-eat meals (e.g., soups) and other meat-based dishes (e.g., meatballs, meat stew) are among the five most common food items in both RDs. *Meat and meat products* and *ready-to-eat meals* contribute most to all environmental impacts. For instance, *meat and meat products* account for 22% and 29% of the climate change impact from men's and women's diets, respectively. In comparison, *ready-to-eat meals* account for 24% and 26% of it (**Fig. 6a**). Similarly, meat products account for more than 24% and 32% of the following impacts in women's and men's diets, respectively: fine particulate matter formation (**Fig. 6b**), terrestrial acidification (**Fig. 6c**), freshwater eutrophication (**Fig. 6d**), marine eutrophication (**Fig. 6e**) and land occupation (**Fig. 6f**). This is due to the animal feed production impacts in major exporting countries (mainly the United Kingdom, the United States, Brazil, India, and Pakistan) to supply intensive livestock systems (Durlinger et al., 2017b). After *ready-to-eat meals* and *meat and meat products*, the consumption of *fruit and fruit products* and *fruit and vegetable juices* is a significant cause of water consumption (**Fig. 6g**). Especially in women's diet, these product categories account for around 20% and 11% of the impact, respectively. Similarly, *milk and dairy products* account for between 14% and 18% of all environmental impacts in women's diets, compared to 8% and 13% in men's diets. *Ready-to-eat meals, meat and meat products,* and beverages (e.g., bottled water and beer) are also important contributors to fossil resource scarcity in both diets, mainly due to energy and raw materials consumption and packaging production, respectively (**Fig. 6h**).

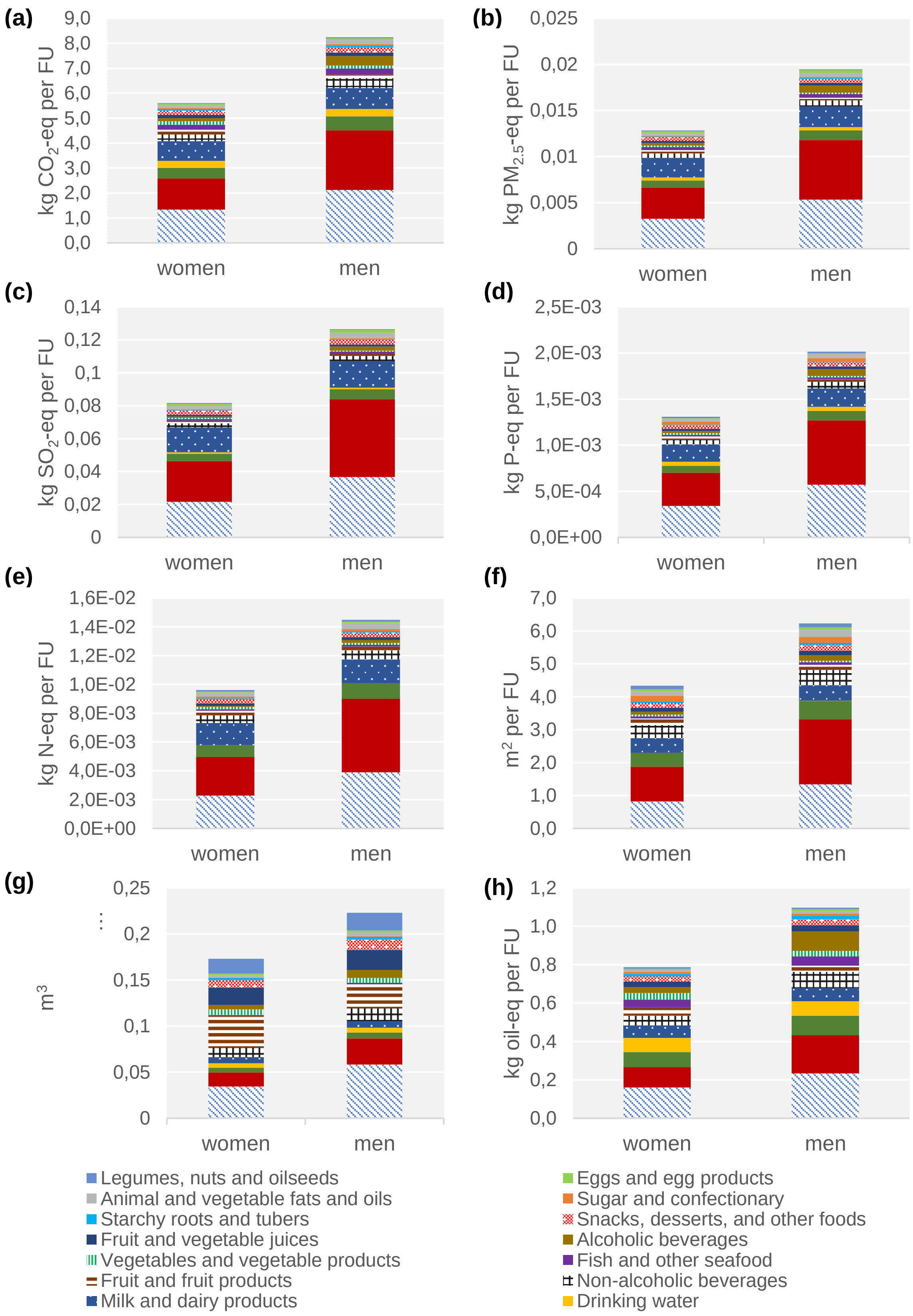

Figure 6. Environmental impacts of average diets in North Rhine-Westphalia per functional unit. (a) climate change; (b) fine particulate matter formation; (c) terrestrial acidification; (d) freshwater eutrophication; (e) marine eutrophication; (f) land occupation; (g) water consumption; (h) fossil resource scarcity.

As for animal welfare, men's diet performs worse than women's diet due to the overall preferences of the former for animal-based products. The products with the highest animal welfare loss intensity are *sugary and confectionery goods* and *fish and seafood*, as shown in **Figure 7**. This can be explained by the number of individuals affected per unit of product, e.g., 485 bees/kg of honey, 52.2 shrimps/kg of seafood or 2.2 fishes/kg of fish, as compared to 0.004 cows/kg of beef, 0.0092 pigs/kg of pork or 0.52 chickens/kg of chicken (see NAf in equations 1 to 3 and **Section S4** in **Table S11 and S12** in **Chapter 3 Appendices**). *Fish and seafood* – including shrimps, herring and salmon – account for around 81% of the ALYS in both diets (**Fig. 7a**). Sugary foods – including honey and candies with gelatine content – are associated with 76% and 81% of total AL losses (**Fig. 7b**); and 54% and 62% of MAL losses (**Fig. 7c**) in men and women's diets, respectively. *Meat and meat products* still make a significant contribution to MAL, accounting for 37% and 30% of it in men's and women's diets, respectively (**Fig. 7c**). This food group also represents between 5% and 10% of the estimated value of ALYS and AL (**Fig. 7a, b)** related to the consumption of other meat and poultry. *Milk, dairy products, and chicken eggs play a minor role in* ALYS and AL (**Fig. 7a, b**).

Figure 8 shows human health impacts as DALYs are broken down by dietary risk factors across several NCDs by gender. The men's reference diet is associated with higher DALYs across the considered NCDs, except for oesophageal and breast cancers. However, both RDs do not entirely fall within the optimal intake levels; hence, these pose a dietary risk. Only the intake of omega-3 (in both diets) and sweetened beverages (in women's) are in line with the optimal levels. As a result, the observed unbalanced diets pose a health risk of developing chronic diseases. Although the loss of DALYs attributable to dietary risk factors is gender-dependent and based on epidemiological studies, significant differences between both diets can be observed. Dietary risk factors exposure per FU is more frequent in men than women, delivering a greater loss of potential healthy years. The prevalent NCDs in both men's and women's diets are cardiovascular diseases, especially ischemic heart disease. A large proportion of DALYs arises from the low intake of legumes and whole grains and the high intake of sodium and trans fatty acids. The latter is mainly associated with consuming bread and butter/margarine, pastries, ready-to-eat meals and processed meat (i.e. sausages). Specifically, dietary risk factors pose health risks of 0.802 and 0.666 DALYs for ischemic heart diseases for men and women, respectively, while 0.503 and 0.348 DALYs are linked to all cardiovascular diseases. Likewise, the total burden of diabetes type I and type II (higher in men's diet) ranges between 0.271 and 0.463 DALYs for both genders, attributed to a high intake of processed meat and red meat. Stroke is associated with more than 0.25 DALYs due to a higher intake of red meat and sodium for both diets. DALYs related to colon and rectum cancer are also significant for both genders (between 0.438 and 0.464), mainly due to the low intake of whole grains and milk.

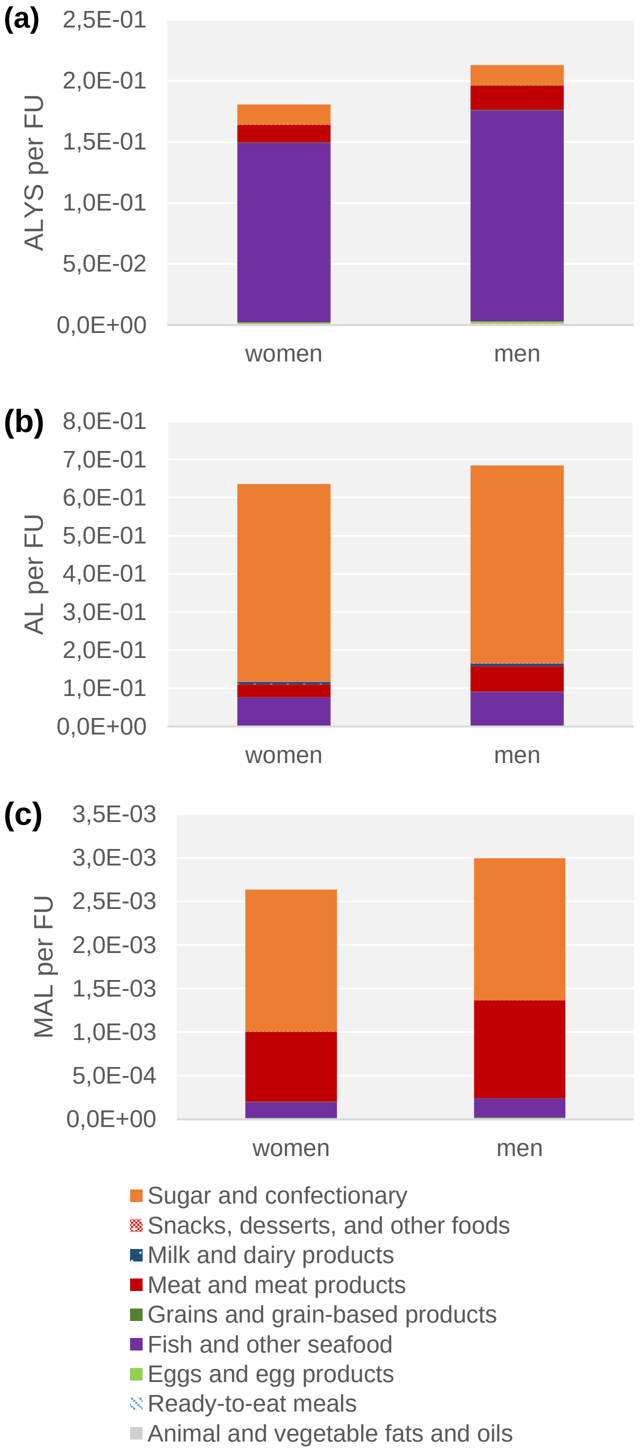

Figure 7. Impacts on animal welfare of average diets in North Rhine-Westphalia per functional unit. (a) Animal Life Years Suffered (ALYS); (b) loss of Animal Lives (AL); (c) loss of morally adjusted Animal Lives (MAL).

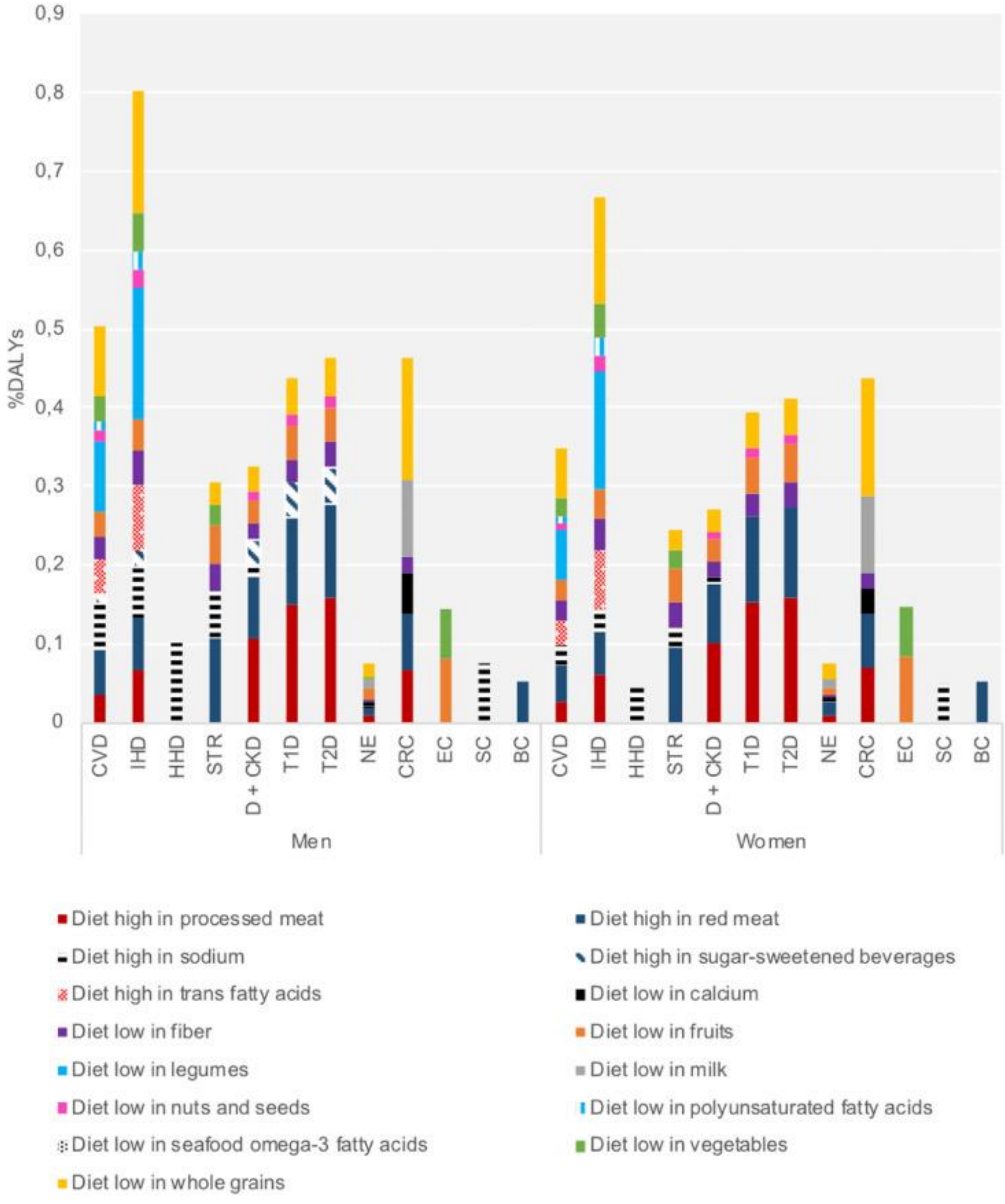

Figure 8. Impacts on human health, by gender, in North Rhine-Westphalia in percent Disability-Adjusted Life Years (%DALYs) attributed to several non-communicable diseases (NCDs) due to the chronic exposure to dietary risk factors caused by the consumption of the FU over a lifetime. CVD: cardiovascular diseases; IHD: ischemic heart disease; HHI: hypertensive heart disease; STR: stroke; D + CKD: diabetes and chronic kidney diseases; T1D: type I diabetes; T2D: type II diabetes; NE: neoplasms; CRC: colon and rectum cancer; SC: stomach cancer; EC: oesophageal cancer; BC: breast cancer.

3.4.2 Impact results from alternative dietary scenarios

As shown in **Figure 9**, all alternative dietary scenarios decrease most environmental impacts relative to the RD in NRW – see Section **S4 Table S16** in **Chapter 3 Appendices** for further details. For instance, DD and MD decrease climate change impacts by 20-30%. In comparison, the impact is more than 50% lower in the VD (**Fig. 9a**). Other impacts such as terrestrial acidification (**Fig. 9c**), freshwater eutrophication (**Fig. 9d**), marine eutrophication (**Fig. 9e**), land occupation (**Fig. 9f**) and fossil resource scarcity (**Fig. 9g**) also decrease significantly. This is mainly due to the reduced consumption of *ready-to-eat meals*, *meat and meat products* in the alternative diets relative to RD, combined with the increased consumption of *vegetables*, *grains and grain-based products*, *legumes, nuts and seeds* (see **section 3.4.1**). However, trade-offs arise for other environmental impacts, such as water depletion, which is 28% and 80% greater in the MD and VD, respectively. This is due to the higher consumption of *legumes, nuts, seeds* (e.g., almonds, nuts, hazelnuts), *fruits* (e.g., strawberries and peaches), and *vegetable fats and oils* (e.g., olive oil) in both diets.

Trade-offs are also observed among animal welfare indicators. For instance, DD and MD lead to a reduction in AL of around 17%- 21% in men’s dietary scenarios and of more than 80% in women’s (**Fig. 9j**). A reduction of between 30% and 70% in MAL is also observed in both men's and women’s scenarios (**Fig. 9k**), due to the reduction of sugary foods consumption. On the contrary, the MD implies a more than three-fold increase in ALYS in men’s scenarios, relative to RD, due to the substantial fish intake. At the same time, DD decreases ALYS by only 1% (**Fig. 9i**). It must be noted that the optimisation to define alternative dietary scenarios generated minor changes in food consumption quantities in DD compared to RD (see **Table S16** in **Chapter 3 Appendices**). In contrast, the MD results in much larger amounts of fish and seafood – i.e., shrimps, salmon, trout, and herring – to meet the dietary and nutritional constraints (see **section 3.3.2.1**).

The three alternative dietary scenarios also yield reduced impacts on human health, translating into health benefits (**Fig. 9l**) – see Section **S4 Table S15** in **the ESM**. All alternative diets significantly decrease DALYs (between 27% and 73%) linked to several NCDs, namely cardiovascular diseases, ischemic heart disease, stroke, colon and rectum cancer, and diabetes type II. VD causes the lowest exposure to dietary risk factors and, hence, the most negligible impact among all diets. However, there is still the risk of developing hypertensive heart disease and stomach cancer in both men and women due to the high intake of sodium observed in VD as well as in DD and MD. DD and MD also show a significant contribution to total DALYs for diabetes type I and II and colon and rectum cancer; this is greater than in VD due to the higher intake of red and processed meat and low intake of calcium and milk. The DD, considered a national reference for a healthy diet, constitutes a decrease of around 30% in most NCDs relative to the RD in NRW. However, DD causes a higher impact on human health than MD and VD, mainly because the selection of products is more similar to RD than in the other two alternative scenarios. However, the intake of fruits, vegetables, and whole grains is still below optimal levels despite the increase.

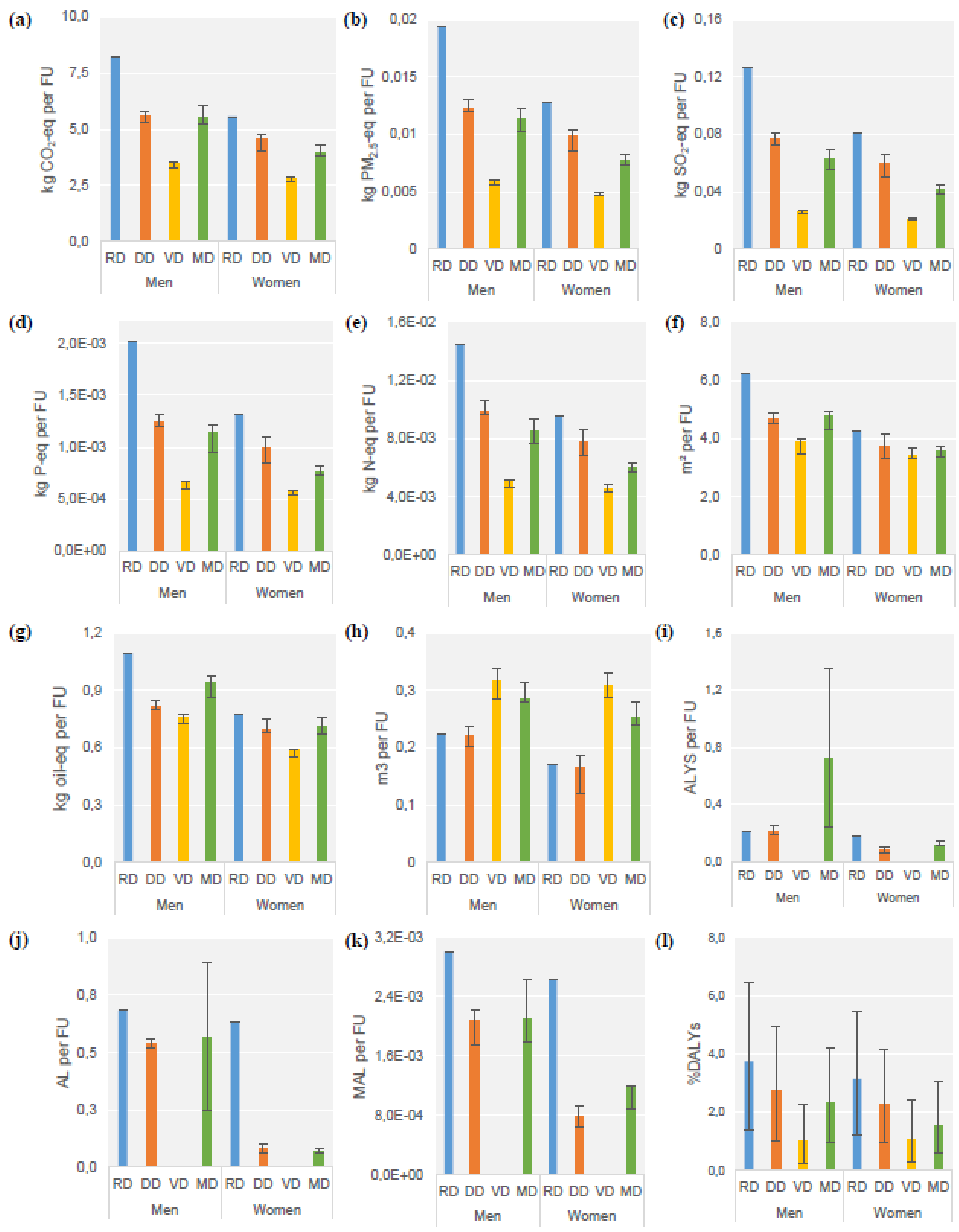

Figure 9. Impacts on the environment and animal welfare of alternative diets to the reference diet in North-Rhine Westphalia. Reference diet (RD), recommended diet by the German Nutrition Society (DD); vegan diet (VD) and Mediterranean diet (MD). (a) climate change; (b) fine particulate matter formation; (c) terrestrial acidification; (d) freshwater eutrophication, (e) marine eutrophication, (f) land occupation, (g) water consumption, (h) fossil resource scarcity; (i) Animal Life Years Suffered (ALYS), (j) loss of Animal Lives (AL); (k) loss of Morally adjusted Animal Lives (MAL); (l) Impacts on human health from all non-communicable

diseases assessed in %DALYs attributed to the chronic exposure to dietary risk factors caused by alternative diets to the reference diets (RD) in North-Rhine Westphalia, of both men and women.

3.5 Discussion

3.5.1 Sustainability assessment under the OH approach

This study expands the traditional LCA framework with quantitative indicators on animal welfare and human health to measure the sustainability of Western diets and potential improvements driven by dietary shifts, considering all dimensions of the OH concept. Applying the framework to the case study of NRW shows that shifting to any of the assessed alternative scenarios (DD, MD and VD) would yield improvements in most indicators assessed. However, a few trade-offs arise, i.e., higher water consumption in VD and MD or higher ALYS in MD relative to RDs. This is mainly due to changes in the diet composition (or *basket of products*), leading to slightly smaller amounts of total food consumed in the alternative dietary scenarios and fewer calories than the RD. This can imply that following the dietary reference energy values for a healthy and balanced diet – according to EFSA dietary reference values (EFSA, 2019a) – can also translate into environmental benefits. Evaluating FUs other than mass-based (e.g., energy- or nutrition-based) could provide a complementary standpoint on dietary shifts (Green et al., 2020; McAuliffe et al., 2020). Although it is not clear if the actual biological function of food is fully represented in energy- or mass-based FUs, this study takes a similar approach to that applied by the European Commission (i.e., based on the basket of products at the country level), which works as a compromise solution to assess large food consumption systems (Castellani et al., 2019; Notarnicola, Tassielli, et al., 2017; Sala, Beylot, et al., 2019). However, this approach for the FU definition entails challenging issues such as how to capture the nutrition provision of food or other essential cultural and social values (Notarnicola, Sala, et al., 2017; Sala, Benini, et al., 2019; Sala, Beylot, et al., 2019). Besides the nutritional quality, sustainable diets should reckon with socio-economic dimensions of food consumption and food product (un)affordability for socially disadvantaged groups (Batlle-Bayer et al., 2020). In the case of NRW diets –mainly capturing middle or upper classes – women were relatively socially disadvantaged in employment status and income within the population for the nutrition survey (Max Rubner Institut, 2008).

Despite the trade-offs mentioned earlier, reducing animal-based products contributes greatly to lower environmental impact values for most indicators in RD, MD and VD. These results are aligned with many LCA studies evaluating the contribution of animal-based products to environmental impacts such as climate change (Batlle-Bayer et al., 2020; Bruno et al., 2019; Heller et al., 2018). According to (Sandström et al., 2018), the share of animal-based products within a diet is a good measure of its environmental footprint. This study also shows that Western diets typically cause greater impacts than vegetarian options (Chapa et al., 2020; Goldstein et al., 2016). Within the EU context, reducing meat (especially beef) and dairy products could remarkably reduce several consumption-based environmental impacts and improve human nutrition (Beylot et al., 2019; Chaudhary et al., 2018; Sala & Castellani, 2019; Sandström et al., 2018). Moreover, this study reveals that high consumption of other animal-based products, such as fish and honey, can worsen animal welfare outcomes based on the indicators from Scherer et al. (2018). In this sense, normalisation and weighting among OH dimensions could help identify more sustainable diets, but this requires arbitrary choices and remains an open challenge in LCA (Hélias & Servien, 2021; Roesch et al., 2020).

Although LCA case studies assessing animal welfare are scarce, outcomes from this study are consistent with the framework of Scherer et al. (2019, 2018), which attributes higher impacts to small animals. This captures how, for instance, the treatment of fish and seafood in industrial aquaculture can be highly unethical, with a scale of damage greater than the suffering in conventional land-based animal farms (Berlinghieri et al., 2021; Rodríguez, 2010). The concerns on the relation between fish welfare, profitable production and the increase of the mortality rate among farmed fish over the past years remain an open ethical question (Størkersen et al., 2021). Acute and chronic stressors, high stocking densities and environmental conditions (i.e., water acidity) in aquaculture systems generate social, swimming, and foraging behaviour changes (i.e., aggressiveness and competition), as well as neurological, physiological and physiological effects by decreasing health conditions with injuries, diseases, parasitic infestations (i.e., fish lice); which overall translate into an increased mortality rate (Jensen et al., 2020; Berlinghieri et al., 2021; Størkersen et al., 2021; Toni et al., 2019). Although the neural structure for the phenomenal consciousness of fish and shrimps withdraws the full experience of physical pain (Key, 2015), there is enough evidence on the development of learning mechanics to avoid unpleasant experiences, indicating sensation of pain (Braithwaite, 2010; Sneddon, 2015). Similarly, the lifespan of honeybees is dramatically reduced in intensive honey production systems, especially during the summer when honey production peaks (Litmann et al., 2016; Schroeder, 2014). It should be highlighted that the potential ecological benefits of beekeeping, including the provision of ecosystem services like pollination, are not considered in this study but should be considered for further sustainability assessments (Gaines-Day & Gratton, 2016; Vrabcová & Hájek, 2020).

Notably, the RD in NRW is more detrimental to human health than the proposed alternative dietary scenarios. Two main factors contribute to diabetes and CVD: a high intake of animal-based and energy-dense foods combined with a low intake of plant-based foods. Several studies report the association of red meat intake with a higher risk of metabolic syndrome, obesity and diet-related NCDs, including coronary heart disease, stroke, and diabetes mellitus (Azadbakht & Esmaillzadeh, 2009; Micha et al., 2010; Rouhani et al., 2014). The use of dietary risk factors is a good measure of human health's impact, in which vegetarian meals present a lower disease burden than meals containing meat (Weidema & Stylianou, 2020). Additionally, women's diets turned out to be more aligned with healthier standards than men's, corroborating results from earlier German studies (Meier & Christen, 2013; Treu et al., 2017). Another important aspect to consider is alcohol intake. Although the GBD considers alcohol consumption as a behavioural risk factor (i.e., not as a dietary risk factor), alcoholic beverages are part of dietary patterns, especially among men and younger segments of the population (Nasreddine et al., 2021; Wilsnack et al., 2009). Alcohol consumption has been associated with stroke, some types of cancers and other disorders (GBD 2019, 2020).

Depending on the impact on target reductions, more specific dietary scenarios could be developed or designed adequately for particular population groups and geographical locations (Hallström et al., 2015). Sustainable consumption patterns and consistent target reduction standards, proper site monitoring and communication along the supply chain are part of solutions to reduce impacts derived from food production and consumption effectively (Poore & Nemecek, 2018). The dilemma between sustainability and economic performance arises when rethinking the dietary implications of shifting from animal- to plant-based options (Marques et al., 2018). Strategies along the food chain, such as technological improvement towards mitigation of environmental impacts and food waste reductions, should align with socioeconomic development and consumer-oriented strategies (Notarnicola, Sala, et al., 2017; Springmann et al., 2018). The effectiveness of supply-side measures is limited if consumers keep choosing high-impact products (Poore & Nemecek, 2018). However, influencing consumers' choices entails a substantial challenge to simplify communicating multi-dimensional sustainability outcomes from complementary analyses, enhance education, dialogue and public awareness (Helander et al., 2021; Potter & Röös, 2021). A sustainable development path towards changing consumption patterns within the EU requires an overall decoupling of environmental impacts from economic growth, combining sustainability metrics and economic indicators that could easily be integrated into decision-making (Sanyé-Mengual et al., 2019).

3.5.2 Methodological limitations and societal implications

Integrating the OH approach into LCA of food diets poses additional methodological challenges and limitations. The first relates to data availability and representativeness, as detailed and updated data on food consumption is not always available at sub-national scales, even within the EU context. The need to use the National Nutrition Survey (NVS II) (Max Rubner Institut, 2008) the most recent and comprehensive data on food consumption at the German federal-state level is a clear example. Hence, bottom-up LCA implies making assumptions to fill data gaps, which requires additional national-level data from Treu et al. (2017). Subjective choices applied to allocating specific products into major food categories are associated with uncertainty. On the one hand, the RD might overlook important aspects of food insecurity by omitting unintentionally vulnerable groups from the surveys (Pfeiffer et al., 2015). On the other hand, Optimeal® relies on FAOSTAT data to estimate the crop mix and the origin of products from 2009 to 2013. Yet, these data can still represent the prevailing food consumption habits in NRW. Despite data gaps, taking a sub-national scope can help assess the sustainability implications of diets, especially for large and heterogeneous countries like Germany, as food consumption is subject to geographical and socio-economic variabilities (Mertens et al., 2018). For instance, in Germany, recent data shows that the observed decrease in meat consumption is related to dietary shifts towards more plant-based options, driven by sustainability concerns (BMEL, 2021; Davis & Geiger, 2017; Pfeiffer et al., 2015). Therefore, it is recommended to gather regional life cycle inventories through primary data as far as possible to capture both spatial and temporal variability in food consumption (Heller et al., 2018). However, this poses enormous data collection challenges that justify the scarce literature on bottom-up LCA case studies of diets based on primary data. When collecting survey data on diets, it is essential to capture gender and age factors and underlying relationships between food consumption habits and sustainability outcomes.

The present study performs uncertainty analysis through Monte Carlo simulation to understand the variability of results due to the variability in food consumption in alternative diets. Substantial results uncertainty is still expected from using average LCIs and impact-intensity results per food item in Optimeal® (Broekema et al., 2019). Depending on the country of origin of respective food products and underlying production and transportation systems, these may not represent spatial and temporal variability in upstream impacts. However, the methodology applied by Optimeal® avoids the need to carry out an LCA per each food product included in the respective diets. At the same time, it is broadly consistent with the PEF framework. It must be noted that impacts from land transformation or LUC-related emissions are not included, which are intrinsically linked to deforestation and soil degradation occurring mainly in developing countries that export agricultural commodities to high-income countries (Crippa et al., 2021). This is a significant driver of LUC emissions embodied in consumption-based German footprints when considering international agri-food trade (Escobar et al., 2020; Sandström et al., 2018). Including LUC would imply the application of consequential LCA approaches to predict price-mediated changes, which requires economic modelling and is out of the scope of the present attributional LCA. The overall environmental impact derived from food consumption at the regional level might be even higher if the diets include consumption in other sectors (outside the household), such as gastronomy, tourism, education, social, and health care services (Beylot et al., 2019). It must also be noted that system boundaries do not include end-of-life (e.g., human excretions, wastewater treatment), which generate additional environmental burdens (Notarnicola, Tassielli, et al., 2017). Including food waste disposal is especially key in addressing overall food systems' sustainability and the implications of EU food waste reduction strategies (Esposito et al., 2016; European Commission, 2017; Helander et al., 2021). Several studies propose new methods to estimate waste along the supply chain in the EU, underlining the importance of improving the evaluation of critical sectors from processing to the household, where plant-based foods are mostly wasted (i.e., cereals, fruits and vegetables) (Caldeira et al., 2019, 2021; De Laurentiis et al., 2020).

Human toxicity impacts were not assessed among the environmental impact categories due to the limitations of the dataset, which does not consider pesticide production and use within the system boundaries. In any case, toxicity impacts are product-specific and influenced mainly by climatic conditions, hindering the consideration of large-scale LCAs in food systems. Human toxicity (cancer- and non-cancer-related) impacts from food consumption have been mainly linked to metal particle emissions from agriculture and food products (Beylot et al., 2019). Human toxicity estimation in LCIA could benefit from more sophisticated non-linear characterisation methods to determine human health impacts caused by emissions and exposure to pollutants and chemicals throughout the life cycle (Li et al., 2020). Additionally, the DALY indicator considers human health burden implications without looking into potential health benefits from nutrition, even though nutrients and food items (or the lack thereof) can be a risk factor to human health. For example, nutrient profiling and scores qualify and disqualify nutrients from meeting quantity, quality, and satiety (Weidema & Stylianou, 2020). Refined human health indicators could potentially be applied in LCA, such as "DALY-Nutrition-Index", to assess DALYs per individual food item (or meal) as nutrition-health damage at the endpoint level (Weidema & Stylianou, 2020). Other examples include the "Nutrient-Rich Foods Index

9.3", "Nutritional Quality Index", and "Fullness Factor™" to assess several nutrition-FUs in terms of nutrition quality and satiety (Chapa et al., 2020).

The lack of standardised metrics on the impacts on animals in LCA makes it challenging to measure animal welfare quantitatively (Notarnicola et al., 2017). Including animal welfare indicators in LCA raises ethical considerations, where the complexity and inconsistency of comparable data and scientific consensus make the analysis even more challenging (Tallentire et al., 2019). The whole issue on the criterion *number (of animals) affected* implies discussing the absolute number of lives lost versus the animals' utility to humans. As Arrhenius et al. (2017) explain whether the methods should be revised or improved, or more consensus on ethical questions should be given to the worthiness of living for animals whose purpose is human food production. Indeed, a more scientific or ethical consensus is required to justify animals' moral treatment and agree on a better definition of an absolute animal welfare measurement (Phillips & Kluss, 2018; Tallentire et al., 2019).

3.6 Conclusions

This study proposes integrating the OH into an extended LCA to assess the sustainability of dietary patterns in NRW (Germany), aiming to identify more sustainable food consumption options for typically Western diets. The RDs of both men and women are compared to alternative scenarios designed to represent a shift towards healthier dietary patterns using quadratic optimisation. Although trade-offs arise, the three scenarios deliver sustainability gains relative to the reference NRW diet. On the one hand, replacing animal-based with plant-based protein sources can increase water consumption. On the other hand, a higher consumption of animal-based products such as fish, seafood and honey has negative implications for animal welfare, given the larger number of animals suffering. This highlights the role that the choice of animal-based products plays in the overall sustainability of Western diets from a OH perspective. Regardless of the selection of animal-based protein sources, the greater the share of plant-based foods, such as fruits, vegetables, legumes and whole grains in a diet, the greater the associated human health benefits. Moreover, reducing consumption of ready-to-eat meals and highly processed foods is clearly recommended to simultaneously improve the health of humans, animals and the environment.

Implementing systemic approaches such as OH into LCA comes with many methodological challenges derived from the availability of reliable and comprehensive food consumption statistics, associated LCI data and LCIA methods. This study highlights the need to a) provide comprehensive LCI data in commercial databases that capture spatial variability in agri-food production systems globally; b) develop consensus-based LCIA methods for animal welfare and diet-related human health indicators; and c) make information on consumers' choices available for facilitating forward-looking assessments of supply- and demand-side impact mitigation measures at different geographical scales. As for the estimation of animal welfare, commercial LCI databases must include data on farm conditions, animal health and well-being, which is still scarce and scattered and often confidential. Additionally, ethical and societal aspects emerge, which may require the application of complementary methodologies, given the lack of scientific consensus and comparable quantitative indicators. Improving OH approaches to LCA could greatly benefit from interdisciplinary collaboration between life and social sciences to tackle human and natural complexities. Considering other life cycle stages such as LUC and end-of-life, it is desirable to estimate the impacts of Western diets from cradle-to-grave and inform decision-making in the EU towards the EU Green Deal and the Sustainable Development Goals. Yet, communication of outcomes to influence consumers' choices remains incredibly challenging in multi-dimensional sustainability assessments like the one proposed by this study from a OH perspective.

4 Optimised diets for improving human, animal, and environmental health in the Rhine-Ruhr Metropolis in Germany

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4.1 Abstract

Dietary shifts are needed to align the global food systems with the planetary boundaries and contribute to Sustainable Development Goals. We employed a Life Cycle Assessment (LCA) framework, extended with indicators on human health and animal welfare, to assess 2020 food consumption data (N=189) collected through an online survey in the Rhine-Ruhr Metropolis (Germany). Feasible optimisation scenarios representing alternative sustainable choices towards overarching environmental, societal and policy goals were explored. Meat and meat products contributed most to overall environmental impacts (e.g., climate change, terrestrial acidification), and fish and seafood to animal welfare loss (e.g., animal lives lost, animal life years suffered). Sodium intake was the most contributing risk factor for life minutes lost. The combined optimisation scenario reduces 55% of greenhouse gas emissions, improves human health indicators by 25% and reduces animal welfare loss substantially (52-97%). This is possible with a shift towards flexitarian and vegetarian dietary scenarios. Although the sample is not representative of the entire population, optimisations deliver sustainability improvements with few changes in dietary scenarios. The extended LCA framework can assess the implications of food consumption towards One Health, provided that further indicators on animal health are developed.

4.2 Introduction

Global food production and consumption are heading beyond safe planetary boundaries, and urgent transformations are necessary to ensure food security and climate change mitigation (Aiking & de Boer, 2020; Gerten et al., 2020). Food systems are increasingly altering ecosystems while causing unprecedented global health burden, including communicable and non-communicable diseases (NCDs) (Ridoutt et al., 2021; Talukder et al., 2022). The UN Food Summit emphasised the need for profound dietary changes for a sustainable future for better human, animal, and ecological health (UN, 2021a; von Braun et al., 2023). Consequently, diets should shift towards more environmentally sound, healthy and ethical consumption patterns that respect planetary boundaries, acknowledging regional differences and socio-cultural values (Vanham et al., 2021).

The European Union's (EU) Green Deal aims to reduce greenhouse gas emissions (GHGE) by 55% in 2030 by transforming the EU food systems (European Commission, 2021b). The EU's Farm to Fork Strategy targets both consumption and production, focusing on environmental and socioeconomic aspects (European Commission, 2020). While EU consumers are becoming more aware of sustainability issues, meat remains relatively cheap and widely available in the food basket (de Boer & Aiking, 2022). In Germany, Western diets high in animal-sourced foods intake predominate, with a total meat supply quantity of 78.9 kg/capita/yr. in 2020 (FAOSTAT, 2023; Helander et al., 2021). The Rhine-Ruhr Metropolis is a densely populated urban area in the federal state of North-Rhine-Westphalia (NRW), one of Germany's leading poultry and pig livestock producers (Deblitz et al., 2022). Nevertheless, concerns have been raised towards agricultural sustainability, animal welfare labels and nutrition (BMEL, 2020a). Developing sustainable solutions and investigating various dimensions encompassing the transformation of urban food systems is important.

Life Cycle Assessment (LCA) is a widely used tool to assess the sustainability of food consumption, compare diets, and support the baseline for alternative scenarios (Heller et al., 2013). While LCA focuses primarily on environmental aspects, more comprehensive sustainability assessments warrant further investigation involving multiple societal dimensions (Nemecek et al., 2016). Progressively, more studies have explored other dimensions, including human health and animal welfare (Jolliet, 2022; Scherer et al., 2019). These indicators intersect the One Health (OH) approach, which combines the health of humans, animals and the environment as essential for transitioning towards more sustainable food systems (Angelos et al., 2017). Although studies scrutinise OH toward the classical approach, narrowing it down to the human-animal interface zoonotic transmission (Lebov et al., 2017), other studies emphasise an extended approach, incorporating environmental interactions, chronic diseases, mental health and wellbeing (Falkenberg et al., 2022; Schmiege et al., 2020).

A recent study integrates animal welfare and human health indicators into an extended LCA framework (Paris et al., 2022a). However, estimating human health impacts is challenging due to the lifetime risk exposure at the population level versus individual daily food intake (Paris et al., 2022b). The "Health Nutritional Index" (HENI) estimates the marginal human health burden attributed to food intake in a single score, facilitating the link between population-level health burden and daily food intake (Stylianou et al., 2021). A few studies applied HENI to assess the health implications of food consumption (Jolliet, 2022; Pink et al., 2022). However, the potential of HENI to assess diets from a multidimensional LCA perspective remains underutilised (Thoma et al., 2022). Moreover, animal welfare is often neglected in LCA, with few exceptions, despite the relevant public concern towards animal farm conditions (Bonnet et al., 2020). Animal welfare is a complex societal issue intrinsically interconnected with human well-being and the environment at different levels (de la Torre García, 2017). Beyond public and political appraisal, animal welfare moves consumer expectations to more ethical production systems, especially in Germany (BMEL, 2020a).

Still, it remains challenging to influence consumer choices as consumption decisions are based mainly on satiety, affordability and cultural values (Batlle-Bayer et al., 2020; Ridoutt, 2021). That is why some studies implement diet optimisation to assess the effects of dietary changes. Optimisation calculates optimal dietary scenarios fulfilling determined sustainability and nutritional criteria closest to actual dietary behaviour, thus being more feasible for individuals to adhere (Kramer et al., 2018; Tyszler et al., 2016). Optimising self-reported dietary practices captures more representative and realistic food choices, identifying minimal dietary changes to achieve sustainability goals, ideally at a sub-national level (Vieux et al., 2022).

Our study aims to optimise the sustainability of dietary patterns in a metropolitan region in Germany using an extended LCA framework combining environmental, human health and animal welfare dimensions. Food consumption data was collected in 2020 via online questionnaires disseminated among inhabitants in the Rhine-Ruhr Metropolis. Three dietary patterns were observed: Prudent, Western type 1 and Western type 2. Four optimisation scenarios representing alternative sustainable choices towards overarching environmental, societal and policy goals were explored: i) reducing GHGE by 55%, ii) zero animal welfare loss, iii) improving health indicators by 25%, and iv) combined scenario. Overall, we aim to identify more effective scenarios in reducing impacts from food consumption towards more sustainable dietary choices, considering the trade-offs among the dimensions.

4.3 Methods

4.3.1 Study design

The study developed an online data collection method adapted to the pandemic between June 2020 and January 2021. Participant recruitment was done extensively via social media networks, community digital networks, and postcards with QR codes advertised in commercial and residential areas within the Rhine-Ruhr Metropolis. This metropolitan region is located in NRW, composed of 21 cities ("*kreisfreien Städte*") and 15 districts ("*Kreise*") with approximately 14 million inhabitants (Destatis, 2022b; IKM, 2021). The area is one of the largest conurbations in Europe, economically relevant as an industrial pole and innovation hub and has recently progressed to become the greenest metropolitan region in Germany (Goess et al., 2016).

Participants of 18 years of age or older completed a general survey on demographics and a validated and cost-effective food frequency questionnaire EPIC II (FFQ) (Nöthlings et al., 2007), developed by the German Institute of Human Nutrition Potsdam-Rehbrücke (Harttig, 2021). Participants under 18 were withdrawn from the study. A written informed consent was provided digitally by recruitment. The Research Ethics Committee, Center for Development Research at the University of Bonn approved ethical clearance. 189 participants (N=189) filled out the FFQ, and 183 completed the socio-demographic survey. The study population is majority female, German, 44 years old on average, highly educated, with an average monthly income of Int$ 5,956 ± 370 (see **Table S1** in **Chapter 4 Appendices**).

4.3.2 Life Cycle Assessment: goal and scope

This LCA study follows the framework proposed by Paris et al. (2022a), based on the ISO14040/44:2006 (ISO, 2006a, 2006b). The system boundaries included crop and animal production, transport of raw materials, processing, packaging production, distribution, retail, consumption, transportation between sub-stages, food losses and waste and food packaging disposal (**Figure 5, Chapter 3**). Waste management and disposal were excluded. Economic allocation was assumed when different co-products were obtained with the same process (European Commission, 2018), except dairy, which follows the International Dairy Federation guide that applies physical allocation among meat and feed, and dairy co-products (skimmed milk powder, cream and milk fat derivates) (Broekema et al., 2019; International Dairy Federation, 2016). Cut-off criteria were applied for a few co-products (citrus pulp, brewer grain, animal manure, and nutshells) due to their low economic value (Broekema et al., 2019). Emissions from land-use changes (LUC) were not covered, as these require modelling techniques to simulate future land transformation caused by future food demand changes.

4.3.3 Life Cycle Inventory (LCI)

4.3.3.1 Food data

The FFQ estimates daily food and nutrient intake over the last 12 months, categorised into 19 major food groups, including diversified food items and beverages. The quantities of specific food items within respective food categories were estimated using food frequencies. The LCI food data was based on the EFSA food and nutrient database (EFSA, 2018b, 2019b). The mapping of food items consisted of reallocating into different food categories, renaming, allocating into the most representative food item within the group or reallocating to proxies. Due to their intake representativeness, 13 food items were added: avocado, broccoli, cherries, decaffeinated coffee, dried fruits, figs, game meat, grapes, olives, rabbit meat, soymilk, tofu and zucchini. For these, LCI was complemented with the EFSA food composition data (EFSA, 2019b), nutrient intake in g/day from the FFQ and other sources (RIVM, 2021) — further details on assumptions are in **Table S2** in **Chapter 4 Appendices**.

Factor analysis was conducted in IBM SPSS v.28.0 (IBM Corp, 2021) over the inter-correlation between food intake, food items and categories to identify patterns in food consumption. The dietary patterns were defined by clustering average group linkages and grouping together the cases within specified patterns. Three distinct dietary patterns were observed within the sample *N=189*: (a) **Prudent (PRU)** (n=73), (b) **Western-type 1 (WT1)** (n=60), and (c) **Western-type 2 (WT2)** (n=56) (**Table S3** in **Chapter 4 Appendices**). PRU (1,897 kcal) has a high intake of fruits, vegetables, and animal protein substitutes, with low animal protein intake. WT1 (1,867 kcal) has a high intake of meat, grains, eggs and alcoholic beverages. WT2 (2,240 kcal) is high in dairy products, fish, eggs, grains, and processed snacks. The average daily intake per person was the functional unit used to compare the observed diets, estimated at 3.44 kg, 2.73 kg, and 3.57 kg of food for PRU, WT1, and WT2, respectively.

4.3.3.2 Inventory data

The environmental background data was available in the software Optimeal® (Broekema et al., 2019), which aggregates impact values and nutrients per 100 g of food product from *farm-to-fork.* This LCI used SimaPro, based on the Agri-footprint 4.0 methodology, and additional data sources in agricultural production, transport, and processing (Durlinger et al., 2017b, 2017a). Energy and water use followed the Product Environmental Footprint (PEF) Guidance 6.3 (European Commission, 2018). Agricultural products' origin considered import mix and underlying transport distances for raw materials, based on FAOSTAT agri-food trade data and additional statistics (Broekema et al., 2019; FAOSTAT, 2013). The transport of raw materials between each sub-stage included the different transport modality features (road, rail, water, and air) (Broekema et al., 2019). Packaging production was based on the Ecoinvent 3 (Wernet et al., 2016) and the ELCD databases (JCR-IES, 2012). The distribution and the retail were modelled as per the PEF Guidance (European Commission, 2018), considering the energy use during the storage time and food losses at the retailer. The consumption level considered energy use for several cooking methods, raw-to-cooked ratio, and food losses (European Commission, 2018). The disposal of packaging material was modelled in the European context using the Ecoinvent database 3.4 (Wernet et al., 2016). Impact values per 100 g of the extra 13 food items were added using data from existing literature. LCI data sources and assumptions in estimating environmental impact categories for food items are in **Table S4 in Chapter 4 Appendices**.

4.3.4 Life Cycle Impact Assessment (LCIA)

The environmental dimension was assessed with eight environmental impact categories at the midpoint level, according to the ReCiPe 2016 characterisation method, in line with the recommendations of the Product Environmental Footprint (PEF) (European Commission, 2018; Huijbregts et al., 2017). The indicators are fine particulate matter formation [kg $PM_{2.5}$ eq]; fossil resource scarcity [kg oil eq]; freshwater eutrophication [kg P eq]; global warming [kg CO_2 eq]; land use or occupation [m^2a crop eq]; marine eutrophication [kg N eq]; terrestrial acidification [kg SO_2 eq] and water consumption [m^3].

Three animal welfare indicators represented the animal health dimension: "Animal Life Years Suffered [ALYS]", "loss of Animal Lives [AL]", and "loss of Morally Adjusted Animal Lives" [MAL], following the proposed framework by Scherer et al. (2018). ALYS represent the loss of quality of life attributed to farming conditions considering German minimum requirements, including improved standards. AL captures premature death and suffering through slaughtering within the EU context. MAL measures the degree of animal awareness of experiencing negative sensations based on neural development. Assumptions and LCI sources for animal products at the national level were retrieved from Paris et al. (2022a). Impact values per 100 g are calculated in this study for rabbit meat, red deer (as game meat), sheep (as lamb meat), and shrimp. The quality of life of rabbit meat and shrimp was calculated based on the stocking density. For sheep meat, we used the days of pasture/year. Wild deer hunting practices were assumed to estimate the impact of game meat on animal welfare. Animal welfare impacts from food items containing animal products (e.g., custard, dressing, mayonnaise, and pork liver) were calculated considering the quantities of the ingredients for each preparation/processing method. Detailed information on the criteria, assumptions, and data sources are found in **Table S5, Chapter 4 Appendices**.

4.3.5 Dietary Risk Factors and HENI

Human health impact is quantified as a marginal health burden using the "Health Nutritional Index" (HENI) proposed by Stylianou et al. (2021). HENI measures the combined health burden of all dietary risk factors (DRFs), scaled to life minutes, considering lifetime exposure. The DRFs were expressed in micro-Disability Adjusted Life Years (µDALYs) per person and day to mortality or morbidity attributed to a defined intake amount of each of the 15 DRFs. Information on the dose-response of all the 15 DRFs on the corresponding diseases was obtained from the GBD 2019 database, as well as the disease burden and mean dietary intakes at the country-level (Germany) (GBD 2019, 2020). All DRFs were standardised to the population of Germany according to age, gender and population number using data from the last census (2011) (Destatis, 2022b). Once GBD does not provide the variance of the intake, we assumed a conservative coefficient of variation of 70%, based on the mean coefficient of variation observed in the US population using the National Health and Nutrition Examination Survey (NHANES) 2011–2016. However, we performed sensitivity analysis by varying DRFs using a wider range of coefficient of variation from 35% to 140% (**Table S8** in **Chapter 4 Appendices)**.

HENI were calculated for all 110 food items by 100g. All NCDs associated with DRFs, as well as DRF definition and exposure risk, can be found in **Table S6 in Chapter 4 Appendices.** Nutrient data was used as input for HENI calculations (e.g., calcium, sodium, omega-3 and trans-fatty-acid intake) based on the EFSA food composition table (EFSA, 2018b). This data comprises more than 60 nutrients (macro and micronutrients) for over 2500 products in several European countries (Broekema et al., 2019)HENI (minutes of life gained or lost) was calculated using **Eq. 10**. It is the result of multiplying the constant -0.53 minutes by the cumulative standardised DRF per gram of dietary risk r in µDALYs and the amount and quantity of dietary risk exposure *d* by each food item.

$$HENI_{food\ item} = -0.53 \sum_r DRF_{r,DALY} \times d_{food\ item} \quad [10]$$

$$1\ \mu DALY = 1\ year\ of\ healthy\ life\ lost\ \times 365\ (days\ per\ year) \times 24\ (hours\ per\ day) \times 60\ (minutes\ per\ hour) \times\ 10^{-6} = -0.53\ minutes$$

Sodium used additional modifiers mediated by systolic blood pressure, dependent on ethnic group and hypertension incidence in the population (Stylianou et al., 2021). We considered both direct and mediated effects (via increased systolic blood pressure). The prevalence of hypertension in Germany (31.6%) was based on epidemiological studies (Neuhauser et al., 2015). The vulnerable population to hypertension was taken as the percentage of African descendants in the population (0.65%), assumed to be proportional to the number of foreigners in Germany from African countries (Destatis, 2022a). Details on calculating DRFs can be found in **S4** in **Chapter 4 Appendices**.

4.3.6 Diet Optimisation

Quadratic optimisation was applied to the three observed diets through 100-run Monte Carlo simulations in Optimeal® to evaluate differences in trade-offs on the shifts of optimised properties among optimisation strategies while satisfying several nutritional constraints. Quadratic programming increases the penalties when changing the grams of each food item, producing shifts on a larger range of food items but less amount in grams of each modified food item. This is meant to capture realistic changes in food consumption to be adopted by consumers, as they are not significantly different from the observed food basket (Broekema et al., 2019; te Pas et al., 2021). The algorithm followed the approach described by te Pas et al. (2021) in **Eq. 11**, where i represents each food item of all 110 food items, x_i is the total quantity in grams of each food item in the current diet, and x_i^*, quantity in grams of each food item of the optimised diet.

$$deviation = \sum_{i=1}^{110} (x_i^* - x_i)^2 \quad [11]$$

Nutrient data comprised 60 nutrients (macro and micronutrients) using the European Food Composition Database (EFSA, 2018b). Nutritional constraints were applied using upper and lower nutrient values for every nutrient according to EFSA average nutrient requirements (EFSA, 2018a, 2019b). The only exception was vitamin D and B12, whose lower values were not considered due to difficulties finding feasible outcomes from Monte Carlo simulations. Linear programming was also conducted as a sensitivity analysis (see **Chapter 4 Appendices, part S5)**. The following arbitrary interventions were defined on top as scenario analysis to represent potential sustainability improvements in line with EU policies and societal demands:

(a) **55% GHGE reductions (55% GHGE):** a hypothetical scenario to reduce GHGE by 55% of each diet aligned to the EU 2030 climate targets as part of the EU's Green Deal.

(b) **Zero animal welfare loss (Zero AWL)**: a scenario to reduce animal suffering by eliminating all animal-based products from the diet. Minimum amounts of fruit, vegetables, whole grains, water, nuts and seeds, legumes and vegetable protein were kept equal to the observed diets to avoid decreasing the intake of these food items and remaining similar to the original diets.

(c) **25% improvement in health indicators (25% Health):** this scenario encourages or discourages the intake of certain food items, groups, or nutrients. It is characterised by an increase of 25% in beneficial DRFs and a decrease of 25% in detrimental DRFs, representing improved human health through modified dietary intake.

(d) **Combined scenario (Combined):** This scenario combines a 25% increase in human health benefits and a 55% reduction of GHGE in diets and evaluates the animal welfare reduction outcomes without removing animal products from the optimised scenario.

4.4 Results

4.4.1 Cross-comparison of observed diets using the OH approach

Results show that WT2 has the highest mean values in almost all environmental and animal welfare indicators compared to WT1 and PRU (see **Figure 10**). The exceptions are water consumption (**Fig. 10k**), which is greater in PRU due to a larger share of plant-based foods (legumes, vegetables, and fruits), and morally adjusted animal lives (MAL) (**Fig. 10c**), which are more pronounced in WT1 due to a higher meat intake.

Among the food categories**,** meat and meat products make the greatest contribution to overall environmental impacts in all diets, ranging from 22% in fossil resource scarcity (**Fig. 10e**) to 47% in terrestrial acidification (**Fig. 10j**). In water consumption (**Fig. 10k**), higher in PRU, around 47% of the impact are due to fruit and fruit products, non-alcoholic beverages, vegetable and vegetable products, and legumes, nuts and oilseeds altogether. The most contributing individual food items to environmental impacts in all diets are beef, sausages, pork/piglet meat, cheese and pastries.

Fish and seafood make the greatest contribution to animal welfare loss in all diets, ranging from (65 to 69%) in animal lives lost (AL) (**Fig. 10a**) and, on average, 36% in animal life years suffered (ALYS) (**Fig. 10b**). Because smaller animals take a higher number of animals affected than larger animals to produce the same amount of food in kilogram. Meat and meat products are the main contributors to MAL in WT1 (79%), in PRU (63%), and WT2 (58%) (**Fig. 10c**). Milk and dairy products also showed a substantial contribution to ALYS in PRU (28%) and WT2 (24%). The food items most impacting animal welfare loss are shrimp, chicken, turkey, fish fingers, and salmon.

HENI captures life minutes lost through NCDs across the observed diets. WT2 causes more life minutes lost than WT1 and PRU (**Fig. 10l**). Cardiovascular diseases account for most minutes of life lost due to NCDs (**Fig. 11a**), especially in PRU. Nearly 10 life minutes are lost in hypertensive heart disease (HHD) and 5 minutes in ischemic stroke (ISTR) in PRU, attributed to high sodium intake. Sodium intake causes a substantial burden in several NCDs in all diets, along with intake of trans-fatty acids (**Fig. 11b**). In contrast, avoiding exposure to DRF may also reduce life loss (gained HENI). For instance, consuming calcium and nuts reduces life loss in colon rectum cancer (CRC) and fruit and fibre intake in Diabetes type II (DT2). The adverse effects of DRF in ischemic heart disease (IHD) attributed to sodium and trans-fatty acids are counterbalanced with minutes gained from whole grains, fibre and nuts, resulting in positive net values in PRU (4.6 ± 3.1 min).

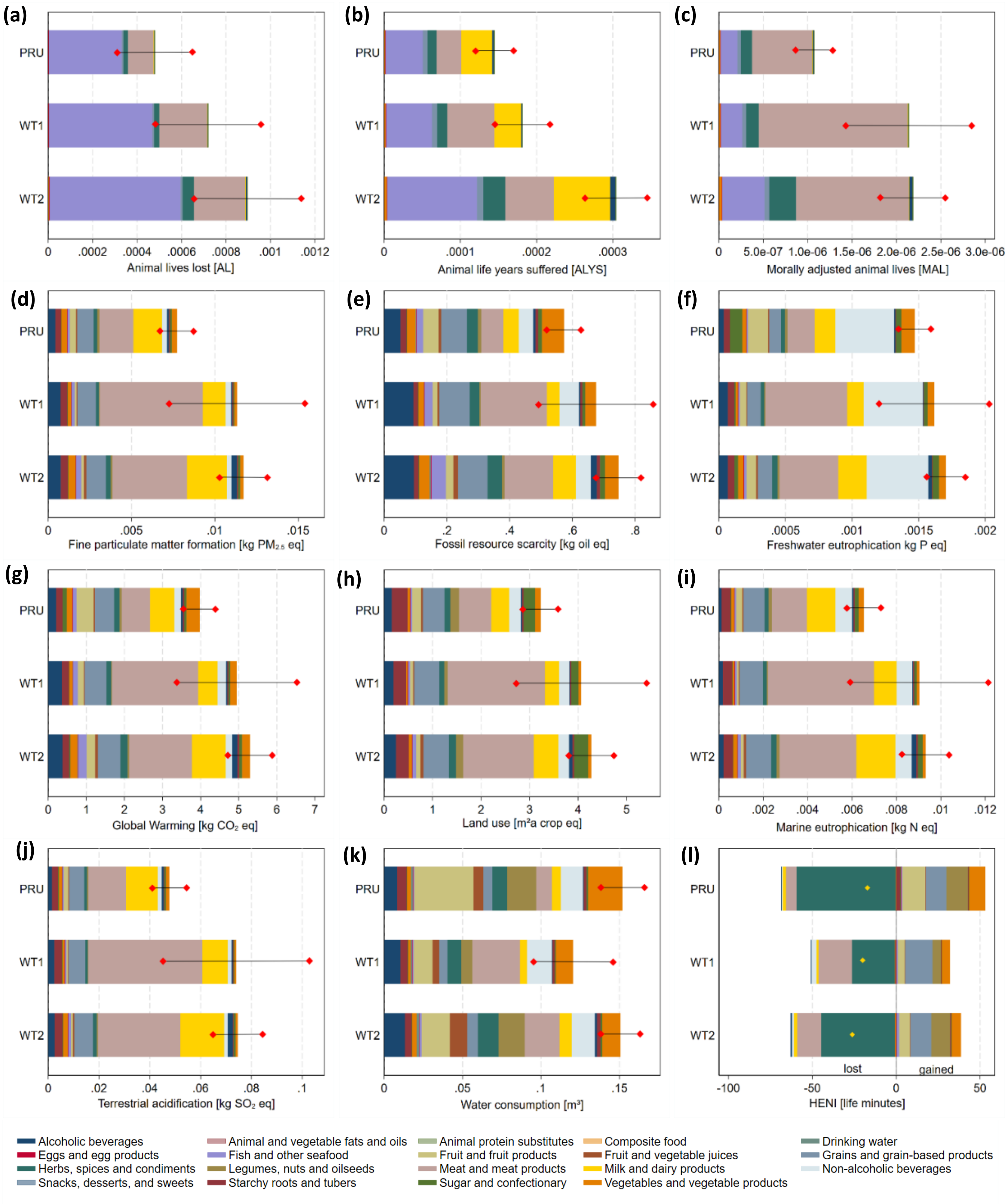

Figure 10. Impacts by food category per diet and day.

Red diamonds represent 95% confidence interval error bars of the average intake considering the number of observations. Yellow diamonds are HENI net values. Stack bars represent the sum of impacts per food category. Bar colours follow the order presented in the legend. Note: PRU: Prudent; WT1: Western-type 1; WT2: Western-type 2; HENI: Health Nutritional Index.

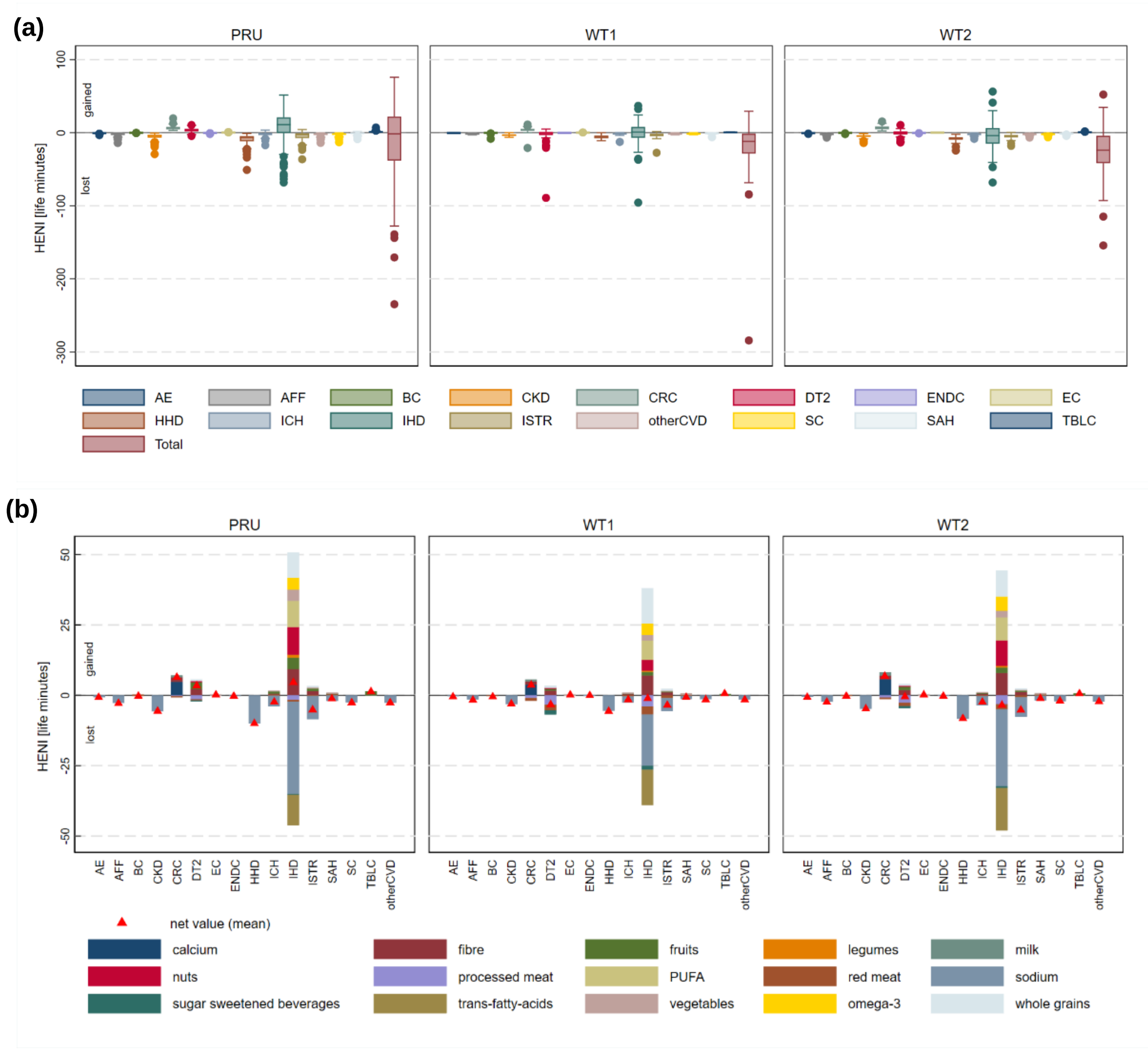

Figure 11. Health Nutrition Index (HENI) for each diet by non-communicable diseases (a) by dietary risk factors attributed to non-communicable disease (b).

(a) Boxplots represent Q1: lower quartile, Q2: median, Q3: upper quartile, error bars are upper and lower adjacent values, and markers are outside values at 95% confidence intervals. (b) Stacked bars represent the sum of HENI by dietary risk factors, and red triangles represent mean values. Note: PRU: Prudent; WT1: Western-type 1; WT2: Western-type 2; AE: Aortic aneurysm; AFF: Atrial fibrillation and flutter; BC: Breast cancer; CKD: Chronic kidney disease due to several causes; CRC: Colon and rectum cancer; DT2: Diabetes mellitus type 2; EC: oesophageal cancer; ENDC: Endocarditis; HHD: Hypertensive heart disease; ICH: Intracerebral haemorrhage; IHD: Ischemic heart diseases; ISTR: Ischemic stroke; SAH: Subarachnoid haemorrhage, SC: Stomach cancer; TBLC: Tracheal, bronchus and lung cancer; otherCVD: other cardiovascular diseases, PUFA: Polyunsaturated fatty acids.

4.4.2 Optimisation scenarios

We performed quadratic optimisation to induce improvements across the indicators under nutritional constraints and criteria representing four optimisation scenarios with minimal alterations in dietary behaviour. Feasible solutions provided small changes in food intake to meet the nutritional requirements and the set criteria (**Figure 12**).

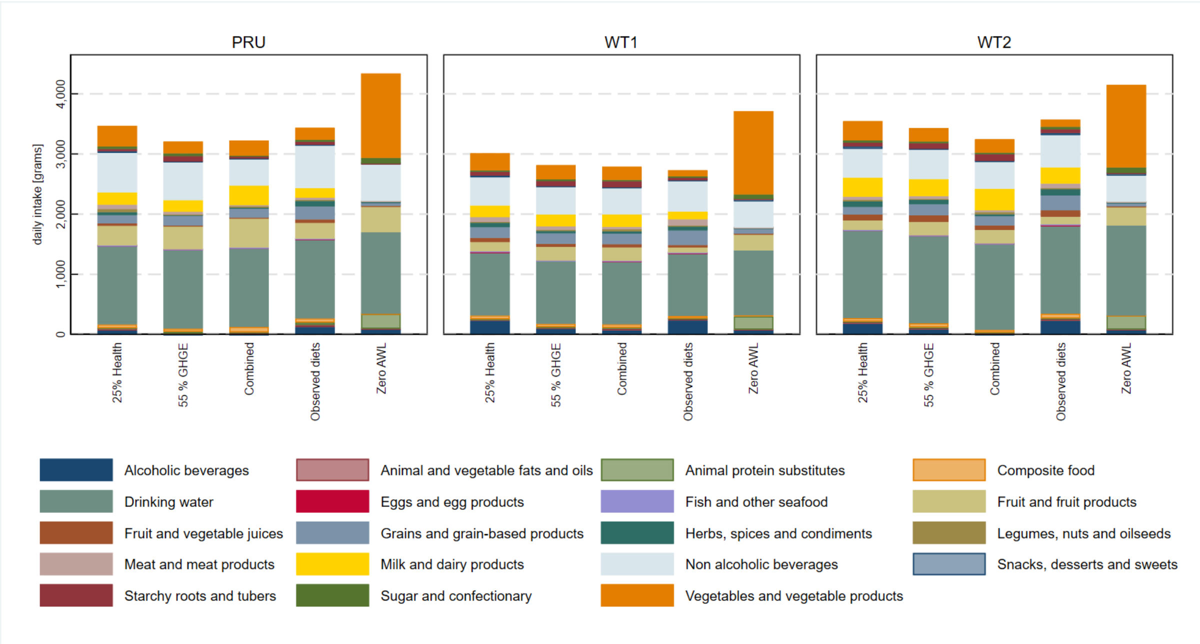

Figure 12. Daily food intake (in grams) per person of optimised scenarios grouped by food categories compared to the baseline (observed diets).

Stack bars represent the sum of intake per food category. Bar colours follow the order presented in the legend (left to right). WT1: Western-type 1; WT2: Western-type 2; PRU: Prudent; Zero AWL: Zero animal welfare loss; 25% Health: 25% health improvement in all dietary risk factors; 55% GHGE: 55% greenhouse gases emission reductions; Combined: a combination of scenario 55% GHGE and 25% Health.

All optimisations led to a 100% reduction in fish and seafood intake due to the higher impact on animal welfare loss, except *25% Health*, which increased by 64% in WT1. Scenarios also presented a reduction in intake of condiments (containing high sodium levels), 83% less in PRU, 49% less in WT1 and 56% less in WT2, due to the impact on human health. PRU, WT1 and WT2 presented a reduction in intake of meat and meat products by 25%, 62% and 35%, respectively, to allow GHGE reductions. The *Combined* and *55% GHGE* scenarios presented an increased intake of egg and egg products, ranging from 224% in WT2 in *Combined* to 200-time fold in PRU in *55% GHGE*. This represents an increased range of 8 g of eggs in WT2, 15 g in PRU and 23 g in WT2 per day (less than an egg). *Zero AWL* increased the intake of animal protein substitutes, particularly in WT1 (50-time fold) and WT2 (18-time fold), which is around 230 g/day to compensate for meat reduction. All scenarios increased the intake of fruit and fruit products from 58% in PRU to 163% in WT1, except *Zero AWL*, which maintained the intake. Scenarios induced a remarkable increase in the intake of vegetables (173% to 352% on average) and legumes, nuts, and oilseeds (107% total average). Except for *Zero AWL*, scenarios led to increased milk and dairy intake to satisfy nutritional and health constraints (5 to 107% change).

In most cases, optimisation helps reduce the impacts across OH dimensions. However, trade-offs arise in some of the indicators. The *55% GHGE* and *Combined* scenarios resulted in the most significant reductions across environmental impact categories. WT2 benefits from greater reductions in environmental impacts. WT1 showed a considerable decrease in fine particular matter formation (**Fig. 13d**), marine eutrophication (**Fig. 13i**) and terrestrial acidification (**Fig. 13j**). Water consumption (**Fig. 13k**) and freshwater eutrophication (**Fig. 13f**) decreased moderately in PRU. *25% Health* contributed the least to improving environmental impact categories and worsened fossil resource scarcity by 7.9% in WT1 (**Fig. 13e**), land use by 13% in PRU (**Fig. 13h**) and water consumption in all diets, from 6% in WT2 to 28% in WT1 (**Fig. 13k**). Likewise, *Zero AWL* also increased water consumption in all diets (24% in PRU to 54% in WT1) (**Fig. 13k**), and in PRU, fossil resource scarcity (**Fig. 13e**) by 9.9% and global warming by 1.4% (**Fig. 13g**).

As for animal welfare loss, WT2 and PRU show greater reductions in AL, ALYS, and MAL, whereas WT1 shows lower reductions after optimisations for the same indicators. All animal welfare indicators were reduced (100%) in *Zero AWL* because this scenario is a purely plant-based diet. *25% Health* did not present significant reductions and increased ALYS by 12.1% in WT1 (**Fig. 13b**). The *Combined* and *55% GHGE* scenarios decreased AL, as *Zero AWL* does (**Fig. 13a**). The *Combined* scenario showed more substantial reductions for ALYS and MAL than *55% GHGE* (**Fig. 13b, Fig. 13c**).

The *Combined* scenario yielded remarkable health gains in all diets, showing a -642.8% reduction in PRU (from -15 to 84 life minutes), -279.4% in WT1 (-19 to 39 life minutes), and - 322.4% in WT2 (-24 to 54 life minutes) (**Fig. 13l**). Impact reductions related to health gains from a negative HENI (life lost) to a positive HENI (life gained). Although notable reductions were observed under *Zero AWL* in PRU (-823.8%) and WT1 (-609.4%), it worsened HENI in WT2 (64% change – from 24 life minutes to -116). *25% Health* scenario improved overall health but less than the *Combined* and *Zero AWL*. *55% GHGE* caused a limited improvement compared to other scenarios, which means that aiming for GHGE reductions is insufficient to improve HENI.

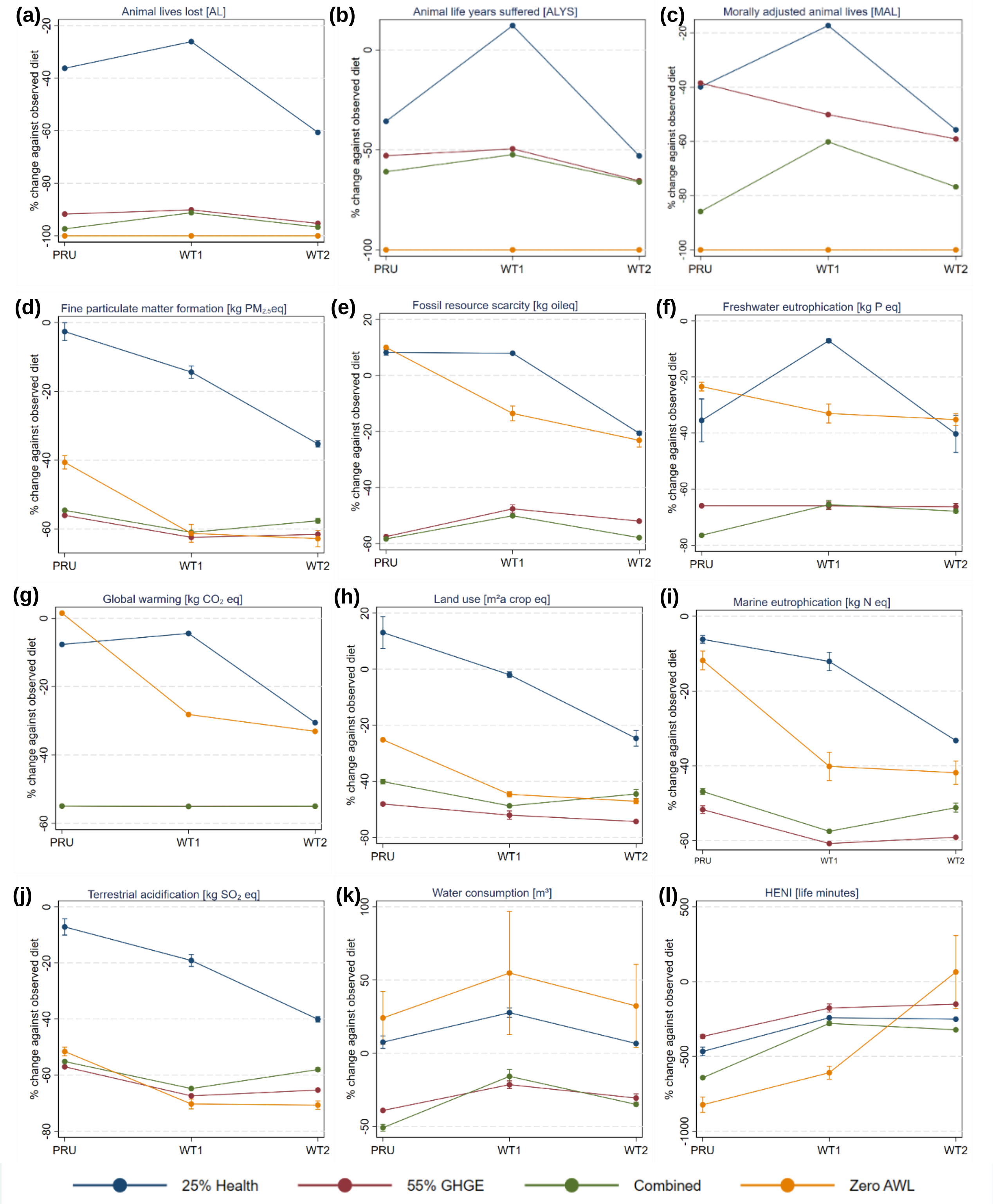

Figure 13. Percentage change against the observed diets of optimisation scenarios.

Dots represent the plot of predicted margins resulting from robust regression analysis of the correlations between dietary patterns and optimisation scenarios' changes against the baseline diet. Standard error bars are present when $p < 0.05$. WT1: Western-type 1; WT2: Western-type 2; PRU: Prudent; HENI: Health

Nutritional Index; Zero AWL: Zero animal welfare loss; 25% Health: improvement of health indicators by 25%; 55% GHGE: 55% GHGE reductions; Combined: a combination of 55% GHGE and 25% Health.

4.5 Discussion

Optimisations identified improved sustainable dietary shifts regarding human health, animal welfare and the environment while respecting nutritional requirements without changing consumption behaviour. Like other studies (Broekema et al., 2020; Kramer et al., 2017), our findings recommend reducing animal-based products while modifying the intake of plant-based ones. Our outcomes suggest a reduction of 41% (on average) of meat and meat products to mitigate 55% GHGE. It might not be necessary to eliminate meat from the diet, as moderate consumption provides essential nutrients, and GHGE intensity also varies among the heterogeneous production systems (Mrówczyńska-Kamińska et al., 2021). The sensitivity analysis using linear programming relative to quadratic optimisation showed no significant outcome differences, except for water consumption (33% difference) because fewer changes occurred in food fruit, vegetables, grains and legumes (see **Chapter 4 Appendices, S5**). From our assessment, WT1 and WT2 performed worse for environmental and animal welfare than PRU. Yet, PRU had higher sodium levels (from salt intake) than other diets, increasing the risk of hypertension and cardiovascular diseases. A reduction of sodium intake of less than 4 g/day should be prioritised to provide health gains of 28 minutes/pers./day. Fish, seafood, and poultry have a higher impact on animal welfare due to the number of animals affected in production systems, corroborating findings from other studies on multidimensional LCAs (Scherer et al., 2019).

This study collected primary food consumption data at the regional level to capture current food consumption patterns for building realistic scenarios (Vieux et al., 2022). Our findings can inform dietary shifts towards more sustainable Western diets, especially in Germany, where regional socioeconomic and cultural differences largely determine food consumption patterns (Treu et al., 2017). Yet, the survey's participant outreach might affect the general applicability of our findings. The sampling strategy did not favour a truly representative population sample, but it increased feasibility and participant consent. The pandemic context in 2020 influenced eating behaviour and self-selection bias. The survey reached a particular population with similar demographic characteristics in terms of gender (77% women), age, ethnicity, education level and income. Nevertheless, regional primary food consumption data remains relevant for assessing dietary shifts as nearby neighbourhoods indicate income level and dietary patterns (LeDoux & Vojnovic, 2014).

Results will likely change if the assessment incorporates representative samples, and consequently, food intake changes.

Optimisation of HENI is challenging due to the assumed linearity of DRFs, meaning that modifying the intake would change impacts proportionally. For a few modifications, this might not be a potential issue; nevertheless, with more considerable intake modifications, improvements for a log-linear model are necessary. We also assumed a coefficient of variation from the NHANES to characterise DRFs. However, the sensitivity analysis showed slight DRF variation within a wide coefficient variation (**Chapter 4 Appendices, S4**). Additionally, sodium mediated by high blood pressure differed from direct sodium intake because hypertension is a risk factor for several diseases. More sophisticated DRFs, combining other behavioural or metabolic risk factors (e.g., body mass index), would better capture other correlations between diet and disease risk in LCA (Weidema & Stylianou, 2020).

The scenarios *55% GHGE* and *Combined* improved the performance among indicators; however, *55% GHGE* did not improve human health. *25% Health* is the least promising scenario, often worsening environmental and animal welfare indicators. *Combined* and, *55% GHGE* favoured other sources of protein, e.g., eggs, dairy and meat substitutes, which could have a higher population acceptance. This highlights the trade-offs commonly reported between environment and health, meaning that only a healthy diet does not comply with the planetary boundaries without additional sustainable shifts along the supply chains and substantial socioeconomic changes (Poore & Nemecek, 2018; Steenson & Buttriss, 2021). However, adhering to a planetary health diet in high-income countries would yield a 61% GHGE reduction of current annual agricultural emissions (Sun et al., 2022). The developed scenarios would potentially fit into the 55% reduction targets of the EU Green Deal (European Commission, 2022). Large-scale dietary shifts may provoke supply and demand adjustments across agri-food markets and diversified sustainability outcomes. This requires global economic models and consequential LCA to simulate international trade and market behaviour in response to exogenous shocks (Springmann et al., 2016; van Meijl et al., 2020).

Zero AWL could be feasible from the optimisation approach, provided there was a more diverse list of food items than the ones in this analysis and co-production allocation was considered part of the model. A limited number of food items under several constraints may exacerbate results, deviating from the realistic behaviour. This explains the significant change in leeks and cabbage intake, which increased fossil resource scarcity, global warming, water consumption and HENI. The individual-level modelling approach varies food item intake, offering a higher acceptance with a specific reduction target. However, broader dietary flexibility could be better achieved using a population target goal (Rocabois et al., 2022). Removing animal-based products from the diet may lead to nutritional inadequacies without introducing suitable substitutes (Humpenöder et al., 2022). However, animal welfare considerations in LCAs have become highly important given Germany's animal welfare initiative and labelling act to meet EU animal welfare policy and consumer aspirations (BMEL, 2022; European Court of Auditors, 2018). Our results indicated fish as the main contributor to animal welfare impact, which could explain why its consumption was eliminated in optimised scenarios. This arises partly from the framework definition and modelling approaches (Scherer et al., 2018) that smaller animals have a greater life loss than larger animals. Also, due to the unethical production practices in industrial aquaculture, including high mortality rate, decreased environmental conditions, and health issues (Berlinghieri et al., 2021; Størkersen et al., 2021). An ethical consensus is still needed in animal welfare assessment, and a better resolution is needed for available products (e.g., only a few fish species were considered).

Additional methodological limitations derive from LCI data in Optimeal®. Trade data is relatively old (2009-2013). However, improving with more updated import mixes is out of scope, as this would imply reassessing LCA for each product. Nevertheless, import mixes for agricultural commodities are assumed to be consistent with the trade data for the Netherlands and, therefore, representative of the Rhine-Ruhr Metropolis due to geographical proximity. Expected changes in environmental footprint will more likely respond to the difference in production systems in the respective exporting countries (Sandström et al., 2018). Other limitations arise from different LCI sources considering different system boundaries due to data limitations. Moreover, minimum vitamin D and B12 requirements should be considered in optimisation constraints since observed diets presented values below daily requirements, which in this study was impossible due to technical limitations. Despite the contributions of this study to include three relevant dimensions of sustainability, additional efforts are needed to address One Health as a whole (i.e. zoonotic disease risk) in both LCI and LCIA, as this directly affects meat consumption, environmental damage, future health outcomes and possible consequences to sustainability (Attwood & Hajat, 2020).

4.6 Conclusions

This study applied an extended LCA framework with indicators for human health and animal welfare to assess the sustainability of diets in the Rhine-Ruhr Metropolis in 2020. Data on food consumption was collected from 189 participants. Three dietary patterns were observed within the population: PRU, WT1 and WT2. Optimisation scenarios were defined to capture more sustainable food choices, which could potentially be adopted by the population – *55% GHGE, 25% Health, Zero AWL* and *Combined*. The scenarios deliver improvements across the OH dimensions with marginal dietary changes but generate trade-offs. Achieving a 55% GHGE reduction target in line with the EU Green Deal goals is feasible through the *Combined* scenario while promoting human health and reducing animal welfare loss. To meet this ambitious aim, it is necessary to minimise average meat consumption by 41%, compensating with other protein sources, such as eggs, dairy, and plant-based, suggesting a shift towards more flexitarian and vegetarian dietary scenarios. Health concerns about high sodium intake were raised due to the assumed interlinkages of sodium with other metabolic risk factors. HENI should be continuously improved for further integration into LCA, addressing human health attributed to several risk factors. Finally, more comprehensive and consistent sample data on food consumption are needed for a more representative regional and country-level assessment, as well as improving the robustness of the proposed LCA method and indicators to better represent the OH.

5 Self-reported changes in eating habits and lifestyle during the first year of the COVID-19 pandemic across metropolitan regions in Brazil and Germany: a survey-based cross-sectional study

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5.1 Abstract

COVID-19 caused profound societal changes to cope with the new circumstances rapidly. The food market changed its quantity, quality, form, and frequency dynamics. Consequently, food-eating habits and lifestyles like physical exercise likely experienced changes. An online-based survey was conducted between June 2020 and January 2021 in the metropolitan regions of Rhine Ruhr (RRM), Greater São Paulo (GSP), other metropolitan regions in São Paulo state (oMRSP), other Brazilian metropolitan regions (oBRMR), and the remaining urban areas in both countries (oUA) representing different contexts of Brazil and Germany. We assessed self-reported changes in 2020 in physical activity level, diet quality, self-reported eating habits, and changes in buying groceries. In Germany, indoor and outdoor activities increased, while in Brazil, there was a decrease in physical activity. The Healthy Eating Index scored higher among Brazilians than Germans. Increased awareness of healthy and sustainable eating habits was observed in GSP, oMRSP, oBRMR, and oUA. In RRM, an increase in convenience foods was noticed. Participants reported discomfort with food purchasing due to hygiene measures and avoided going to the supermarket. Also, food supply at the grocery shops was reported to be often unavailable and in lower quantities. A real-time assessment of self-reported changes in eating habits and lifestyle during the lockdown in 2020 in different contexts is insightful for rethinking strategies to improve conditions in the post-COVID-19 era and prepare for future pandemics.

5.2 Introduction

COVID-19 conveyed uncertainties and changes in behaviour to adapt quickly to disruptions in the food systems, affecting daily life in Brazil and Germany, like in many other middle-income and OECD countries (Benton, 2020). These profound societal changes transformed behaviour, social interactions, and eating and lifestyle habits. Several food systems disruptions occurred, changing the dynamic of food markets and increasing the vulnerability of food supply chains (Benton, 2020; Oliveira et al., 2020; Power et al., 2020). In the early stages of the COVID-19 pandemic, supermarket shelves appeared emptied of crucial food and non-food items in OECD countries (Hobbs, 2020). The lack of labour in food production destabilised the food supply in Germany due to frequent outbreaks and migration restrictions (Mitaritonna & Ragot, 2020; Schneider & Götte, 2022). In addition, the necessary hygiene measures led to uncomfortable shopping due to the regular mandatory use of masks, distance measures, sanitising fluids, and disinfection of food products, such as observed in the strict Brazilian protocols (Finger et al., 2021; Rizou et al., 2020).

Purchases of pantry items increased worldwide, i.e., frozen and packaged foods, while fresh produce items decreased (IFIC, 2020). Unhealthy eating habits have been associated with emotional eating to divert attention from stress, boredom, and fear caused by the uncertainties of the pandemic (Araiza & Lobel, 2018; Jia et al., 2021; Moynihan et al., 2015). Consumers piled stock of food items, increasing the demand for online delivery services (Bakalis et al., 2020). Studies noted a higher volume of ultra-processed and high-energy-density foods purchased in the United States (US), Europe, and Latin America (Morales et al., 2023; Ruíz-Roso et al., 2020; Sobba et al., 2021). São Paulo metropolitan area and other middle-income metropolitan regions reported changes in lifestyle and dietary patterns by increasing high-calorie foods and reducing healthy food consumption (Jia et al., 2021; Rundle et al., 2020; Sidor & Rzymski, 2020).

Moreover, confinement measures significantly decreased physical activity levels and increased sedentary behaviour worldwide (Ammar et al., 2020; García-Álvarez et al., 2020; Gualano, 2020; Peçanha et al., 2020). The habit of watching television and using the Internet was intensified among adults during the pandemic in the US (Bhutani & Cooper, 2020; Nielsen, 2020). In Spain, alcohol consumption and tobacco use were amplified during quarantine (García-Álvarez et al., 2020). However, in Italy, a greater adherence to the Mediterranean diet, an increase in physical activity, and a decrease in habits harmful to health, such as smoking, were recorded (Di Renzo et al., 2020).

The literature on the effects of COVID-19 on eating habits and lifestyle is a growing field, with examples and contexts varying from specific groups within and between countries and regions (Di Renzo et al., 2020; Galali, 2021; Lamy et al., 2022; Thakur & Mathur, 2023). Our study adds the perspective of the impacts of COVID-19 in metropolitan areas in Brazil (a middle-income country) and Germany (an OECD country). These urban regions offer different socio-cultural contexts to allow analyses on self-reported changes in eating habits and lifestyle during the first year of the pandemic, where control measures (e.g., lockdowns) were more prominent because larger cities were typical hotspots of new COVID-19 infections (Sharifi & Khavarian-Garmsir, 2020)We intend to investigate self-reported changes in urban populations in two contexts. Self-reported behavioural changes are relevant to understanding the effects on health and well-being in different geographical locations and using them as lessons for future pandemics.

5.3 Material and methods

5.3.1 Study design, setting, and participants

This cross-sectional survey-based study evaluates self-reported dietary habits and lifestyle changes during the first year (2020) of the COVID-19 pandemic in metropolitan regions in two different contexts (Brazil and Germany). The survey contains questions about (a) sociodemographic and general information, (b) self-reported changes in diet behaviour and buying groceries, (c) self-reported changes in physical activity, and (d) a food frequency questionnaire. The original German questionnaire was modified to adapt to the Brazilian socio-cultural context. The survey was available online from June 2020 to January 2021. The recruitment was initiated in Germany on June 14th, 2020, and ended on January 14th, 2021. In Brazil, it was initiated on September 16th, 2020, and ended on January 17th, 2021. It was disseminated via social media and e-mails to facilitate online participation during the lockdown. Due to the low response rate in Germany, advertisements containing a QR code were distributed in commercial and residential buildings under limited lockdown conditions.

A free and written informed consent form was provided digitally before participation. Only adults declaring to be 18 years old or older were recruited. Participants younger than 18 were directly sent to the end of the survey webpage and excluded. The research was approved by the Research Ethics Committee of the Faculty of Pharmaceutical Sciences, University of São Paulo (CAAE 31781720.9.0000.0067) and the Research Ethics Committee, Center for Development Research (ZEF), University of Bonn, Germany (13c_19), respecting the Declaration of Helsinki (Doenges & Dik, 1964).

We used Cochran’s sample size equation with a 95% confidence interval and a 5% margin of error. The percentage of the adult population (18 to 75 years old) was 69.1% in Brazil and 71.1% in the state of North-Rhine Westphalia in Germany (IBGE, 2018; IT.NRW, 2023). Thus, a sample size of 329 in Brazil and 316 in Germany was calculated. One thousand twenty-four participants registered for the survey (N = 1,024). Although the German population's sample size is smaller than estimated, the sample has a 6.69% margin of error within a 95% confidence interval.

5.3.2 Measurements and Procedures

5.3.2.1 Sociodemographic and General Information

Information on gender, age, marital status, level of education, number of inhabitants in the household, income at the household level, and ethnicity (nationality in Germany and ethnic groups in Brazil) was collected following the demographic standards of both countries (Statistisches Bundesamt, 2016; IBGE, 2008, 2010; IT.NRW, 2013). These sociodemographic variables are dietary and lifestyle behaviour determinants and possible confounders (Krieger et al., 2018). To harmonise monthly household income from both countries, we used the Purchasing Power Parity (PPP) conversion factor from the World Bank Database based on the gross domestic product (GDP) and expenditures in international PPP dollars (Int$) (World Bank Group, 2023). The location (city of residency) was used to classify the metropolitan regions based on population density (EUROSTAT, 2021; GV-ISys, 2019b, 2019a; IBGE, 2021a, 2021b, 2021c, 2021d). Additionally, we collected information on the employment situation before and during COVID-19 (in the lockdown of 2020) to capture abrupt changes in the working environment and employment status.

5.3.2.2 Physical activity and general health status

Physical activity assessment followed the validated methods described by the *International Physical Activity Questionnaire* (IPAQ) short-form (Craig et al., 2003; van Poppel et al., 2010). This method estimates individual energy expenditures in Metabolic Equivalents of Tasks (METs) expressed in METs minutes/week. The calculation of MET values was obtained by multiplying the time spent (in minutes) on walking, moderate, or vigorous activities by the number of days spent on each activity per week. A multiplying factor is added to each activity: walking 3.3, moderate 4.0, and vigorous 8.0. The total physical activity consisted of walking, moderate, and vigorous MET scores. For sitting, the total minutes per day spent sitting was considered. Data processing, cleaning, and normalisation procedures were performed using the IPAQ methods (IPAQ, 2005).

Moreover, information on self-reported changes in physical activities during the COVID-19 pandemic was collected, considering the participant's perception of being more or less physically active (indoors or outdoors) and the increase in sitting due, among other things, to working from home ('home office'). Information was collected on self-reported physical health evaluation (from "not healthy at all" to "extremely healthy"), self-reported non-communicable diseases, smoking habits, pregnancy, or breastfeeding to capture the general health status of the participants.

5.3.2.3 Diet quality score

Food consumption data were collected using two food frequency questionnaires (FFQ). In Brazil, a simplified FFQ was developed with the general survey and included food groups and items based on the Food Guide for the Brazilian population (Brasil, 2014). In Germany, participants completed the EPIC II (Nöthlings et al., 2007), a validated FFQ specifically developed for the German population (Harttig, 2021). We evaluated the dietary quality of both countries using a diet quality indicator, the *Healthy Eating Index* (HEI), adapted from the Mediterranean Diet Score (MDS) (Gil et al., 2015; Trichopoulou et al., 1995; Waijers et al., 2007). HEI sets scores for all food groups common in both countries, using food groups as the main component for scoring. Food frequencies of both FFQ were harmonised (never = 0; every month or less = 0.0164; 2-3 times per month 0.0822; 1-3 times per week = 0.2849; 4-6 times per week = 0.7123; every day or more = 1.8333) and aggregated to each food group. Each food category's corresponding frequency median values were set as cut-off criteria, scoring from 0 to 1 (**Table 3**).

Table 3. Healthy Eating Index components and scoring criteria.

Components	Scoring Criteria
Cereals, tubers, and roots	< median 0 ≥ median 1
Fruit	< median 0 ≥ median 1
Vegetables	< median 0 ≥ median 1
Meat and eggs	< median 1 ≥ median 0
Fish and seafood	< median 0 ≥ median 1
Milk and milk products	< median 0 ≥ median 1
Pulses and oilseeds	< median 0 ≥ median 1
Oils and fats	< median 1 ≥ median 0
Sugar and sweets	< median 1 ≥ median 0
Beverages	For coffee, tea, and water < median 0 ≥ median 1 For soft drinks and juices < median 1

	≥ median 0
Ultra-processed foods	< median 1 ≥ median 0
Alcohol	Men 1 Women 1

5.3.2.4 Self-reported changes in eating habits and buying groceries

Participants self-reported changes in eating habits and buying groceries during COVID-19 were collected using Likert scale matrices ranging from "to a great extent", "somewhat", "very little", to "not at all". Options "I do not know /I prefer not to respond" or "not applicable" were also available. These questions were elaborated on following the questionnaire structure of the iCare study (Bacon et al., 2021). The objective was to collect information on personal perceptions of eating habits and food supply changes during the lockdown, including diet quality, consumption of convenience foods, staples, and fresh produce, reasons for dietary changes, including health and sustainability, food purchasing habits, hygiene, shortages in quality or quantity, and financial reasons.

5.3.3 Statistical analysis

General descriptive statistics were applied to sociodemographic and other general information data. We conducted power calculations to compute sample size, power, and minimum effect size. Robust linear regression analysis evaluated significant differences and correlations between the metropolitan areas and gender in PAL, food intake, and HEI. Logistic regression analysis and the marginal effects were calculated to assess the probability of changes in eating habits and food supply to identify differences between the correlation of sex and metropolitan regions. Likert scale from "not at all" to "in great extent" was transformed into binary variables (dummies) varying from 0 = "no change" to 1 = "change". The STATA vs. 16 (Stata Corp LLC, 2019) was used for all statistical analyses. Data cleaning, categorisation, harmonisation, and standardisation were conducted in SPSS 28 (IBM Corp, 2021).

5.4 Results

5.4.1 Participants

The total number of participants summed n = 818 in Brazil and n = 206 in Germany. Around n = 923 (90.1%) responses were considered valid. Missing cases, invalid and incomplete answers were treated as missing (n = 101, 9.9%). Power calculation results indicate that no significant effect (< 0.80) can be inferred from intermediate populated areas (towns and suburbs) and thinly populated rural areas. Most of the population lived predominantly in urban areas and were located in metropolitan regions (*n* = 890). In the analysis, we included all densely populated areas, primarily urban areas and small towns within the metropolitan regions. However, we excluded lesser populated areas not located within any metropolitan region (*n* = 33). The female/male ratio could have been more optimal; however, we decided to include both sexes in the analysis to be consistent, although no significant effect size was observed for Germany's male population (*n* = 44). Undeclared gender was also excluded from the analysis, resulting in a final population size of *N* = 887 participants. The flow chart in **Figure 14** illustrates the *n* of participants in each part of the study.

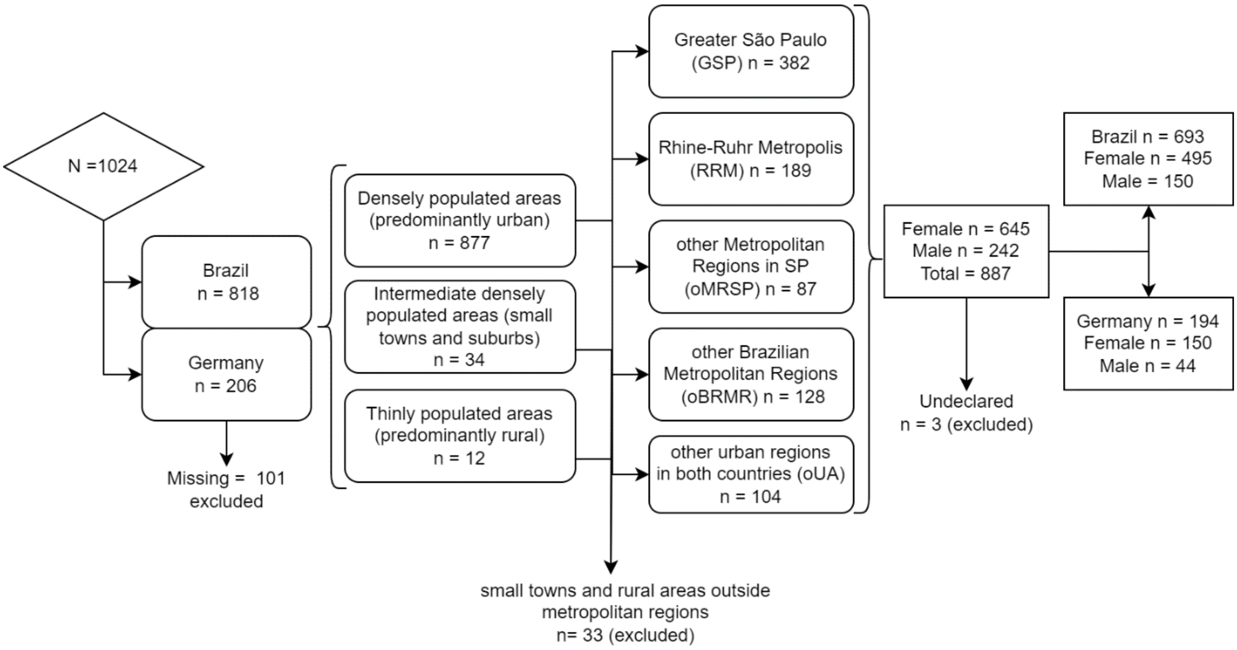

Figure 14. Study participant inclusion and exclusion criteria.

There were 887 valid participants in the study: 693 participants in Brazil and 194 in Germany. Brazilian participants were from three different metropolitan regions: Greater São Paulo (GSP, n = 382), other Metropolitan Regions in São Paulo State (oMRSP, n = 87), and other Brazilian Metropolitan Regions (oBRMR, n = 128). In Germany, the participants were from the Rhine-Ruhr Metropolis (RRM, n = 189). Other urban regions (oUA, n = 104) were composed of cities from Brazil (n = 98) and Germany (n = 6), agglomerated to form a sample with effect.

5.4.2 Characteristics of Study Participants

The demographic characteristics of the study population are relatively homogenous among different locations: majority female, in the mid-40ies, highly educated, belonging to middle-upper classes, according to income, ethnicity, and household composition (**Table 4**). Female participants were predominant (74.4% in Brazil and 73.5% in Germany) within the age range of 44.5 ± 0.5 years old. Most participants declared to be married (47.8%) or single (31.8%). Few participants reported being single but living with a partner (8.4%), divorced or living apart (9.8%), or widowed (1.6%). Regarding ethnicity, most participants in Germany declared they possessed German nationality (87.1% of 194 valid answers). Only 5.7% had German and other nationalities, 3.1% different nationalities, and 2.6% European nationalities. In Brazil, answers regarding participants' self-declared ethnicity showed a majority of Whites (78.7%), followed by "Pardos" ("brown" in Portuguese, European and African descendants [(Britannica (eds.), 2009)) (13%), and few Asian descendants (3.8%), African descendants (3.3%) and Indigenous (0.1%).

Table 4. Sociodemographic and health characteristics of selected study participants.

Variables	Categories	Greater São Paulo	Metropolitan regions in São Paulo State	Other Brazilian Metropolitan Regions	Rhine-Ruhr Metropolis	Other Urban Areas	Total
Gender valid = 887	Female	270 (70.9 %)	66 (75.9%)	95 (74.2 %)	145 (77.1%)	69 (67.0%)	645 (72.7%)
	Male	111 (29.1%)	21 (24.1%)	33 (25.8%)	43 (22.9%)	34 (33.0%)	242 (27.3%)
Age Valid = 879 Missing = 8	Mean ± Std. Err.	43.9 ± 0.8	42.4 ± 1.4	48.8 ± 1.3***	43.6 ± 1.1	44.8 ± 1.3	44.5 ± 0.5
Marital Status Valid = 887	Married	183 (48.0%)	47 (54.0%)	57 (44.5%)	85 (45.2%)	52 (50.5%)	424 (47.8%)
	Single	127 (33.3%)	23 (26.4%)	44 (34.4%)	53 (28.2%)	35 (34.0%)	282 (31.8%)
	Single but living with a partner / registered civil partnership	20 (5.3%)	5 (5.8%)	5 (3.9%)	38 (20.2%)	6 (5.8%)	74 (8.4%)
	Divorced/living apart	40 (10.5%)	9 (10.3%)	19 (14.8%)	11 (5.9%)	8 (7.8%)	87 (9.8%)
	Widowed	8 (2.1%)	2 (2.3%)	2 (1.6%)	0 (0.0%)	2 (1.9%)	14 (1.6%)
	Undeclared	3 (0.8%)	1 (1.2%)	1 (0.8%)	1 (0.5%)	0 (0.0%)	6 (0,7%)
Nationality (Germany) Valid = 194	German nationality	-	-	-	164 (87.2%)	5 (83.3%)	169 (87.1%)
	German with other nationality	-	-	-	10 (5.3%)	1 (16,7%)	11 (5.7%)
	European nationality	-	-	-	5 (2.7%)	0 (0.0%)	5 (2.6%)
	Other nationality	-	-	-	6 (3.2%)	0 (0.0%)	6 (3.1%)
	Undeclared				3 (1.6%)	0 (0.0%)	3 (1.5%)
Ethnicity	Whites	314 (82.6%)	66 (75.9%)	99 (77.9%)	-	64 (66.7%)	543 (78.7%)

Valid = 690 Missing = 3	African descendants	9 (2.4%)	2 (2.3%)	7 (5.5%)	-	5 (5.2%)	23 (3.3%)
	"Pardos"	32 (8.4%)	16 (18.4%)*	17 (13.4%)	-	25 (26.0%)***	90 (13.0%)
	Asian descendants	21 (5.5%)	3 (3.4%)	0 (0.0%)	-	2 (2.1%)	26 (3.8%)
	Indigenous	0 (0.0%)	0 (0.0%)	1 (0.8%)	-	0 (0.0%)	1 (0.1%)
	Undeclared	4 (1.1%)	0 (0.0%)	3 (2.4%)	3 (1.6%)	0 (0.0%)	7 (1.0%)
Education Valid = 887	Primary education (incomplete)	0 (0.0%)	1 (1.1%)	0 (0.0%)	1 (0.5%)	1 (1.0%)	3 (0,3%)
	Primary education or equivalent	2 (0.5%)	3 (3.5%)	1 (0.8%)	0 (0.0%)	2 (1.9%)	8 (0.9%)
	Secondary education (incomplete)	2 (0.5%)	1 (1.1%)	1 (0.8%)	0 (0.0%)	1 (1.0%)	5 (0.6%)
	Secondary education or equivalent	13 (3.4%)	8 (9.2%)	2 (1.5%)	12 (6.4%)	10 (9.7%)	45 (5.1%)
	General Higher Education Entrance Qualification "Abitur"	-	-	-	55 (29.3%)	2 (1.9%)	57 (6.4%)
	Technical post-secondary higher education	11 (2.9%)	4 (4.6%)	1 (0.8%)	0 (0.0%)	3 (2.9%)	19 (2.1%)
	Bachelor or equivalent (incomplete)	63 (16.5%)	10 (11.5%)	11 (8.6%)	1 (0.5%)	16 (15.5%)	101 (11.4%)
	Advanced technical college	-	-	-	5 (2.7%)	0 (0.0%)	5 (0.6%)
	University level (Bachelor/Master/Doctor)	289 (75.9%)	60 (69.0%)	111 (86.7%)	113 (60.1%)	68 (66.0%)	641 (72.3%)
	Preferred not to respond	1 (0.3%)	0 (0.0%)	1 (0.8%)	1 (0.5%)	0 (0.0%)	3 (0.3%)
Household size valid = 887	Mean ± Std. Err.	2.7 ± 0.1	2.9 ± 0.1	2.5 ± 0.1	2.4 ± 0.1*	2.9 ± 0.1	2.6 ± 0.0
Household monthly income (PPP Int$[§]) Valid = 811 Missing = 76	Mean ± Std. Err.	4,164.02 ± 118.00	3,142.17 ± 226.32***	4,441.37 ± 159.03	5,904.21 ± 369.92***	4,118.56 ± 269.42	4,472.66 ± 108.37
Self-reported physical health evaluation Valid	Extremely healthy	21 (5.5%)	4 (4.6%)	10 (7.9%)	25 (13.4%)	8 (7.8%)	68 (7.7%)
	Very healthy	121 (31.9%)	30 (34.5%)	57 (44.9%)	90 (48.1)	32 (31.1%)	330 (37.3%)
	Moderately healthy	177 (46.6%)	37 (42.5%)	51 (40.1%)	65 (34.8%)***	44 (42.7%)	374 (42.3%)

= 884, Missing = 3	Not quite healthy	48 (12.6%)	12 (13.8%)	9 (7.1%)	7 (3.7%)***	14 (13.6%)	90 (10.2%)
	Not healthy at all	13 (3.4%)	4 (4.6%)	0 (0.0%)	0 (0.0%)	5 (4.8%)	22 (2.5%)
Self-reported non-communicable diseases (NCDs) Valid = 884, Missing = 3	No chronic illnesses	166 (38.8%)	42 (38.9%)	68 (40.7%)	75 (42.6%)	42 (38.9%)	393 (39.8%)
	Cardiovascular diseases	22 (5.1%)	6 (5.6%)	10 (6.0%)	4 (2.3%)	11 (10.2%)	53 (5.4%)
	Cancer	7 (1.6%)	1 (0.9%)	0 (0.0%)	3 (1.7%)	1 (0.9%)	12 (1.2%)
	Nutrition deficiencies	7 (1.6%)	3 (2.8%)	2 (1.2%)	1 (0.6%)	2 (1.9%)	15 (1.5%)
	Diabetes	28 (6.5%)	4 (3.7%)	3 (1.8%)	3 (1.7%)**	3 (2.8%)	41 (4.2%)
	Dyslipidaemia	38 (8.9%)	10 (9.3%)	13 (7.8%)	0 (0.0%)	8 (7.4%)	69 (7.0%)
	Thyroid problems	43 (10.0%)	14 (13.0%)	22 (13.2%)	9 (5.1%)*	3 (2.8%)*	91 (9.2%)
	Food intolerance	12 (2.8%)	4 (3.7%)	11 (6.6%)*	20 (11.4%)***	4 (3.7%)	51 (5.2%)
	Hypertension	48 (11.2%)	12 (11.1%)	20 (12.0%)	19 (10.8%)	16 (14.8%)	115 (11.7%)
	Allergies	9 (2.1%)	1 (0.9%)	0 (0.0%)	7 (4.0%)	1 (0.9%)	18 (1.8%)
	Arthritis	2 (0.5%)	0 (0.0%)	2 (1.2%)	0 (0.0%)	0 (0.0%)	4 (0.4%)
	Asthma	13 (3.0%)	1 (0.9%)	3 (1.8%)	4 (2.3%)	2 (1.9%)	23 (2.3%)
	Autoimmune diseases	1 (0.2%)	1 (0.9%)	2 (1.2%)	2 (1.1%)	1 (0.9%)	7 (0.7%)
	Chronic lung diseases	1 (0.2%)	0 (0.0%)	1 (0.6%)	1 (0.6%)	0 (0.0%)	3 (0.3%)
	Colitis	0 (0.0%)	0 (0.0%)	0 (0.0%)	6 (3.4%)	0 (0.0%)	6 (0.6%)
	Endometriosis	0 (0.0%)	1 (0.9%)	0 (0.0%)	2 (1.1%)	1 (0.9%)	4 (0.4%)
	Fibromyalgia	1 (0.2%)	0 (0.0%)	2 (1.2%)	3 (1.7%)	1 (0.9%)	7 (0.7%)
	Digestive disorders	3 (0.7%)	1 (0.9%)	0 (0.0%)	0 (0.0%)	1 (0.9%)	5 (0.5%)
	Kidney diseases	1 (0.2%)	1 (0.9%)	1 (0.6%)	1 (0.6%)	0 (0.0%)	4 (0.4%)
	Mental health issues	6 (1.4%)	1 (0.9%)	1 (0.6%)	1 (0.6%)	4 (3.7%)	13 (1.3%)
	Migraine	4 (0.9%)	1 (0.9%)	0 (0.0%)	3 (1.7%)	1 (0.9%)	9 (0.9%)
	Multiple sclerosis	1 (0.2%)	1 (0.9%)	0 (0.0%)	2 (1.1%)	0 (0.0%)	4 (0.4%)
	Musculoskeletal disorder	3 (0.7%)	1 (0.9%)	2 (1.2%)	3 (1.7%)	0 (0.0%)	9 (0.9%)
	Osteoarthritis	2 (0.5%)	0 (0.0%)	1 (0.6%)	5 (2.8%)*	3 (2.8%)*	11 (1.1%)
	Tendonitis	2 (0.5%)	0 (0.0%)	1 (0.6%)	0 (0.0%)	0 (0.0%)	3 (0.3%)

	Neurodermatitis	1 (0.2%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (0.1%)
	Obesity	1 (0.2%)	0 (0.0%)	1 (0.6%)	1 (0.6%)	0 (0.0%)	3 (0.3%)
	Other diseases	6 (1.4%)	2 (1.9%)	1 (0.6%)	1 (0.6%)	3 (2.8%)	13 (1.3%)
Pregnant/ Nursing valid = 884, missing = 3	No	281 (73.9%)	62 (71.3%)	96 (75.6%)	179 (95.7%)	75 (72.8%)	693 (78.4%)
	Pregnant	2 (0.5%)	2 (2.3%)	1 (0.8%)	2 (1.1%)	1 (1.0%)	8 (0.9%)
	Nursing	9 (2.4%)	3 (3.4%)	2 (1.6%)	2 (1.1%)	2 (1.9%)	18 (2.0%)
	Not applicable	88 (23.4%)	20 (23.0%)	28 (22.0%)	4 (2.1%)	25 (24.3%)	165 (18.7%)
Smoking Valid = 882 Missing = 5	Non-smoker	321 (84.7%)	73 (83.9%)	117 (92.1%)	171 (91.4%)	92 (90.2%)	774 (87.8%)
	Smoker	58 (15.3%)	14 (16.1%)	10 (7.9%)	15 (8.0%)	10 (9.8%)	107 (12.1%)
	Prefer not to respond	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (0.6%)	0 (0.0%)	1 (0.1%)

Selected participants: N = 887 (See Fig 14). The values displayed are within a 95% confidence interval.

Significance: p-values 0.05*, 0.01**; 0.001*** based on robust linear regression.

[+] "brown" in Portuguese, European, and African descendants (Britannica (eds.), 2009).

[§] International Purchasing Power Parity dollars.

As for education, participants showed a higher educational level: 72.3% obtained a university-level degree, 11.4% were initiated at the University level, but it was incomplete by the time of the study, 6.4% had the general higher education entrance qualification (“Abitur” for Germany); very few participants had below secondary education level. The mean household size was 2.6. Therefore, the participants lived together with 1or two others. The average household monthly income of the whole sample was Int$ 4472.66 ± 108.37 6, significantly higher in the RRM (5,904.21 ± 369.92, $p \leq 0.001$), representing middle-upper social classes.

The results on the general health status showed that most participants self-declared to be healthy: “Moderately healthy” (42.3%), “very healthy” (37.3%), and “extremely healthy” (7.7%). The percentage of participants who self-declared to be “not quite healthy” was 10.2%, particularly within the metropolitan locations in Brazil ($p \leq 0.001$). In terms of self-declared diet-related non-communicable diseases (NCDs) – considering a multiple choice answer selection – the results from the most reported to the lowest were declared as follows: No chronic illnesses (39.8%), Hypertension (11.7%), Thyroid problems (9.2%), Dyslipidaemia (7%), Cardiovascular diseases (5.4%), Food intolerance (5.2%), Diabetes (4.2%), Asthma (2.3%), Allergies (1.8%), Nutrition deficiencies (1.5%), Mental health diseases (1.3%), other diseases (1.3%), Cancer (1.2%) and Osteoarthritis (1.1%). NCDs reported less than 1%, as seen in Table 2. Most participants were not pregnant (78.4%), not applicable (18.7%), only 8 participants (0.9%) reported being pregnant, and 18 (2%) were nursing. Most participants were non-smokers (87.8%); 12.1% said being smokers.

5.4.3 Employment situation during COVID-19

The employment situation during COVID-19 in 2020 changed from very little to no change (82.5%), considering multiple-choice responses. **Figure 15** shows the flows of change that occurred in each type of employment situation. Around 40% of employment changed to home office, 18% reported no change, 14% constituted system-relevant professions, and 10% shifted to short-time work. Full-time employment changed to home office (50%), system-relevant profession (18%), and short-time work (11%). Sixty-two percent (62%) of self-employed and 36% of unemployed reported no change during COVID-19.

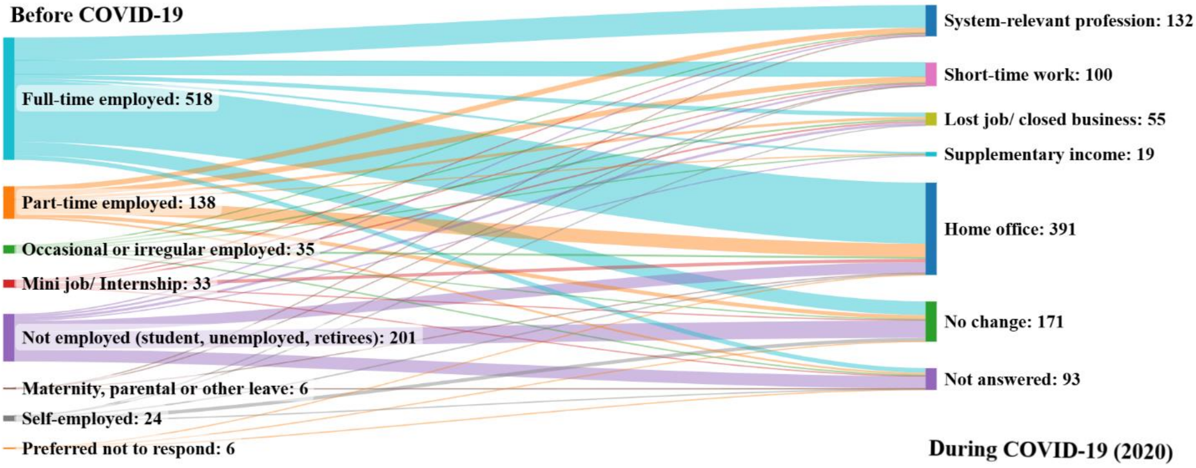

Figure 15. Employment situation before and during the COVID-19 pandemic in 2020.

5.4.4 Physical Activity Level (PAL)

In general, metropolitan regions in Brazil presented lower levels and a self-reported reduction of physical activity during the pandemic. In contrast, the activity level in Germany was higher, with an observed increase during COVID-19. Linear regression results showed a significant difference in the RRM ($p < 0.001$), which presented higher mean values for both females and males (3,282 ± 233.1 and 3,484.9 ± 376.8 MET-min/week, respectively ($p \leq 0.05$)) compared to the other metropolitan and urban areas and both sexes (from 1,827.9 to 1,958.7 MET-min/week) (**Fig. 16a**). Regarding physical activity level (PAL), walking ($p = 0.005$) and vigorous ($p = 0.042$) physical activity levels presented significantly higher means (900.0 ± 64.4 and 832.6 ± 62.3, respectively) compared to moderate levels, with considerably higher means in RRM compared to all other metropolitan regions. These results are complemented by the self-reported changes in physical activity levels during COVID-19 (**Fig. 16b**). Nearly 50% (on average) reported being less physically active during the pandemic in the metropolitan regions of GSP, oMRSP, and oBRMR. In contrast, RRM responses indicated a perception of being more physically active outdoors and indoors (34% together), plus having an unchanged high activity level (27%). Around 10% of the participants reported feeling more sedentary due to increased working hours in the home office, with an average of 6.3 ± 0.1 hours per day spent sitting. Additional results are in the **Chapter 5 Appendices, Fig. S1**.

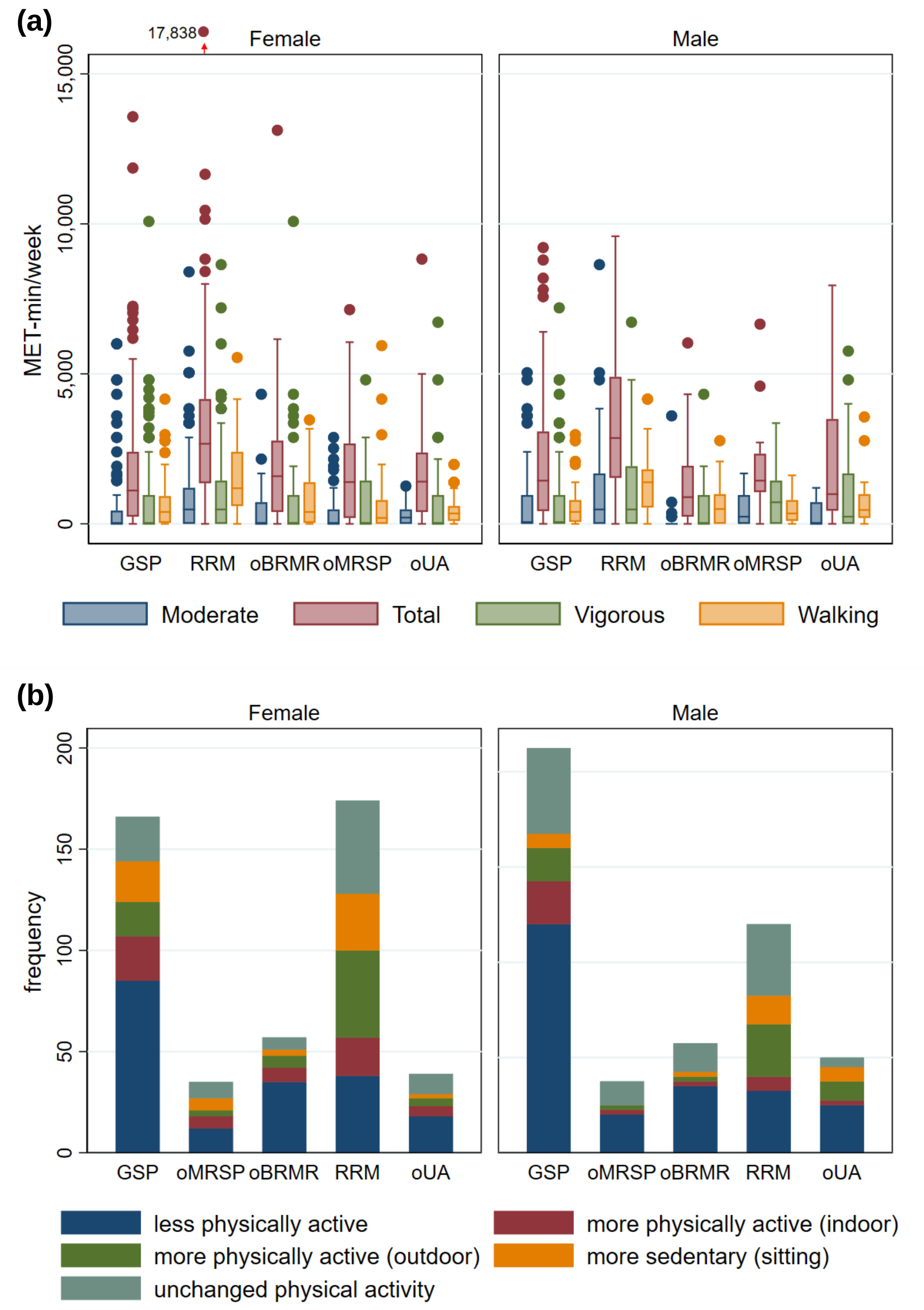

Figure 16. Physical Activity Level (PAL) and self-reported changes in physical activity during COVID-19.

(a) Metabolic Equivalents of Tasks (MET-min/week) of vigorous, moderate, and walking activities by sex and metropolitan regions. (b) Self-reported changes in physical activity during the pandemic in frequency of responses**.** Boxplots represent Q1: lower quartile, Q2: median, Q3: upper quartile, error bars are upper and lower adjacent values, and markers are outside values at 95% confidence intervals. Valid answers n=569, confidence interval at 95%. Legend: GSP: Greater São Paulo; oMRSP: other metropolitan regions in São Paulo state; oBRMR: other Brazilian metropolitan regions; RRM: Rhine-Ruhr Metropolis; oUA: other urban areas.

5.4.5 Healthy Eating Index (HEI)

Results from robust regression analysis demonstrated no significant differences between males and females within the same locations. However, significant differences were observed across metropolitan regions. HEI was significantly higher ($p \leq 0.05$) in oBRMR (16.38 ± 0.26), oUA (16.30 ± 0.33), and GSP (15.90 ± 0.16) compared to oMRSP (15.36 ± 0.26) and RRM (15.21 ± 0.24) a scale from 0 to 29 (**Figure 17**). HEI results can be interpreted by looking at the differences in food consumption based on the reported food frequencies (**Table 5**). Although RRM consumed significantly more bread, vegetables, fruits, and nuts, it also had a higher frequency consumption of cheese, sausages, processed foods, desserts and sweets, coffee, juices (processed), ready-to-eat meals, water, butter, and oil than the other regions, with some exceptions. The consumption of beer was higher in oUA, rice and pasta in oMRSP, and cheese in oBRMR. In GSP, oMRP, oBRMR, and oUA, the consumption was higher for carbohydrates such as cereals, rice and pasta, pulses, potatoes, natural juices, and proteins, such as meat, poultry, and eggs than in the German metropolis.

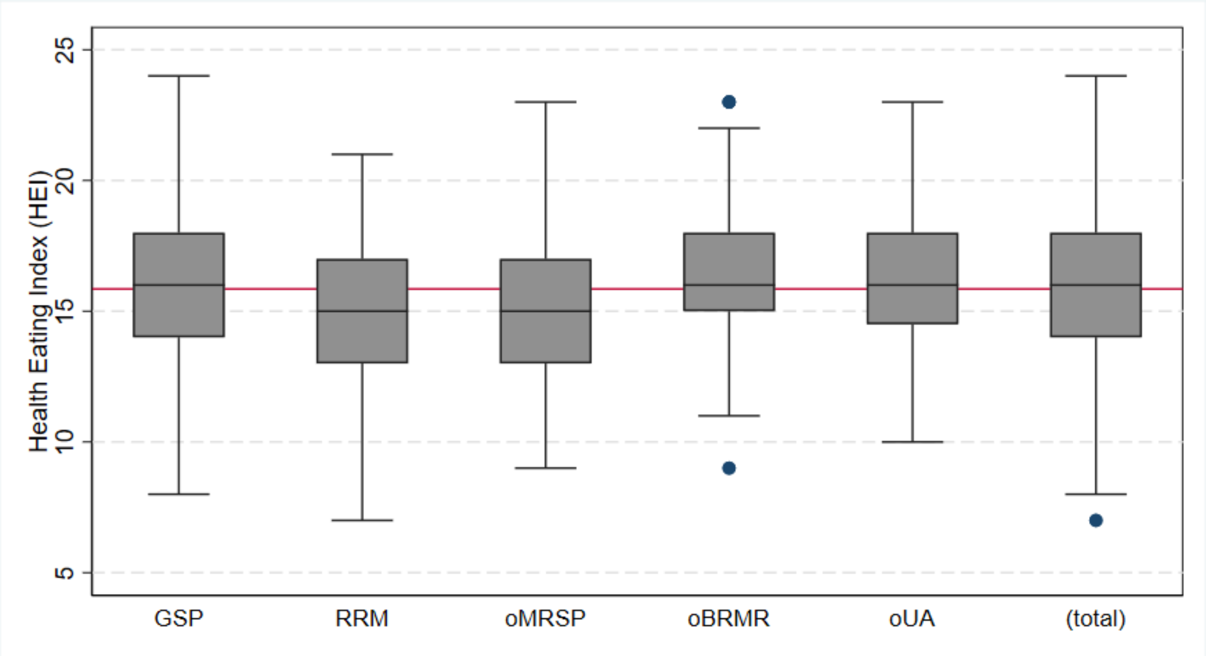

Figure 17. Healthy Eating Index (HEI) by metropolitan regions.

Boxplots represent the lower quartile (25% percentile), median, and upper quartile (75% percentile). Error bars are upper and lower adjacent values. Markers are outside values at 95% confidence intervals. The red lines represent total mean values. Legend: GSP: Greater São Paulo; oMRSP: other metropolitan regions in São Paulo state; oBRMR: other Brazilian metropolitan regions; RRM: Rhine-Ruhr Metropolis; oUA: other urban areas.

Table 5. Means and respective standard errors of food frequencies by food group and metropolitan regions.

	GSP		**RRM**		**oMRSP**		**oBRMR**		**oUA**	
Food groups	Mean	Std. Err.	Mean	Std. Err.	Mean	Std. Err.	Mean	Std. Err.	Mean	Std. Err.
Bread	0.65	0.02	1.53**	0.04	0.63	0.04	0.61	0.04	0.78*	0.04
Cereals	0.49	0.02	0.33**	0.03	0.42	0.04	0.47	0.04	0.53	0.04
Rice & pasta	1.04	0.03	0.34**	0.02	1.27*	0.07	1.01	0.06	1.16	0.07
Pulses	0.52	0.02	0.17**	0.01	0.57	0.04	0.54	0.04	0.70**	0.03
Potatoes	0.34	0.02	0.24**	0.02	0.33	0.03	0.37	0.03	0.37	0.03
Vegetables	0.75	0.02	1.60**	0.04	0.73	0.03	0.76	0.03	0.80	0.04
Fruits	0.73	0.02	1.59**	0.04	0.67	0.04	0.75	0.03	0.75	0.05
Nuts	0.31	0.02	0.75**	0.05	0.26	0.04	0.33	0.03	0.26	0.04
Milk	0.44	0.02	0.51	0.05	0.42	0.05	0.42	0.04	0.53	0.04
Yoghurt	0.29	0.02	0.34	0.03	0.28	0.04	0.29	0.03	0.22	0.03
Cheese	0.53	0.02	0.96**	0.05	0.46	0.04	0.63*	0.03	0.61	0.04
Meat	0.47	0.02	0.18**	0.02	0.53	0.04	0.46	0.03	0.53	0.03
Poultry	0.44	0.02	0.07**	0.01	0.51	0.03	0.45	0.03	0.49	0.03
Sausages	0.18	0.01	0.37**	0.04	0.20	0.03	0.16	0.02	0.22	0.03
Fish	0.16	0.01	0.17	0.01	0.11**	0.01	0.16	0.02	0.12*	0.02
Eggs	0.47	0.02	0.31**	0.02	0.48	0.04	0.51	0.03	0.55	0.04
Ready-to-eat meals	0.17	0.01	0.31**	0.02	0.20	0.02	0.13	0.02	0.18	0.02
Ultra-processed foods	0.23	0.02	1.15**	0.05	0.20	0.03	0.19	0.02	0.29	0.05
Dessert & sweets	0.25	0.02	0.31**	0.03	0.20	0.03	0.22	0.03	0.23	0.03
Coffee & tea	0.80	0.02	1.68**	0.04	0.80	0.04	0.75	0.03	0.87	0.05
Juice (processed)	0.16	0.02	0.29**	0.04	0.23	0.04	0.09*	0.02	0.13	0.03
Juice (natural)	0.30	0.02	0.07**	0.01	0.33	0.04	0.37	0.03	0.32	0.04

Soft drinks	0.18	0.02	0.26*	0.04	0.19	0.03	0.20	0.03	0.18	0.03
Water	0.95	0.01	1.79**	0.02	0.98	0.01	0.98	0.01	1.04**	0.02
Butter	0.61	0.02	0.70*	0.04	0.49*	0.05	0.51*	0.04	0.65	0.04
Oils	0.69	0.02	1.75**	0.03	0.64	0.05	0.72	0.03	0.78	0.05
Beer	0.15	0.01	0.14	0.02	0.18	0.03	0.12	0.02	0.21*	0.03
Spirits	0.10	0.01	0.04**	0.00	0.06	0.01	0.06	0.02	0.07	0.02
Wine	0.12	0.01	0.21**	0.02	0.06**	0.01	0.14	0.02	0.12	0.02
Mixed drinks	0.04	0.01	0.03	0.01	0.02*	0.01	0.03	0.01	0.02*	0.01

Significance: * p ≤ 0.05, ** p ≤ 0.001 robust linear regression.

Reference frequency: (never = 0; every month or less = 0.0164; 2-3 times per month 0.0822; 1-3 times per week = 0.2849; 4-6 times per week = 0.7123; every day or more = 1.8333).

Greater São Paulo; oMRSP: other metropolitan regions in São Paulo state; oBRMR: other Brazilian metropolitan regions; RRM: Rhine-Ruhr Metropolis; oUA: other urban areas.

5.4.6 Self-reported changes in eating habits and buying groceries

Logistic regression analysis results ranging from self-reported 0 = no change to 1 = change demonstrated that results differed depending on gender and metropolitan regions (**Fig. 18**). A change related to the increase of fresh food (**Fig. 18B**), improvement of the diet (**Fig. 18C**), enhanced awareness of healthy eating and sustainability (**Figs. 18D** and **18E**), and avoidance of eating animals (**Fig. 18F**) was noticeable in Brazil, while in Germany, there was an increase in the consumption of convenience food (**Fig. 18A**). Regarding changes in buying groceries, participants reported that they avoided going out to the grocery shops (**Fig. 18H**), and food supplies were often of lower quality in Germany (**Fig. 18L**). In Brazil, on the other hand, the changes related to having another person getting the supplies (**Fig 18G**), discomfort during purchase (**Fig. 18I**), disinfecting food packaging (**Fig. 18J**), and supplies were often observed as unavailable (**Fig. 18K**).

Looking into the different metropolitan regions, the RRM had a higher probability of increasing the consumption of convenience food (0.86 ± 0.02, $p < 0.000$) compared to other areas (0.14 - 0.21) (**Fig. 18A**). Also, the perception that the diet improved was higher in GSP (0.86 ± 0.02), oMRSP (0.91 ± 0.03), oBRMR (0.84 ± 0.04) and oUA (0.77 ± 0.05) than in the RRM (0.35 ± 0.03, $p < 0.000$) (**Fig. 18C**). Enhanced awareness of sustainability was significantly lower in the RRM (0.18 ± 0.03, $p < 0.000$) than in the other locations (GSP = 0.70 ± 0.03; oMRSP = 0.63 ± 0.06; oBRMR = 0.78 ± 0.04 and oUA = 0.68 ± 0.05) (**Fig. 18E**). Discomfort during food purchasing due to the restricted hygiene measures has a significantly higher level of probability ($p < 0.000$) in GSP (0.71 ± 0.02), oMRSP (0.67 ± 0.5), oBRMR (0.76 ± 0.02) and oUA (0.68 ± 0.05), compared to RRM (0.08 ± 0.02) (**Fig. 18I**). Disinfecting food packaging had a significantly higher likelihood ($p = 0.001$) in GSP, oMRSP, oBRMR, and oUA (0.3 ± 0.06 to 0.41 ± 0.03) than in RRM (0.23 ± 0.03) (**Fig. 18J**).

When comparing gender, the probability of increased healthy eating awareness was significantly higher in females (0.69 ± 0.02) than in males (0.56 ± 0.03, $p < 0.001$) (**Fig. 18D**). Enhanced understanding of sustainability was also significantly higher in females (0.21 ± 0.03) than in males (0.09 ± 0.04, $p = 0.037$). Moreover, avoiding eating animal products was substantially more in females (0.61 ± 0.02, $p = 0.047$) than in males (0.53 ± 0.03) (**Fig. 18F**). Females also had a higher probability of having help from another person to get food supplies (0.58 ± 0.02, $p = 0.001$) than males ($p < 0.000$) (**Fig. 18G**). For females, the food supply was significantly more unavailable (0.53 ± 0.02, $p< 0.000$), especially in oBRMR. In oBRMR, gender differences appeared more pronounced than in other regions in **Figs. 18G and 18K**. More results are available in the **Chapter 5 Appendices, Fig. S2**.

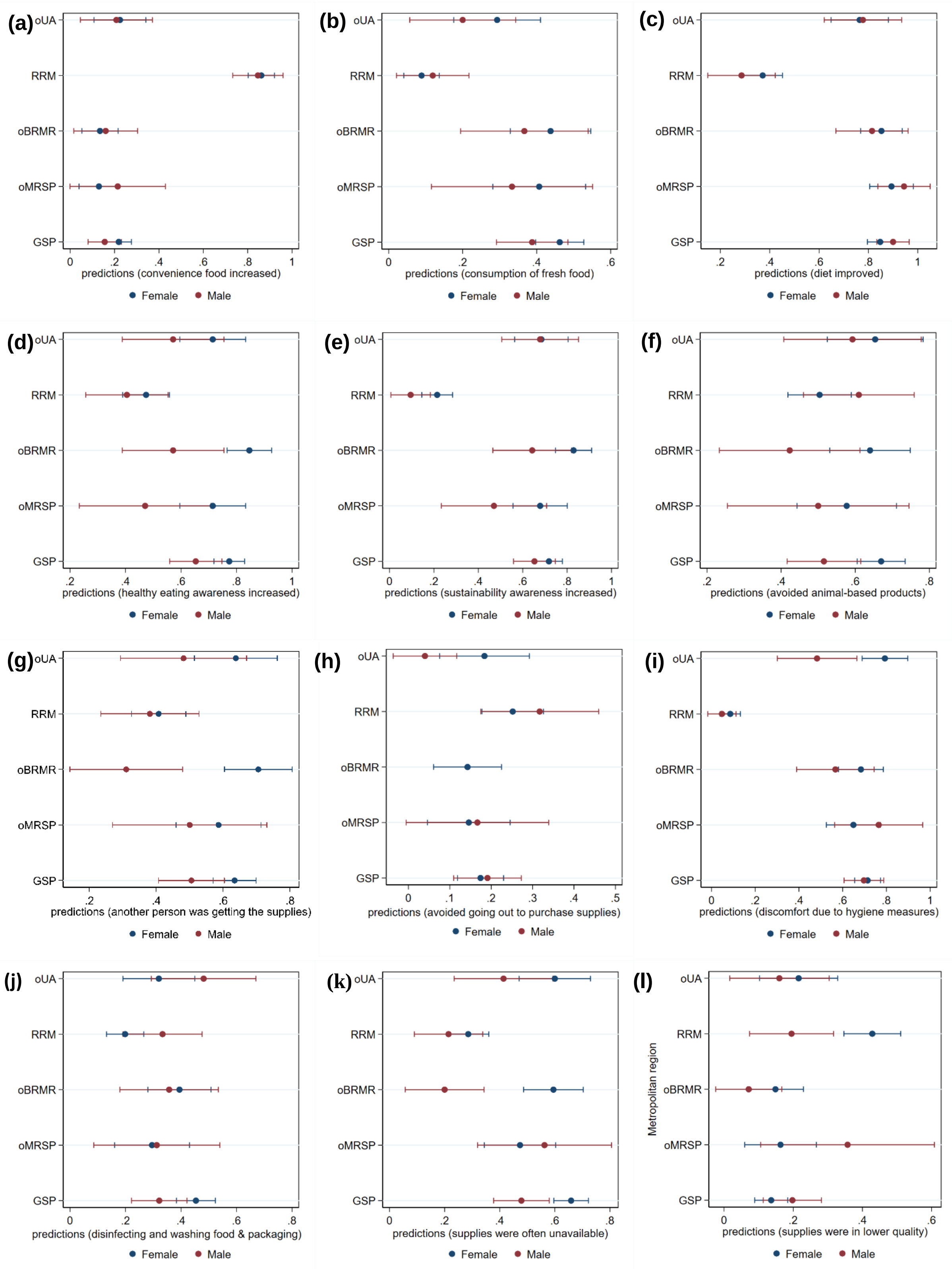

Figure 18. Self-reported changes in eating habits and buying groceries between sex and the different metropolitan regions. Dots represent adjusted predictions from no change (0) to change (1) of

the logistic regression correlations between sex and metropolitan areas. Error bars represent the 95% confidence intervals. Legend: GSP: Great São Paulo; oMRSP: other metropolitan regions in São Paulo state; oBRMR: other Brazilian metropolitan regions; RRM: Rhine-Ruhr Metropolis; oUA: other urban areas. Note: Only relevant and significant results are shown.

5.5 Discussion

Our findings show distinct self-reported eating habits and lifestyle changes in Brazilian and German metropolitan regions. Although comparing these two countries is not the study's main objective, it is important to discuss these differences within their socio-cultural contexts. While the Brazilian population's concerns were mostly related to improving eating habits and hygiene measures to maintain health, in Germany, priority was given to more physical activity to improve human well-being during the confinement period. Participants suffered changes in the working environment, such as becoming essential workers, transferring to home office work, short-time work, or even losing their jobs or businesses. The perception of the transmission risk made many participants avoid supermarkets and increase the recommended hygiene measures (i.e., long queues, distancing, use of masks and disinfectants). Food availability and quality have also created perceptions of food insecurities in the food supply.

Beneficial changes in eating habits were observed in the metropolitan regions of GSP, oMRSP, oBRMR, and oUA, concerning increased consumption of fresh food, awareness of healthy and sustainable eating, and a higher HEI than in the RRM. Traditional Brazilian food consumption is based on whole foods (rice, beans, tubers, vegetables) (Brasil, 2014). However, in recent years, the Brazilian diet has possibly worsened due to reduced vegetables and fruit and increased consumption of ultra-processed foods (de Carvalho et al., 2021). Differences in eating habits in our study can be explained by the characteristics of the population, composed of many urban middle-aged and highly educated women, and due to the working time flexibility in home office, which could have influenced the decision to eat healthier and more sustainably. Our survey did not include questions about who was responsible for purchasing and preparing meals. This would provide insights into whether females played an important role in household decision-making regarding food and nutrition.

It is essential to highlight that COVID-19 has affected food security in several parts of the world (FAO-WFP, 2020). The pandemic exposed vulnerabilities in Brazil. The inability to cope with the increasing unemployment and poverty rates provoked around 9 million people to be unable to generally afford a meal in 2020, despite the government's emergency measures (De Carvalho et al., 2021). A recent study in Germany also demonstrated that 3.5% of the population is still at risk of food insecurity even after COVID-19, especially children and older adults (WBAE & BMEL, 2023). Therefore, our findings must be interpreted with limitations because they represent perceived changes in the middle-upper class urban population and do not consider the vulnerable food-insecure population amid COVID-19.

A more significant concern about hygiene and disinfection was observed in GSP, oMRSP, oBRMR, and oUA. Brazilian health authorities highly recommended hygiene measures and personal protection, including everyday food hygiene and disinfecting procedures of food products and packaging, such as washing with water, soap, and alcohol-based sanitisers (Finger et al., 2021). Moreover, the concern about "cleanliness" is personally valued and fundamentally cultural in Brazil (Barbosa & Veloso, 2014), which might have been extrapolated due to the infection risk and the unequal and insufficient access to healthcare (Aquino et al., 2020). Another phenomenon during the pandemic is the expansion in food delivery, which explains why many participants have "another person getting the [food] supplies". The delivery industry in Brazil was intensified in the digital environment via mobile apps to deliver services of ready-to-eat foods and beverages that are convenient to the consumer (Botelho et al., 2020). Our questionnaire should have considered whether employment was formal or informal. However, informal work, such as delivery services, was particularly affected during the pandemic, lacking labour rights and increased health risks (Defossez, 2022; Tran et al., 2022).

In RRM, the German metropolis, many participants reported consuming more convenience foods, staples (such as bread), and less fresh produce. Nevertheless, the intake of fruits and vegetables in the RRM was still significantly higher than in other metropolitan regions. This was corroborated by the fact that participants declared that reducing the frequency of visiting supermarkets and convenience foods would make them easier to store. Consuming "comfort food" to satisfy anxiety cravings increased during the pandemic in Italy (Scarmozzino & Visioli, 2020). The RRM metropolis has an average German western-type diet, with a higher consumption frequency of bread and processed foods, including sausages, dairy, and sweets (Paris et al., 2022a, 2023). Additionally, food supplies were often perceived as of lower quality. COVID-19 made the food safety issues in the food supply chain more evident, including socioeconomic vulnerabilities and health risks (Marchant-Forde & Boyle, 2020; Rizou et al., 2020). Many disruptions occurred in the food supply (Benton, 2020; Power et al., 2020) caused by less migration of seasonal workers during the harvesting season, increased socioeconomic inequalities, and frequent COVID-19 outbreaks among workers in the food industry, especially in meat processing facilities (Mitaritonna & Ragot, 2020; Schneider & Götte, 2022).

In terms of PAL, the contrasting contexts of the two countries resulted in different outcomes. In RRM, there was a higher level of PAL and increased outdoor and indoor physical activities, with walking being the most popular activity among women and vigorous activities among men. This aligns with surveys on physical activity in Germany, where middle-aged and older adults with a high level of education were particularly likely to increase physical activity during the pandemic, considering that the PAL was widespread in the population before the pandemic (Nowossadeck et al., 2021; Manz & Krug, 2021). However, a noticeable reduction in physical activity levels was self-reported in the studied Brazilian regions. Self-isolation and obligatory hygiene and social-distancing measures, such as the use of masks and limited access to green urban spaces, could be the leading reasons behind the lower level of physical activity in both countries' contexts (Governo do Estado de São Paulo, 2021; Lima et al., 2021; Manz & Krug, 2021; Ximenes & Maglio, 2020).

The sociodemographic characteristics were homogenous among the studied metropolitan regions – middle-aged women, highly educated from the middle and upper classes, which needs to be considered when interpreting our study's results. This limitation derived from the sampling strategy (convenience sampling) and the survey dissemination media (online) implied that only participants with internet access had the opportunity to participate. Due to this selection bias, the sample cannot be considered representative but skewed, as described above. Also, there was self-selection bias, in which the participant felt attracted by the topic and intentionally decided to participate. However, achieving a representative sample constitutes a challenge per se, where the designed-based approach of random sampling is not always applicable (Zhao, 2021).

Strikingly, nearly 60% of the participants reported avoiding eating meat (or eating less) due to their enhanced awareness of the presumed zoonotic origin of the SARS-CoV2 pathogen. This suggests interesting questions for further research on meat consumption practices, including whether such changes during the pandemic are sustained into post-pandemic society.

5.6 Conclusion

This study investigates self-reported changes in eating habits, buying groceries, physical activity, and other individual habits during the first year of the COVID-19 pandemic across metropolitan regions in Brazil and Germany. Considering the homogeneity of the sample, with a high proportion of middle-aged and highly educated females from the middle and upper classes in both countries, it is possible to infer that in Brazilian metropolitan regions, greater emphasis was given to healthy and sustainable eating and concerns related to hygiene measures and food delivery. In the German RRM metropolis, convenient food consumption increased as people avoided going to the supermarket, and the perception that supply was of lower quality was higher. An increase in physical exercise was observed in the German metropolis, while in Brazilian metropolitan regions, physical activity decreased. Our study is relevant to understanding better behavioural changes in different cultural and spatial contexts to cope with emergencies, awareness, and preparedness for future pandemics.

6 Synthesis

This study was undertaken as part of a comprehensive effort to identify potential risks, develop sustainable solutions, and explore various dimensions related to urban challenges, health of food systems, and sustainable development following the One Health Approach. The primary contribution of this thesis is the sustainability assessment of food consumption sustainability and diet optimisation and the evaluation of dietary behaviour changes in urban areas in Germany and Brazil. Nonetheless, the application of these findings is constrained by methodological issues, the definition of holistic transdisciplinary approaches, and the need for sample representativeness.

The study focused on assessing the sustainability of food consumption in the Rhine-Ruhr-Metropolis and optimising dietary scenarios that minimise health risks for humans, animals, and the environment. Dietary changes are necessary to improve the sustainability of diets in line with the One Health approach. Achieving a transformation in food systems requires a holistic and systemic approach, and it remains one of the most significant challenges facing humanity today as it continues to drive scientific, innovative, and policy changes (von Braun et al., 2023), to which this thesis aims to contribute. Another focus of the study was on evaluating self-reported changes in eating habits and lifestyle in the Rhine-Ruhr Metropolis and Brazilian metropolitan regions during the COVID-19 pandemic. The COVID-19 pandemic has inevitably impacted perceptions related to food consumption and health risk awareness (Bisoffi et al., 2021), which have also affected the research and object of this study (i.e., food consumption). As a result, adapting to new data collection strategies and seeking answers about food consumption during COVID-19 became essential to continue the study.

Based on an initial analysis of secondary data, it appears that the type of animal product consumption significantly impacts both animal welfare and the environment. However, increasing the consumption of plant-based foods could improve overall health indicators. Upon further examination of primary data, it was found that a combined scenario involving a 55% reduction in greenhouse gas emissions and a 25% improvement in human health indicators could lead to a 97% decrease in animal welfare loss, depending on the baseline dietary pattern. This highlights the importance of shifting towards more vegetarian and flexitarian options to improve sustainability performance. It is worth noting that the dietary shifts examined only included soy milk and tofu as substitutes for meat and dairy. Plant-based alternatives may have different nutrition, environmental, and economic implications.

This transition towards more plant-based options is particularly pertinent in Western diets, where animal-sourced food consumption is already high (Pingali et al., 2023).

Life Cycle Assessment offers a comprehensive and holistic approach that can be integrated with the One Health concept. To enhance its traditional focus on environmental impact categories, LCA has expanded to include indicators for nutrition, human health impact, and animal welfare. However, there are methodological limitations associated with using LCA. The accuracy of life cycle inventories depends on factors such as data availability, assumptions, and data resolution. For this study, inventory at the European level was used instead of regional data due to data availability within the LCA software Optimeal®.

Furthermore, it was found that optimisations were only possible using Attributional LCA, as predicting future changes, particularly in land use change emissions, requires more sophisticated modelling approaches used in Consequential LCAs. This study did not incorporate land use changes (LUC) emissions, which would have significantly impacted the results. Land use changes are relevant because several impact categories of OECD countries are essentially exported to other middle- and low-income countries, contributing to LUC and their environmental consequences (Meier et al., 2014).

In a recent study on animal welfare, a framework was proposed that uses simplified indicators to estimate the loss of animal welfare (Scherer et al., 2018). These indicators are based on criteria such as space, time, and moral value and consider factors like animal lives lost, animal life years suffered, and morally adjusted animal lives. The study suggests that the loss of a greater number of lives would impact smaller animals more severely, as it would take more of them to generate one portion size compared to a larger animal. This raises important ethical questions about how humans value an animal's life versus its perceived utility to society. Interestingly, this study found that honey, fish, and seafood intake have a greater impact on animal welfare than beef, pork, or chicken. However, how these findings influence consumer choices remains unknown and is an area for future research. The German government has already made some improvements to comply with animal welfare legislation (BMEL, 2023), but there are still ongoing ethical debates about fish, seafood, and insects. These debates question whether these animals feel pain and how to consider animal welfare in their production systems (Boppré & Vane-Wright, 2019; Størkersen et al., 2021; Wolffrom & Lopes dos Santos, 2004). Regardless of the species, it is important to have a scientific consensus on including animal welfare in LCA and continuously improving animal farming conditions.

Assessing the impact of food consumption on human health proved challenging during this study's evaluation. Numerous difficulties were encountered when calculating the lifetime burden of daily food consumption on human health. The percentage of DALYs in relation to the overall health burden was applied to address this issue. However, this method could only assess the health burden compared to all-cause mortality, assuming that the dietary risk exposure occurred over a lifetime. To improve the methodology, HENI, which estimates the health burden by considering population-level exposure to dietary risks and generates a health burden in DALYs per gram of dietary risk, was utilised (Stylianou et al., 2021). Due to data and time constraints, the conversion factor used in the dietary risk factor estimation was retrieved from the US nutrition study NHANES (Stylianou et al., 2021). Future studies should enhance the model's sensitivity. As consumers increasingly prioritise health aspects, developing a comprehensive and straightforward indicator that can accurately inform them of the health impacts of individual food items is crucial. Understanding how particular food items impact people's health in line with nutrition recommendations is valuable information.

A comparative study was conducted on the Rhine-Ruhr Metropolis and metropolitan regions in Brazil to examine the impact of the pandemic on eating habits and lifestyle changes. These findings can aid in understanding the effects on human health and well-being and preparing for future pandemics. Notably, the sustainability assessment in the Rhine-Ruhr metropolis was conducted during the pandemic, profoundly influencing daily habits and behaviours related to health and sustainability. The comparison with Brazil added depth to this analysis. It highlighted the differences in both research areas, revealing that changes in Germany were associated with increased physical activity to improve well-being, while in Brazil, they were associated with more healthy eating and enhanced food hygiene. Despite the insightful findings, the study's limitations must be acknowledged, including the self-selection bias and the impact of COVID-19 on willingness to participate. Nonetheless, these results provide valuable insights into food consumption patterns, sustainability issues, and associated behaviours.

There are concerns regarding the One Health approach that emanated from this study. It aims to balance and optimise the health of people, animals, and ecosystems (OHHLEP et al., 2022). Still, it has evolved in practice often towards addressing only zoonotic diseases and antimicrobial resistance (Falkenberg & Schmiege, 2023). Some One Health topics are also part and parcel of the Planetary Health approach, which focuses on sustainability, environmental impacts, and sustainable diets (de Castañeda et al., 2023; Whitmee et al., 2015). Although this thesis was initially designed to fit into the One Health concept and covers its three dimensions (i.e., animal, human, and environmental health), it overlaps substantially with the Planetary Health approach in terms of sustainability assessments, nutrition, and dietary changes but not regarding animal health (de Castañeda et al., 2023; Falkenberg & Schmiege, 2023).

There is an ongoing debate about whether animal welfare is linked to animal health. Animal health should not be restricted only to the absence of diseases but also include an animal mental health dimension, especially with regard to emotions and negative experiences of pain and suffering of animals (Nicks & Vandenheede, 2014). The environment plays a crucial role in the physical and mental health of animals and humans. However, environmental degradation caused by human activities is a significant concern. Agricultural production is an essential component of the food system, and it is where animals and plants interact at the ecosystem and health levels within the economic and government spheres (European Commission, 2021a). The current food systems contribute little to the three dimensions of One Health but, through some serious modifications, as outlined in this thesis, have the potential to ascend from being part of the problem to becoming part of the solution.

7 Outlook

This chapter presents a foundation for future research on sustainable dietary shifts and healthier food systems, addressing underlying research questions in the following sub-chapters.

7.1 Definition of Transdisciplinary Approaches

Throughout this research, the One Health concept evolved and changed. As mentioned, the One Health concept has evolved and grown in its application to the animal-human interface, where the environment plays a crucial role in transmitting zoonotic diseases. Recently, One Health has taken on a more action-oriented approach with a broader definition, gaining a governance outlook for transforming current food systems into healthier future ones (OHHLEP et al., 2022). Similarly, Planetary Health has attracted international attention for promoting healthier diets from sustainable food systems (UN, 2021a). This research has overlapped interchangeably between these transdisciplinary approaches, making fitting into a single category challenging. Instead, it is more appropriate to consider this research as a combination of both approaches. Clear definitions are necessary to define the boundaries of each approach and their applicability, providing a clear path for building more resilient food systems in terms of health and sustainability in governance and science.

7.2 Methodological improvements

Life Cycle Assessment proprietary software, such as Optimeal®, offers a comprehensive nutrition-LCA inventory but has limitations. Unfortunately, not all inventory data were transparently presented, particularly regarding LCA sub-stages and LUC impacts. The availability of this information would significantly improve the depth of analysis, allowing the identification of environmental impact by sub-stage. Moving forward, it is crucial to focus on gathering regional data and detailed information on life cycle sub-stages while embracing more sophisticated modelling approaches that include LUC and health impacts derived from environmental impacts. While such methodologies are available, they were not in the scope of this thesis. Additionally, data availability at the regional level would improve the resolution of results, informing LCA practitioners and local governance about dietary shifts for sustainability aims at the regional level.

The animal welfare assessment in this study was based on the Scherer et al. (2018) framework but could be improved with more comprehensive criteria. Future research should focus on several key areas, including a) involving expert opinions to develop scientifically sound criteria for evaluating animal suffering and pain, b) improving data quality by collecting empirical qualitative data from current farming practices, c) broadening the range of animal species included to enhance data resolution and better reflect dietary habits, and d) making LCI data available within proprietary LCA software to allow for a more standardised assessment. Furthermore, in light of the growing concern over zoonotic diseases and AMR risks, there is a need for methodological advancements that consider animal health as a whole, including health risks for both animals and humans resulting from zoonotic disease transmission through food consumption. By assessing both physical animal health and animal welfare, science can achieve a more comprehensive understanding of the animal health dimension, which is essential for ensuring the sustainability and health of our food systems.

Estimating the impact of diets on human health has proven challenging, as discussed in Chapter 3. To address this issue, a new methodology was developed to understand better the health effects of specific food items on individuals within a population. However, additional research is needed better to characterise the factors and account for regional assessment differences. Models should also be developed to capture the non-linear nature of health data in optimisation programming. Furthermore, including factors such as sodium intake highlighted the importance of considering behavioural and metabolic risk factors and dietary risks. This underlines the critical link between nutrition and overall health and warrants further investigations.

7.3 Regional sustainable development

Working with regional data can offer advantages in obtaining more realistic baseline dietary information to promote localised nutritional shifts. Germany's social and cultural differences result in a heterogeneous food consumption pattern. While this research has limitations regarding sample representativeness, it can serve as a case study to encourage sustainable consumption in the Rhine-Ruhr region. To better inform dietary shifts in alignment with local sustainability goals and policies, it is necessary to have more representative data incorporating a larger number of municipalities and a representative sample of the population, ideally at the regional level but also potentially extending to the national level. Considering Germany's current dietary trends, science and innovation must work together, particularly in urban areas where diet changes occur rapidly. A market niche in plant-based meat and milk alternatives is flourishing to meet the needs of a growing flexitarian population (Gebhardt, 2020; Hellstern et al., 2024). Further research is needed on consumer preferences, sustainability and health information provided to consumers, affordability, adherence to plant-based diets, and the long-term environmental consequences and nutritional benefits of new plant-based alternatives.

The following research is relevant to applying the developed extended LCA framework to the studied Brazilian metropolitan regions. Brazil is a country of continental proportions with a rich dietary diversity and a powerful but environmentally damaging agri-business frontier. The concepts of One Health and Planetary Health in the context of sustainable nutrition for healthier food systems are still to be explored scientifically there and beyond. Given the limited coverage of food LCA (Life Cycle Assessment) in the Global South, expanding the comprehensive LCA practice beyond OECD countries is imperative. The dietary habits and production systems in tropical regions vastly differ from those in temperate areas, implying distinct sustainability outcomes. Therefore, it is crucial to understand the environmental impacts of food production and consumption in countries of the Global South to identify effective strategies to promote sustainable and healthier food systems.

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Appendices

This section provides supplementary information and material for the main empirical chapters 3, 4, and 5, which were published in peer-reviewed journals.

i. Chapter 3 Appendices: Eletronic Supplementary Material: "Changing dietary patterns is necessary to improve the sustainability of Western diets from a One Health perspective"

This material was submitted as electronic supplementary material and can be downloaded as a Word file at https://doi.org/10.1016/j.scitotenv.2021.151437.

S1. Estimation of average food consumption in the reference diet and the dietary scenarios

Table S1. Mapping between major food categories in the NVS II (2008) and specific food items according to EFSA (2018).

Food Category	Treu 2017 (NVS II Germany level)	NVS II 2008 (national level)	EFSA2018 (EUlevel)	Re-categorization	Food group rearrangement
Bread	Bread (brown, wholegrain, white) toast, buns	Whole and multigrain bread, mixed or brown bread, white bread, crispbread (all sorts), wholegrain and multigrain bread rolls, white bread/rye bread, pretzel rolls/pretzel/spear, other (corn, rice bread, toast), sandwiches	Wheat bread and rolls, rye bread and rolls, mixed wheat and rye bread and rolls, multigrain bread and rolls	Wheat bread and rolls, rye bread and rolls, mixed wheat and rye bread and rolls, multigrain bread and rolls	Bread
Cereals and cereal products	Pasta, muesli, rice, cereals, pancakes	Flours, rice, Cereals (processed), muesli (dry) Pasta, other (bulgur, millet)	Rice, wheat milling products, pasta, cereal flakes	Rice, pasta, breakfast cereals, milling products	Cereals and cereal products
Pastries	Fruit cake, pound cake, cookies, salty pastry, croissants, Danish pastries	Sweet (cakes and pies), spicy (pizza, onion pie, etc.) Small baked goods (sweet and spicy), cookies	Pastry and cakes, biscuits and cookies	Cakes and sweet pastries, biscuits, savoury pastry (pizza)	Baked goods
Cereal based dishes	-	Noodle dishes, rice dishes, dumplings	Pasta cooked	Pasta cooked (noodle dishes)	Cereal based dishes

Fruit vegetables raw	Tomatoes, cucumber, pepper	Vegetable raw (lettuce, tomato)	Tomato, pepper paprika, cucumber, melons	Fresh tomato, cucumber, pepper, paprika	Fresh vegetables
Fruit vegetables cooked/canned.	Pickled gherkin (can), tomato puree, tomato cooked, pepper cooked, tomato sauce	Pickled cucumbers, olives, canned preserves	Tomato ketchup, tomato purée Pickles	Processed tomatoes (tomato purée) Pickle	Processed vegetables
Root vegetables raw	Carrot, radish, onions, white cabbage, kohlrabi, lettuce, fennel, raw vegetable salad	Vegetable raw (lettuce, tomato)	Beets, carrots	Carrot	Fresh vegetables
Bulb vegetables raw			Onion	Onion	Bulbs
Cabbage raw			Head cabbage	Cabbage	Fresh vegetables
Leafy vegetables raw			Leafy vegetables (kale, endives), lettuce, iceberg lettuce	Leaf vegetables, lettuce	Fresh vegetables
Stalk vegetables raw			Leek	-	Stems
Mixed vegetables raw			Parsley	-	-
Root vegetables cooked/canned	Cooked carrot, celery, onions, garlic, broccoli, cauliflower, red cabbage, sauerkraut, spinach, greens (for making soup), leek cooked, asparagus and vegetable mix	Vegetables, heated (broccoli vegetables, carrot vegetables)	Beets, carrots	Carrot	Cooked vegetables
Bulb vegetables cooked/canned			-	-	-
Cabbage cooked/canned			-	Sauerkraut/cooked cabbage	Cooked vegetables
Leafy vegetables cooked			Spinach	Spinach	Cooked vegetables
Stalk vegetables cooked/canned			-	-	Stems
Mixed vegetables cooked/canned			-	-	-
Other vegetables	Chicory, capers, horseradish	-	-	-	-
Legumes	Bean, peas, lentils, bean sprouts	Roasted soybean, canned kidney beans	Beans, green beans, beans with pod, lentils, peas,	Beans, lentils	Legumes

Mushrooms	Common mushroom	Mushrooms (pfifferling and champignon)	Cultivated mushroom	Cultivated mushroom	Mushrooms
Vegetable-based meals	Mixed vegetables (raw and cooked	Salad mix with fresh and cooked vegetables, vegetables with sauces	Prepared mixed salad, vegetable sauce, vegetable soup, vegetable-based meals	Vegetable-based meals prepared with a mixed vegetable salad	Vegetable-based meals
Potatoes and potato products	Potatoes, mashed potatoes, fries, potato dumplings, potato crisps	Potatoes cooked with salt, mashed potatoes, potato pancakes, potato dumplings Other tubers, e.g. Batata, Jerusalem artichoke	Starchy roots and tubers: potatoes, maincrop potatoes, french fries, boiled potatoes, other starchy roots, and tubers	Boiled potatoes, potatoes and products French fries and potato crisps	Potatoes and potato products
Dishes based on potatoes	-	Potato salad, potato casserole	Potato-based meals	Potato-based meals	Potatoes and potato products
Pomaceous fruit raw	Apple, pear	Fruit in unprocessed form, fruit cooked/processed, dried fruit	Apple & pear (pome fruit)	Apple and pear	Pome fruit
Pomaceous fruit cooked/canned	Apple sauce		Apple compote	Apple compote	Fruit compote
Berries raw	Grapes, strawberries, melon		Berries and small fruits (strawberry)	Strawberry	Berries and small fruits
Berries cooked/canned	Raisin cooked, lingonberry heated		Strawberry jam (marmalade, fruit spread)	Strawberry jam	Marmalade
Stone fruit raw	Peach, plum, nectarine, sweet cherry		Stone fruit (peaches)	Peach	Stone fruit
Stone fruit cooked/canned	Peach can, cherry compote		-	-	-
Citrus fruit raw	Orange, mandarin		Citrus (orange and mandarine)	Orange and mandarine	Citrus
Citrus fruit cooked/canned	Lemon heated		-	-	-
Other fruits raw	Banana, kiwi, pineapple, mango		Miscellaneous fruit (kiwi & bananas)	Kiwi and bananas	Miscellaneous
Other fruits cooked/canned	Olives (can)		-	-	-
Mixed fruit	Fruit salad		-		-
Dried fruit	Fruit mix dried, raisin		Dried fruit	Dried fruit	Dried fruit
Fruit compote	Fruit compote, red fruit pudding		Fruit compote, apple compote	Apple compote	Fruit compote

Nuts and seeds	Peanuts, walnuts.	Cashew puree, peanut	Tree nuts, almonds, cashews, hazelnuts, walnuts	Tree nuts (general)	Nuts and seeds
Butter	Butter.	Butter (with herbs, with yoghurt, with sour cream	Animal fat, butter	Butter	Oils and fats
Other animal fats	Lard/pig fat	-	-		-
Margarine	Margarine	Margarine, half-fat margarine, mixed with olive oil	Margarine (low and average fat)	Margarine	Oils and fats
Oils	Olive oil, sunflower oil	-	Vegetable oil, olive oil	Vegetable oil	Oils and fats
Other vegetable fats	Coconut butter	-	Fats of mixed origin	-	-
Milk and mixed milk drinks	Cow milk, cacao drinks, milkshakes	Milk/mixed drinks, e.g. Cow's milk 3.5% fat, cocoa, milkshake	Cow milk, milk flavoured	Cow milk, flavoured milk	Milk and milk drinks
Dairy products	Yoghurt with and without fruits, condensed milk, (sour) cream, buttermilk, kefir, whey	Milk products, e.g. Kefir, buttermilk, soured milk, whey Yoghurt, yoghurt with flavouring Additives (for milk and yoghurt: full-fat, Reduced-fat, skimmed, not specified) Cream, sour cream, coffee cream Condensed milk, other (milk powder)	Evaporated milk, fermented milk, whey products, yoghurt plain, buttermilk, cream	Evaporated milk, fermented milk, whey, yoghurt plain, buttermilk, cream	Dairy products
Cheese and curd cheese	Gouda, Camembert, Edam cheese, cream cheese, curd cheese	Cheese and curd, e.g. Semi-hard cheese (edam & gouda), soft cheese (camembert), cream cheese and Pure quark with/without preparations (for the types of cheese mentioned: full-fat, Reduced fat, not specified) Sour milk, cooked, whey processed cheese	Cheese, quark, spreadable cheese, camembert, cheddar, danbo, edam, gouda, mozzarella	Gouda, Edam, Camembert, cream cheese, quark	Cheese

Dishes based on milk/products	Pudding (in sweets)	Rice pudding, muesli, cornflakes (prepared) Cheese dishes	Starchy pudding, white sauce with cheese	Starchy pudding (rice pudding); cheese sauce	Dishes based on milk products
Beef, veal	Beef: roast meat, steak, beef. Veal: wiener schnitzel	Meat, e.g. Beef, veal, pork Poultry meat, the meat of other animals Minced meat, offal Meat-based dishes: frikadelle (meatballs), schnitzel, stew (goulash)	Livestock meat: beef, veal, pork, lamb	Beef, veal, pork, lamb Meat-based dishes: meatballs, meat stew, meat burger	Livestock meat
Pork	Pork schnitzel, goulash, cooked smoked ham, roast meat, steak, cutlet.		-		
Poultry	Chicken breast fillet, turkey breast, grilled chicken, poultry ragout, duck		Poultry: chicken, turkey	Chicken, turkey	Poultry
Meat of other animals	Lamb (fillet, roast meat, cutlet), saddle of venison, rabbit meat, wild boar		Game meat	Game meat (mammals and birds)	Meat of other animals
Offals	Liver (pork, chicken)		Offal	Offal (pork liver)	Offal
Minced meat	Meatballs, minced meat		Mixed minced meat (pork and beef)	Mixed minced meat	Mixed meat
Other processed meat	Smoked meat.	Meat products and sausages, e.g. Bratwurst, smoked pork, salami, Krakauer, Smoked meat, ham	Preserved meat: ham, bacon Meat specialities, paté	Ham, smoked meat (bacon)	Preserved meat
Sausages	Salami, sausage, liver sausage, mortadella, bockwurst, ham sausage, leberkäse		Sausages: sausage, fresh sausage, smoked, dry sausage	Dry sausage (salami); sausage (bratwurst); smoked sausage (bockwurst); fresh and lightly cooked sausage (ham sausage);	Sausages
Fish, fish products and seafood	Fillet of salmon, salmon (smoked, cooked), herring (can), trout (smoked, fried), fish-	Fish and fish products, e.g. Roasted salmon fillets, smoked trout Crustaceans and shellfish, e.g. Crab, prawn,	Fish: herring, salmon, trout, tuna, cod, hake Fish products, fish cakes, fish fingers, Fish offal	Fish: salmon and trout, herring, tuna Crustaceans: shrimps Dishes based on fish: fish fingers	Fish, fish products and seafood

	finger, rosefish, herring, tuna, prawn	grilled king prawn, Mussel freshly cooked Dishes based on fish/crustaceans, e.g. Fish fingers, mussels in a white wine stock	Crustaceans (shrimps), molluscs (squid), amphibians, insects		
Eggs	Chicken egg. Excluding eggs in pastries, soups and sauces	Eggs, e.g. Scrambled eggs, pan-fried eggs, boiled egg Egg-based dishes, e.g. Omelet, egg salad, egg in mustard sauce	Fresh egg (chicken egg); egg-based meal (e.g., omelette)	Fresh egg (chicken egg); egg-based meal (e.g., omelette)	Eggs and egg products
Soups (without stews)	Beef stock, noodle soup, lentil soup, vegetable soup, pea soup, tomato soup	Soups and stews, e.g. Noodle soup with chicken Potato soup with meat sausage	Ready-to-eat soups Vegetable soup Meat/poultry soup	Ready-to-eat soups (noodle soup with chicken; potato soup with sausages)	Soups and stews
Sauces and spicy ingredients	Brown sauce, mustard, ketchup, cheese sauce/cream sauce, béchamel sauce, mayonnaise, salad dressing (yoghurt, vinegar/oil)	Sauces and seasoning ingredients - sauces, e.g. Hot sauces, cold sauces (also Fruit sauces and ketchup) - seasoning ingredients, e.g. Mustard, vinegar	Savory sauces White sauce (bechamel, cheese sauce) Brown sauce Vegetable sauce; Mustard Vinegar wine Tomato ketchup Curry sauce Dressing Mayonnaise	Brown sauce, white sauce	Savory sauces (no data available for NRW)
				Mustard, vinegar, ketchup, mayonnaise, salad dressing	Condiments (no data available for NRW)
Sweets, ice cream and desserts	Chocolate, ice cream, gumdrop, pudding, chocolate bar, rice pudding	Sweets, e.g. Chocolate, chocolate-containing products, confectionery and sweets, muesli bars, fruit bars - ice cream, e.g. Cream ice, soft ice cream	White sugar Chocolate (cocoa products) Bitter chocolate Milk chocolate Confectionary (non-chocolate Licorice candies Fruit sauce Molasses and other syrups Honey Ice and desserts	Chocolate (cocoa products) Bitter chocolate Milk chocolate Confectionary (non-chocolate Licorice candies	Sugar and confectionery
				Ice and desserts Ice cream (milk-based) Starchy pudding Custard	Ice cream and desserts
Sweet spreads	Jam, honey, hazelnut spread	Sweet spreads, e.g. Fruit spreads, jam, honey, syrup,		Honey, fruit sauce, molasses and syrups	Sugar and confectionery

		Spreads containing cocoa or nuts	Ice cream (milk-based) Starchy pudding Custard		
Sweeteners - thereof sugar	Sugar, sweetener	Sweeteners, e.g. Sugar, sugar substitutes, sweeteners		White sugar	Sugar and confectionery
Others thereof soya products	Vegetarian spread (yeast-based) soy drinks, vegetarian burgers	-	-	-	-
Snack food	-	Snack food	Snack food (mix of nuts, chocolate and chips), pretzels	Snack food (mix)	Snack food
Non-alcoholic beverages	-	Water, e.g. Mineral water, drinking water Coffee and tea (green/black), e.g. Cappuccino, coffee, green tea, black tea. Herbal and fruit tea, e.g. Peppermint tea, mate tea, rooibos tea	Drinking water Tap water Well water Bottled water Water icer Soft drinks Teas (infusion) Coffee (beverage) Coffee imitates Cocoa beverage	Water: mineral water/drinking water Coffee: coffee beverage Tea: infusion (herbal, black)	Non-alcoholic beverages
Fruit juices	-	Fruit juices/nectars, e.g. Apple spritzer, orange fruit juice, Multivitamin juice - vegetable juices, e.g. Carrot juice, tomato juice Fruit juice drinks, e.g. Ace fruit juice, wellness drink Other (e.g. Non-alcoholic beer), e.g. Malt beer, non-alcoholic sparkling wine	Fruit and vegetable juices Fruit juice Concentrate fruit juice Fruit nectar Mixed fruit juice Powdered fruit juice Vegetable juice Mixed vegetable juice Mixed vegetable and fruit juice	Fruit juice (apple & orange) Vegetable juice (tomato juice) Mixed fruit juice Fruit nectar	Fruit juices
Alcoholic beverages	-	- beer e.g. Dark beer, pils, radler - wine, sparkling wine, e.g. Red wine, white wine, mulled wine - spirits, e.g. Clear, whiskey, eggnog, grappa - other (e.g. Alcopops, cocktails), e.g. Punch, spritzer	Beer and beer-like Wine Fortified and liqueur wines Wine-like drinks Liqueur Spirits Alcoholic mixed drinks	Beer and beer-like regular beers, white wine, red wine, liqueur, spirits, alcoholic mixed drinks	Alcoholic beverages

Sources: (Broekema et al., 2019; EFSA, 2018; Max Rubner Institut, 2008; Treu et al., 2017)

Table S2 Reference diet in North-Rhine Westphalen per capita and day for men and women.

Food group category	Representative food items	Men		Women	
		Share	g/day	Share	g/day
Cereals			304.00		233.00
Bread and rolls		0.58	175.00	0.57	133.00
	wheat bread and rolls	0.37	112.00	0.37	85.12
	rye bread and rolls	0.07	22.75	0.07	17.29
	mixed wheat and rye bread and rolls	0.08	24.50	0.08	18.62
	multigrain bread and rolls	0.05	15.75	0.05	11.97
Baked goods		0.15	46.00	0.14	32.00
	cakes, tarts, sweet pastries	0.12	36.80	0.11	25.60
	biscuits	0.01	2.81	0.01	1.95
	savoury pastries (assumed as pizza)	0.02	6.39	0.02	3.56
Cereal and cereal products		0.12	36.00	0.14	32.00
	rice	0.01	1.87	0.01	1.66
	pasta	0.04	12.60	0.05	11.20
	breakfast cereals (e.g. müsli)	0.04	10.80	0.04	9.60
	flour (wheat) and cereals (bulgur, millet)	0.04	10.73	0.04	9.54
Cereal based dishes	*noodle dishes (cooked pasta)*	0.15	47.00	0.15	36.00
Vegetables			105.00		119.00
Fresh vegetables		0.51	53.91	0.55	66.00
Fruit vegetables		0.28	29.06	0.31	36.38
	tomato	0.66	19.06	0.66	23.86
	peppers and paprika	0.12	3.44	0.12	4.30
	cucumber	0.23	6.56	0.23	8.21
	brassica (assumed as cabbage)	0.01	0.94	0.01	1.56
	leaf vegetables (lettuce & other leafy vegetables)	0.08	8.91	0.08	9.87
	carrot raw	0.14	15.00	0.15	18.19
Processed vegetables		0.12	12.19	0.11	12.99
	processed tomatoes – assumed as tomato purée	0.10	10.78	0.10	11.43
	Pickle (reallocated in cucumbers)	0.01	1.41	0.01	1.56
Cooked vegetables		0.18	19.22	0.17	20.79
	carrot (cooked) assumed as "carrot", raw	0.06	6.09	0.06	6.76
	sauerkraut (cooked cabbage) is assumed as "head cabbage"	0.11	11.25	0.10	11.95
	spinach	0.02	1.88	0.02	2.08
Bulbs	*onion*	0.05	5.63	0.04	5.20
Stem	*leek*	0.04	4.69	0.04	5.20
Mushrooms	*cultivated mushrooms*	0.01	0.94	0.01	1.04

Legumes		0.08	8.44	0.07	7.79
	green beans	0.16	1.39	0.16	1.28
	peas without pods (fresh)	0.42	3.57	0.42	3.30
	beans	0.28	2.33	0.28	2.16
	lentils	0.14	1.14	0.14	1.05
Vegetable-based meals			103.00		110.00
	mixed salads	0.48	49.44	0.48	52.80
	vegetable-based meals	0.52	53.56	0.52	57.20
Potatoes and potato products			98.00		76.00
Potatoes and potato products		0.92	90.00	0.93	71.00
	potato (boiled)	0.52	46.80	0.52	36.92
	potato products are assumed to be potato salad	0.25	22.50	0.25	17.75
	main crop potato	0.10	9.00	0.10	7.10
	french fries and chips	0.13	11.70	0.13	9.23
Potato based meals	*potato salad*	0.08	8.00	0.07	5.00
Fruit and fruit products			214.00		261.00
Pome fruit		0.51	109.72	0.47	122.93
	apple	0.44	93.26	0.40	104.49
	pear	0.08	16.46	0.07	18.44
Fruit compote	*apple compote*	0.03	6.35	0.03	7.57
Berries and small fruits	*strawberry*	0.10	21.76	0.13	33.10
Marmalade	*strawberry jam*	0.00	0.91	0.00	0.95
Stone fruit	*peach*	0.06	13.60	0.08	21.75
Citrus		0.11	23.58	0.12	30.26
	orange	0.07	15.32	0.08	19.67
	mandarine	0.04	8.25	0.04	10.59
Miscellaneous		0.16	33.55	0.16	40.66
	kiwi	0.02	4.03	0.02	4.88
	banana	0.14	29.52	0.14	35.78
Dried fruit	*dried fruit (excluded, value included in tree nuts, in snacks)*	0.00	0.00	0.00	0.00
Nuts and seeds	*tree nuts (data not available for nut types)*	0.02	4.53	0.01	3.78
Fats and oils			26.00		17.00
	butter	0.47	12.32	0.46	7.85
	margarine	0.34	8.89	0.35	5.88
	vegetable oil	0.18	4.79	0.19	3.27
Dairy products and cheese			258.00		240.00
Milk and milk mix drinks		0.52	134.00	0.45	108.00
	cow milk	0.49	126.12	0.42	101.65
	flavoured milk	0.03	7.88	0.03	6.35
Dairy products		0.31	79.00	0.37	89.00
	evaporated milk	0.01	2.58	0.01	2.40

	fermented milk	0.10	26.57	0.13	30.14
	yoghurt (only plain is considered)	0.14	37.19	0.18	42.20
	buttermilk	0.05	12.14	0.06	13.78
	cream	0.00	0.52	0.00	0.48
Cheese and quark		0.17	45.00	0.18	43.00
	hard-cheese	0.06	14.81	0.06	14.15
	Quark (reallocated in Yoghurt)	0.06	15.38	0.06	14.70
	cream cheese	0.01	1.71	0.01	1.63
	camembert	0.01	2.28	0.01	2.18
	edam	0.01	3.42	0.01	3.27
	gouda	0.03	7.41	0.03	7.08
Dishes based on milk and products	*milk rice, pudding (assumed as starchy puddings)*		19.00		19.00
Meat and meat products			97.00		52.00
Meat			46.00		26.00
Livestock meat			27.70		13.25
	beef	0.42	11.64	0.42	5.56
	veal	0.06	1.66	0.06	0.79
	pork	0.47	13.02	0.47	6.23
Meat of other animals			1.39		0.66
	lamb	0.04	1.16	0.04	0.56
	game (excluded and reallocated as general meat products)	0.01	0.22	0.01	0.11
Poultry			10.45		7.85
	chicken	0.85	8.89	0.85	6.67
	turkey	0.15	1.57	0.15	1.18
Offal	*offal excluded, value reallocated as general meat products*		0.52		0.49
Minced meat	*minced*		7.32		4.42
Meat products			0.74		0.60
Meat products and sausages			52.00		27.00
Processed meat			0.90		0.93
	ham	0.79	0.71	0.79	0.74
	bacon	0.21	0.19	0.21	0.20
Sausages			51.10		26.07
	sausages	0.18	9.20	0.18	4.69
	fresh sausage (e.g. ham sausage)	0.24	12.26	0.24	6.26
	cooked/smoked sausage	0.36	18.40	0.36	9.38
	dry sausage (e.g. salami)	0.22	11.24	0.22	5.74
Dishes based on meat			60.00		31.00
	meat-based meals (“Schnitzel”)	0.32	19.20	0.32	9.92
	meatballs/burger (“Frikadelle”)	0.42	25.20	0.42	13.02

	meat stews	0.26	15.60	0.26	8.06
Fish products and seafood			15.00		13.00
Fish		0.88	13.15	0.88	11.40
	salmon and trout	0.74	9.73	0.74	8.44
	herring	0.26	3.42	0.26	2.96
Prawn		0.07	1.01	0.07	0.87
Mussel	*reallocated to fish products*	0.06	0.84	0.06	0.73
Fish products			13.84		10.73
Eggs and egg products			22.00		18.00
Egg	*fresh chicken egg*	0.82	18.00	0.72	13.00
Egg-based meals	*assumed as omelette*	0.18	4.00	0.28	5.00
Ready-to-eat soups	*mix of vegetable and meat soup (assumed as potato soup with sausages)*		92.00		71.00
Sugar, confectionery and desserts			56.00		51.00
Sugar and confectionery		0.45	25.00	0.49	25.00
	chocolate (as representative of cocoa products)	0.35	8.65	0.35	8.65
	confectionary (non-chocolate, assumed as gelatin candies)	0.19	4.75	0.19	4.75
	white sugar	0.34	8.48	0.34	8.48
	honey	0.05	1.28	0.05	1.28
	syrups	0.07	1.85	0.07	1.85
Desserts		0.55	31.00	0.51	26.00
	ice desserts	0.22	6.82	0.22	5.72
	ice cream (assumed milk-based vanilla flavoured)	0.40	12.40	0.40	10.40
	starchy pudding	0.13	4.03	0.13	3.38
	custard	0.25	7.75	0.25	6.50
Snack food			9.00		6.00
	mix of chocolates, tree nuts and chips	0.88	7.92	0.88	5.28
	pretzels	0.12	1.08	0.12	0.72
Non-alcoholic beverages					
Water			1177.00		1147.00
	drinking water (included as tap water)	0.04	51.79	0.04	50.47
	tap water	0.56	659.12	0.56	642.32
	bottle water	0.30	349.57	0.30	340.66
	still mineral water	0.10	116.52	0.10	113.55
Coffee beverages			628.00		552.00
Tea			129.00		272.00
	herbal	0.77	99.33	0.77	209.44
	black	0.23	29.67	0.23	62.56
			225.00		197.00

Fruit juice, nectar juice	*fruit juice*	0.09	21.23	0.09	18.59
	apple juice	0.41	92.66	0.41	81.12
	orange juice	0.35	79.14	0.35	69.29
	fruit nectar	0.05	10.74	0.05	9.40
	mixed fruit juice	0.08	18.55	0.08	16.24
	vegetable juice	0.01	2.68	0.01	2.35
Soft drink			234.00		92.00
	soft drink, fruit content	0.24	56.16	0.24	22.08
	soft drink flavoured	0.46	107.64	0.46	42.32
	cola beverages	0.30	70.20	0.30	27.60
Alcoholic beverages					
Beer			219.00		39.00
	beer and alike	0.20	43.80	0.20	7.80
	beer regular	0.80	175.20	0.80	31.20
Wine			37.00		34.00
	white wine	0.31	11.47	0.31	10.54
	red wine	0.69	25.53	0.69	23.46
Cider	*wine-like drink*	0.04	1.07	0.03	0.99
reallocated as "wine-like"	*fortified and liqueur wines*	0.01	0.19	0.01	0.17
	wine like drinks	0.03	0.89	0.02	0.82
Spirits			3.00		1.00
Alcoholic mixed drinks	*assumed as 1/3 spirits 2/3 soft drink fruit based*		2.00		1.00
	spirits	0.3	0.7	0.3	0.3
	fruit soft drink	0.7	1.3	0.7	0.7

Table S3. Dietary recommendations for alternative diet scenarios.

Food Group	DD (DGE, 2021a)	**VD** **(Richter et al., 2016)**	**MD** **(Bach-Faig et al., 2011; Fidanza and Alberti, 2005)**
Cereals, cereal products, potatoes	1-2 servings a day Bread and cereals and 1 serving a day potatoes, pasta, rice preferably wholegrain (400-760g)	2-3 meals a day Bread, cereals, pasta, rice preferably wholegrain (400-760g)	1-2 servings per meal bread/pasta/rice, preferably wholegrain 3 servings a week of potatoes
Vegetables	3 servings a day (~400g) Cooked and raw vegetables	3 servings a day (~400g) Cooked and raw vegetables, with a	More than 2 servings a day of vegetable variety, cooked and raw 2-3 servings a week of legumes

		preference for dark greens for calcium	
Fruit	2 servings a day (~250g) Fruit Nuts (25g - serving)	2 servings a day (~300g) fruit 50g dry fruit or juices 1-2 servings of nuts (30-60g), preferably almonds for calcium	1-2 servings a day of fruit variety 1-2 servings a day of olives and nuts
Milk & milk products	1-2 servings a day 200-250g milk 50-60g cheese Preferably low fat	1-3 servings per week of plant-based protein sources (legumes, grains)	2 servings a day of milk and dairy
Meat, sausages, fish & eggs	Weekly intake 300-600g meat or sausages 150-300g fish Max. 3 eggs		Weekly intake 2 servings of white meat 3 servings fish 2-4 eggs Less than 2 servings of red meat 1 serving of processed meat
Fats & oils	Daily intake 10-15g vegetable oils 15-30g margarine or butter	2-4 servings a day of unprocessed omega-3-rich oils	2 servings a day of olive oil
Beverages	1.5 L water and infusions	Water and fortified beverages with low-calorie 1-2 L	1-2L Water and infusions Red wine 1-2 servings a day
Comments	Avoid salt and sugary foods, and do not include alcohol consumption	Supplements with microalgae omega-3, B12 vitamin, vitamin D, fortified beverages with calcium, the addition of iodised sea salt	Contains herbs and bulbs for seasoning Consists of 2 servings of sugary foods a week Focus on local supply and culinary traditions

Table S4. Average food consumption across the different dietary scenarios* in grams per day for men and women. Brackets indicate min and maximum, respectively.

FOOD ITEM	MEN (GRAMS PER DAY)				WOMEN (GRAMS PER DAY)			
	RD	**DD**	**VD**	**MD**	**RD**	**DD**	**VD**	**MD**
Almond, sweet	0.0	4.2 (1.4, 5)	5 (5, 5)	5 (5, 5)	0.0	2.4 (1.7, 3.1)	10 (10, 10)	5 (5, 5)
Apple	93.3	95 (95, 95.2)	93.5 (91.5, 94.6)	86.7 (57.5, 101.9)	104.5	99.7 (61.3, 127.5)	104.8 (99.8, 109.6)	84 (26.6, 127.5)
Bacon	0.2	0.2 (0.2, 0.2)	-	0 (0, 0)	0.2	0 (0, 0)	-	0 (0, 0)
Bananas	29.5	35.0 (35, 35)	29.9 (28.3, 30.7)	5 (5, 5)	35.8	35 (35, 35)	36.3 (32.8, 40.1)	0 (0, 0)
Beans	2.3	10 (10, 10)	10 (10, 10)	10 (10, 10)	2.2	6.5 (4.2, 9.1)	20 (20, 20)	10 (10, 10)
Beans, green, without pods	1.4	10 (10, 10)	5 (5, 5)	5 (5, 5)	1.3	1.9 (1.6, 2.3)	20 (20, 20)	5 (5, 5)
Beans, with pods	0.0	20 (20, 20)	0 (0, 0)	0 (0, 0)	0.0	10 (10, 10)	20 (20, 20)	0 (0, 0)
Beef meat	11.6	5.0 (5, 5)	-	5 (5, 5)	5.6	5 (5, 5)	-	1.6 (1.6, 1.6)
Beer and beer-like beverage	43.8	2 (2, 2)	43.8 (43.2, 43.8)	38.2 (27.5, 44.7)	7.8	2 (2, 2)	8 (7.7, 8.2)	0 (0, 0)
Beer, regular	175.2	2 (2, 2)	175 (174.3, 175)	10 (10, 10)	31.2	2 (2, 2)	10 (10, 10)	10 (5.1, 10)
Beetroot	0.0	20 (20, 20)	0 (0, 0)	0 (0, 0)	0.0	20 (20, 20)	20 (20, 20)	0 (0, 0)
Biscuits	2.8	6.9 (1.2, 12.6)	-	0 (0, 0)	2.0	0 (0, 0)	-	0 (0, 0)
Bitter chocolate	-	-	-	-	-	-	2.7 (1.3, 4.3)	-
Black tea, infusion	29.7	30.3 (27.1, 33.5)	29.8 (29.4, 30.5)	25.5 (20.3, 28.4)	62.6	335 (335, 335)	62.7 (60.8, 65)	47.5 (21.5, 65.4)
Bottled water	349.6	100 (100,100)	349.2 (329.3, 361.9)	100 (100,100)	340.7	100 (100,100)	340.7 (339.8, 340.7)	314.9 (327.6, 361.8)
Butter	12.3	5.8 (1.5, 10.2)	-	0 (0, 0)	7.8	0 (0, 0)	-	0 (0, 0)
Buttermilk	12.1	13.4 (12, 14.6)	-	11.4 (9.7, 12.4)	13.8	12.5 (11, 17.1)	-	17.7 (11.6, 24)
Carrots	21.1	30 (30, 30)	50 (50, 50)	50 (50, 50)	25.0	30 (30, 30)	30 (30, 30)	50 (50, 50)
Cashew nuts	0.0	9.3 (0.5, 18)	2.6 (1.9, 3)	0 (0, 0)	0.0	7.3 (1.2, 12)	8 (8, 8)	0 (0, 0)
Cereal flakes	10.8	19.2 (1.6, 30.8)	43.8 (43.7, 43.8)	43.8 (43.7, 43.8)	9.6	18.3 (3.3, 32.4)	11.7 (7.9, 15.6)	43.8 (43.8, 43.8)
Cheese	14.8	19.8 (11.3, 31.8)	-	0 (0, 0)	14.2	14 (9.5, 18.9)	-	0 (0, 0)
Cheese, Camembert	2.3	2 (2, 2)	-	0 (0, 0)	2.2	1.8 (1.4, 1.8)	-	0 (0, 0)
Cheese, Cheddar	0.0	3 (2.6, 3)	-	0 (0, 0)	0.0	1.4 (1.2, 1.6)	-	0 (0, 0)
Cheese, Danbo	0.0	2 (2, 2)	-	0 (0, 0)	0.0	1.7 (1.4, 1.8)	-	0 (0, 0)
Cheese, Edam	3.4	3 (3, 3)	-	2.1 (1.9, 3)	3.3	3 (2.7, 3)	-	10 (5.1, 10)

Cheese, Gouda	7.4	5 (5, 5)	-	3 (2.5, 4.1)	7.1	5 (4.8, 5)	-	8.9 (5, 9.4)
Cheese, Mozzarella	0.0	5 (3.7, 5)	-	0 (0, 0)	0.0	0.7 (0.6, 0.9)	-	0 (0, 0)
Cheese, processed spreadable	1.7	4 (2.7, 5)	-	0 (0, 0)	1.6	0 (0, 0)	-	0 (0, 0)
Chicken egg	18.0	14 (13, 13)	-	19.3 (19.2, 21.2)	13.0	13 (13, 13)	-	19.3 (19.3, 19.3)
Chicken meat	8.9	4 (4, 4)	-	7.3 (7.3, 7.3)	6.7	4 (3.3, 4)	-	7.3 (7.3, 7.3)
Chocolate (cocoa) products	8.7	1 (1, 1)	-	1.4 (1.4, 1.4)	8.7	0 (0, 0)	-	1.4 (1.4, 1.4)
Cider	1.1	1 (1, 1)	1.1 (1.1, 1.1)	0 (0, 0)	1.0	1.6 (1.4, 1.6)	1.2 (1.2, 1.3)	0 (0, 0)
Coffee	628	628.1 (611.2, 630.8)	628 (583.7, 630)	250 (205, 250)	552.0	552.4 (539.6, 573.8)	552 (543.3, 553.2)	250 (205, 205)
Cola beverages	70.2	70.8 (61.5, 81.2)	70.3 (69.5, 72.2)	64.2 (47.5, 74.4)	27.6	23 (15.6, 28.6)	27.8 (26.6, 29.3)	8.9 (5, 13.4)
Confectionery (non-chocolate)	4.8	1 (1, 1)	-	1.4 (1.4, 1.4)	4.8	0 (0, 0)	-	1.4 (1.4, 1.4)
Cooked smoked sausage	18.4	3.5 (3.5, 3.5)	-	0 (0, 0)	9.4	2.5 (2.1, 3.5)	-	0 (0, 0)
Cow milk	126.1	100 (100,100)	-	124.6 (103.5, 133)	101.6	100 (95.4, 100)	-	115 (115, 115)
Cream	0.5	0 (0, 0)	-	0 (0, 0)	0.5	0 (0, 0)	-	0 (0, 0)
Cucumbers	8.0	30 (30, 30)	50 (50, 50)	50 (50, 50)	9.8	20 (20, 20)	20 (20, 20)	50 (50, 50)
Cultivated mushroom	0.9	20 (20, 20)	20 (20, 20)	20 (20, 20)	1.0	20 (20, 20)	20 (20, 20)	20 (20, 20)
Custard	7.8	2 (2, 2)	-	0 (0, 0)	6.5	0 (0, 0)	-	0 (0, 0)
Dry sausage	11.2	2 (2, 2)	-	0 (0, 0)	5.7	2 (1.5, 2)	-	0 (0, 0)
Egg-based meal	4.0	3 (3, 3)	-	0 (0, 0)	5.0	3 (3, 3)	-	0 (0, 0)
Evaporated milk	2.6	4.6 (3.7, 5.7)	-	0 (0, 0)	2.4	0 (0, 0)	-	0 (0, 0)
Fermented milk products	26.6	15 (15, 15)	-	24.5 (18.6, 27.3)	30.1	15 (15, 15)	-	31.4 (16, 46.6)
Fish products	13.8	15.6 (10.9, 22.7)	-	0 (0, 0)	10.7	11 (6.2, 19.2)	-	0 (0, 0)
Flavored milk	7.9	7.5 (7.5, 7.5)	-	1.8 (1.6, 2.1)	6.4	0 (0, 0)	-	0 (0, 0)
French fries	11.7	13.7 (7.6, 22.1)	10 (5.3, 12)	0 (0, 0)	9.2	0 (0, 0)	10.9 (7.7, 14.6)	0 (0, 0)
Fresh and lightly cooked sausage	12.3	3 (3, 3)		2.4 (2.4, 2.4)	6.3	3 (2, 3)	-	2..4 (2.4, 2.4)
Fruit and vegetable juices	18.5	10 (10, 10)	14.8 (6.4, 20.5)	16.3 (14.3, 17.1)	16.2	10 (10, 10)	16.4 (15.9, 16.9)	6.7 (4.5, 8.2)
Fruit compote	6.3	7.3 (5.7, 8.8)	6.7 (6.5, 6.9)	0 (0, 0)	7.6	2.5 (1.8, 3.2)	15 (15, 15)	0 (0, 0)
Fruit juice	21.2	10 (10, 10)	21.4 (21, 21.6)	15.5 (11.3, 17.8)	18.6	10 (10, 10)	18.8 (17.8, 19.7)	0.7 (0.7, 1.1)
Fruit nectar	10.7	10 (10, 10)	11 (10.7, 11.2)	3.2 (2.7, 3.9)	9.4	4.6 (3.4, 6)	9.7 (9.2, 10.2)	0 (0, 0)
Fruit sauce	-	1.5 (1, 1.9)	0.5 (0.5, 0.5)	0 (0, 0)	-	-	-	0 (0, 0)
Ham, pork	0.7	3.5 (3.5, 3.5)	-	2.4 (2.4, 2.4)	0.7	1.3 (1.1, 1.7)	-	0 (0, 0)

Hazelnuts	0.0	0.1 (0.1, 0.2)	3 (2.7, 3.6)	2 (2, 2)	0.0	0 (0, 0)	8 (8, 8)	2 (2, 2)
Head cabbage	12.2	30 (30, 30)	30 (30, 30)	30 (30, 30)	13.5	20 (20, 20)	30 (30, 30)	30 (30, 30)
Herbal tea, infusion	99.3	99.4 (98.3, 100.8)	99.3 (98.8, 99.5)	99.7 (98.4, 101.4)	209.4	209.9 (204.6, 218.2)	209.4 (209.3, 209.4)	209.8 (207.1, 214.1)
Herring	3.4	5.8 (5.7, 6.8)	-	52.1 (28.8, 78.7)	3.0	8.3 (5.9, 15.1)	-	17.5 (17.5, 17.5)
Honey	1.3	1 (1, 1)	-	0 (0, 0)	1.3	0 (0, 0)	-	0 (0, 0)
Ice cream, milk-based	12.4	2 (2, 2)	-	0 (0, 0)	10.4	1.8 (1.5, 2.6)	-	0 (0, 0)
Iceberg-type lettuce	0.0	30 (30, 30)	30 (30, 30)	30 (30, 30)	0.0	20 (20, 20)	30 (30, 30)	30 (30, 30)
Ices and desserts	6.8	2 (2, 2)	-	-	5.7	0 (0, 0)	-	0 (0, 0)
Jam	0.9	4 (1, 7.6)	1.7 (1.6, 2)	0 (0, 0)	0.9	0 (0, 0)	2.3 (1.7, 3)	0 (0, 0)
Juice, apple	92.7	10 (10, 10)	92.8 (91.5, 94.5)	86.5 (85.4, 101.2)	81.1	10 (10, 10)	81.4 (77.9, 86.2)	62.8 (-6.4, 91.4)
Juice, orange	79.1	10 (10, 10)	79.3 (78.1, 80)	73.6 (51.4, 83.3)	69.3	10 (10, 10)	69.5 (66.2, 73.5)	52.5 (12.1, 75.6)
Juice, tomato	2.7	3.2 (3.1, 3.4)	0 (0, 0)	1.6 (1.5, 1.6)	2.4	3.1 (2.8, 3.5)	2.4 (2.4, 2.5)	0 (0, 0)
Kiwi	4.0	10 (10, 10)	4.2 (4.1, 4.3)	0 (0, 0)	4.9	8 (8, 8)	15 (15, 15)	0 (0, 0)
Leaf vegetables	8.9	30 (30, 30)	30 (30, 30)	30 (30, 30)	9.9	20 (20, 21.1)	50 (50, 50)	30 (30, 43.6)
Leek	4.7	20 (20, 20)	10 (10, 10)	10 (10, 10)	5.2	20 (20, 20)	5.3 (5.2, 5.5)	10 (10, 10)
Lentils	1.1	4.9 (3.5, 6.1)	10 (10, 10)	10 (10, 10)	1.1	9 (3.8, 14.8)	1.6 (1.4, 1.8)	10 (10, 10)
Lettuce, excluding iceberg-type lettuce	0.0	30 (30, 30)	30 (30, 30)	30 (30, 30)	0.0	20 (20, 20.4)	20 (20, 20)	30 (30, 30)
Main-crop potatoes	9.0	10.9 (8.3, 12.8)	25 (25, 25)	25 (25, 25)	7.1	25 (25, 25)	7.5 (7, 8.1)	25 (25, 25)
Mandarins	8.3	10 (10, 10)	5 (5, 5)	3 (2.5, 3.3)	10.6	10 (10, 10)	20 (20, 20)	0 (0, 0)
Margarine, low-fat	0.0	0 (0, 0)	0 (0, 0)	0 (0, 0)	0.0	0 (0, 0)	3.8 (1.4, 6.9)	0 (0, 0)
Margarine, normal fat	8.9	2.3 (1, 4.1)	2.8 (2, 4.8)	0 (0, 0)	5.9	0 (0, 0)	5 (5, 5)	0 (0, 0)
Meat and meat products	0.7	3.5 (3.5, 3.5)	-	0 (0, 0)	0.6	2.7 (1.9, 3)	-	0 (0, 0)
Meatballs	25.2	3 (3, 3)	-	1.6 (1.6, 1.6)	13.0	3 (3, 3)	-	0 (0, 0)
Meat burger	0.0	7.2 (2.6, 13.1)	-	0 (0, 0)	0.0	2.1 (1.6, 3.1)	-	0 (0, 0)
Meat stew	15.6	3 (3, 3)	-	1.6 (1.6, 1.6)	8.1	3 (3, 3)	-	0 (0, 0)
Meat-based meals	19.2	3 (3, 3)	-	1.6 (1.4, 1.6)	9.9	3 (3, 3)	-	0 (0, 0)
Melons	0.0	20 (20, 20)	0 (0, 0)	-	0.0	10 (10, 10)	0.2 (0.2, 0.2)	0 (0, 0)
Mixed beef and pork meat	7.3	4 (4, 4)	-	7 (4.9, 10.2)	4.4	4 (3.5, 4)	-	1.6 (1.6, 1.6)
Mixed wheat and rye bread and rolls	24.5	70 (70, 70)	43.8 (43.8, 43.8)	43.8 (43.7, 43.8)	18.6	75 (75, 75)	60 (60, 60)	43.8 (43.8, 43.8)

Molasses and other syrups	1.9	2 (2, 2)	2.1 (2, 2.2)	1.4 (1.4, 1.4)	1.9	1 (0.9, 1)	3.4 (2.4, 4.7)	1.4 (1.4, 1.4)
Multigrain bread and rolls	15.8	25 (25, 25)	43.8 (43.8, 43.8)	43.8 (43.7, 43.8)	12.0	75 (75, 75)	60 (60, 60)	43.8 (43.8, 43.8)
Mutton/lamb meat	1.2	0.2 (0.2, 0.2)		1.6 (1.4, 1.6)	0.6	0.2 (0.2, 0.2)	-	0 (0, 0)
Olive oil	0.0	0 (0, 0)	20 (20, 20)	20 (20, 20)	0.0	0 (0, 0)	5 (1.1, 11)	20 (20, 20)
Onions, bulb	5.6	10 (10, 10)	15 (15, 15)	15 (15, 15)	5.2	5 (5, 5.3)	5.4 (5.2, 5.6)	15 (15, 15)
Oranges	15.3	16 (13.9, 18.1)	10 (10, 10)	9.9 (7.4, 9.9)	19.7	16.3 (13.4, 19.7)	19.9 (19.1, 20.9)	6.9 (4.6, 7.9)
Parsley, herb	0.0	2.8 (2.2, 3.4)	0 (0, 0)	5 (5, 5)	0.0	10 (9.4, 10)	0.4 (0.4, 0.4)	4.1 (3.3, 5.3)
Pasta, cooked	47.0	49.1 (35.9, 60.8)	-	17.6 (0.8, 31.7)	36.0	31.6 (16.1, 40.8)	-	0 (0, 0)
Pasta, wheat flour, without eggs	12.6	16.2 (11.4, 20.3)	43.8 (43.8, 43.8)	43.8 (43.7, 43.8)	11.2	5.2 (2.1, 7.8)	11.9 (10.4, 13.6)	43.8 (43.8, 43.8)
Pastries and cakes	36.8	38.7 (16.8, 54.6)	-	0 (0, 0)	25.6	8.4 (0.2, 15.1)	-	0 (0, 0)
Peaches	13.6	15 (15, 15.1)	70 (70, 70)	70 (70, 70)	21.8	18.6 (15, 22.2)	30 (30, 30)	70 (70, 70)
Peanut	0.0	4.2 (0.2, 6.1)	2.7 (1.9, 3.2)	0 (0, 0)	0.0	0 (0, 0)	3.2 (1.2, 5.2)	0 (0, 0)
Peanuts butter	0.0	3.6 (1.4, 5.3)	0 (0, 0)	0 (0, 0)	0.0	0 (0, 0)	3.1 (1, 5)	0 (0, 0)
Pear	16.5	20 (20, 20)	70 (70, 70)	70 (70, 70)	18.4	20 (20, 20)	30 (30, 30)	70 (70, 70)
Peas	0.0	2.2 (1.7, 2.6)	3 (3, 3)	3 (3, 3)	0.0	1.7 (1.3, 2.1)	20 (20, 20)	3 (3, 3)
Peas, green, without pods	3.6	5.7 (4.6, 6.9)	3.1 (3, 3.2)	3 (3, 3)	3.3	5 (3.7, 6.6)	20 (20, 20)	3 (3, 3)
Pepper, black and white	0.0	1 (1, 1)	0.4 (0.3, 0.4)	1 (1, 1)	0.0	1 (1, 1)	1 (0.8, 1)	0 (0, 0)
Peppers, paprika	3.4	20 (20, 20)	3.5 (3.4, 3.5)	1.4 (1.3, 1.5)	4.3	12 (12, 12)	15 (15, 15)	0 (0, 0)
Pizza and pizza-like pies	6.4	10.1 (6.2, 14)	-	0 (0, 0)	3.6	0 (0, 0)	-	0 (0, 0)
Pork/piglet meat	13.0	8 (8, 8)	-	7.9 (5.2, 11.1)	6.2	8 (3.1, 8)	-	1.6 (1.6, 1.6)
Potato based dishes	8.0	9.7 (8, 11.1)	5.4 (2.9, 6.9)	0 (0, 0)	5.0	0 (0, 0)	5.6 (4.9, 6.2)	0 (0, 0)
Potato boiled	46.8	48.3 (36.3, 58.1)	46.8 (44.3, 47.5)	37.1 (16.7, 47)	36.9	50 (50, 50)	37.4 (34, 41.5)	1.5 (1.4, 2.8)
Potato crisps	0.0	2 (1, 3.8)	0 (0, 0)				2.9 (1.5, 5.2)	0 (0, 0)
Potatoes and potato products	22.5	24.2 (18.6, 29.1)	21.5 (16.8, 23.9)	11.5 (5.8, 14.4)	17.8	50 (50, 50)	18.3 (16.6, 20.3)	0 (0, 0)
Prepared mixed vegetable salad	49.4	20 (20, 20)	47.8 (32.6, 56)	40.5 (22.9, 50.3)	52.8	20 (20, 20)	50 (50, 50)	22.8 (-2.6, 43.1)
Pretzels	1.1	2 (1.9, 2)	0 (0, 0)	0 (0, 0)	0.7	0 (0, 0)	3.1 (1.7, 4.6)	0 (0, 0)
Quark	15.4	15 (15, 15)	-	8.1 (5.1, 9.6)	14.7	14 (12.2, 15.6)	-	0 (0, 0)
Ready-to-eat soups	92.0	40 (40, 40)	-	88.8 (71.9, 96.8)	71.0	50 (50, 50)	-	50.2 (-0.9, 82.4)
Rice	1.9	4.2 (2.6, 5.9)	2 (1.9, 2.1)	0 (0, 0)	1.7	0 (0, 0)	2.3 (2.1, 2.7)	0 (0, 0)
Rye bread and rolls	22.8	27.8 (12, 41.5)	43.8 (43.7, 43.8)	43.8 (43.7, 43.8)	17.3	4.7 (2.2, 8.4)	60 (60, 60)	43.8 (43.8, 43.8)
Salmon and trout	9.7	11 (8.3, 14.5)	-	27.1 (14.2, 51.6)	8.4	10 (10, 10.6)	-	17.5 (17.5, 17.5)

Salt iodised	-	0.2 (0.2, 0.2)	0 (0, 0)	2 (1.8, 2)		-	-	2 (2, 2)
Sausages	9.2	3.5 (3.5, 3.5)	-	0 (0, 0)	4.7	3.5 (2.3, 3.5)	-	0 (0, 0)
Shrimps	1.0	1 (1, 1)	-	4.3 (3.3, 5.8)	-	-	-	0 (0, 0)
Snack food	7.9	2 (2, 2)	6.9 (3.4, 8.2)	0 (0, 0)	5.3	0 (0, 0)		0 (0, 0)
Soft drink, flavoured	107.6	20 (20, 20)	37.5 (37.5, 37.5)	37.5 (37.5, 37.5)	42.3	28.4 (0.7, 54)	42.6 (40, 45.7)	20.1 (0.4, 29.3)
Soft drink, fruit content	57.5	20 (20, 20)	37.5 (37.5, 37.5)	37.5 (37.5, 37.5)	22.8	17.8 (12.5, 22.9)	23 (22, 23.9)	6.5 (4.4, 9.1)
Spinach (fresh)	1.9	30 (30, 30)	50 (50, 50)	50 (50, 50)	2.1	30 (30, 30)	50 (50, 50)	50 (50, 50)
Spirits	3.7	1 (1, 1)	3.7 (3.6, 3.7)	0 (0, 0)	1.3	0 (0, 0)	-	0 (0, 0)
Starchy pudding	23.0	24.8(18.2, 29.7)	-	1.4 (1.4, 1.4)	22.4	16 (8.1, 22.6)	-	0 (0, 0)
Still mineral water	116.5	100 (100,100)	116.4 (112.6, 118.3)	116.8 (115.3, 118.2)	113.6	100 (100,100)	113.6 (113.3, 113.6)	115.5 (108.3, 126)
Strawberries	21.8	40 (40, 40)	70 (70, 70)	70 (70, 70)	33.1	4 (40, 40)	33.3 (32.1, 34.8)	70 (70, 70)
Sunflower oil	0.0	0 (0, 0)	4.3 (2.8, 7)	0 (0, 0)	0.0	0 (0, 0)	5 (0.7, 10.7)	0 (0, 0)
Sunflower seed	0.0	8.4 (-0.6, 15.5)	3 (3, 3.5)	3 (3, 3.3)	0.0	6.5 (3.4, 10.8)	3.4 (1.2, 5.4)	3 (3, 3)
Tap water	710.9	1000 (1000, 1000)	710.9 (706.9, 713)	711.1 (705.7, 716.1)	692.8	1000 (1000,1000)	692.8 (692.4, 692.8)	693.8 (670.6, 728.9)
Tomato ketchup	0.0	1.5 (1, 2)	0 (0, 0)	0 (0, 0)	-	-	-	0 (0, 0)
Tomato purée	10.8	30 (30, 30)	55 (55, 55)	55 (55, 55)	11.4	13.3 (9.7, 19)	11.8 (10.8, 12.5)	55 (55, 55)
Tomatoes	19.1	30 (30, 30)	50 (50, 50)	50 (50, 50)	23.9	30 (30, 30)	35 (35, 35)	50 (50, 50)
Tree nuts	4.5	5 (5, 5)	7.4 (5.1, 8.5)	3 (3, 3)	3.8	0 (0, 0)	8 (8, 9)	3 (3, 3)
Turkey meat	1.6	1.5 (1.5, 1.5)	-	7.3 (4.5, 7.3)	1.2	1.5 (1.5, 1.5)	-	0 (0, 0)
Veal meat	1.7	1.2 (1.2, 1.2)	-	7.3 (4.8, 7.3)	0.8	1.2 (1.2, 1.2)	-	0 (0, 0)
Vegetable oil	4.8	0 (0, 0)	9 (5.9, 15.5)	0 (0, 0)	3.3	0 (0, 0)	8.2 (0.7, 16)	0 (0, 0)
Vegetable/herb soup	-	0.9 (0.8, 1)	52.8 (44.6, 56.8)	0 (0, 0)	57.2	57.9 (53.2, 64.3)	25 (25, 25)	41.1 (4.1, 63.3)
Vegetable-based meals	53.6	54.7 (48.6, 59)	0 (0, 0)	50.6 (41.2, 54.2)	0.0	0.7 (0.6, 0.8)	0.2 (0.2, 0.2)	0 (0, 0)
Vinegar, wine	-	0.4 (0.4, 0.4)	0 (0, 0)	0 (0, 0)	-	-	0.1 (0.1, 0.1)	0 (0, 0)
Walnuts	0.0	0.6 (0.5, 1)	3.1 (2.7, 3.7)	2 (2, 2)	0.0	0 (0, 0)	3.6 (1.4, 5.9)	2 (2, 2)
Wheat bread and rolls	112.0	25 (25, 25)	106.1 (-41.2, 171)	89.9 (-36.1, 143.6)	85.1	73.7 (-12.1, 135.4)	20 (20, 20)	43.8 (43.8, 47.3)
Wheat milling products	10.7	16.1 (0.5, 31.7)	43.8 (43.8, 43.8)	43.8 (43.7, 43.8)	9.5	0 (0, 0)	11.4 (7.2, 17.1)	43.8 (43.8, 43.8)
White sugar	8.5	1 (1, 1)	1.4 (1.4, 1.4)	0 (0, 0)	8.5	0 (0, 0)	10.7 (6.2, 14.9)	0 (0, 0)
Wine, red	25.5	2 (2, 2)	25.5 (25.3, 25.25)	35 (35, 35)	23.5	2 (2, 2)	10 (10, 10)	35 (35, 35)

Wine, white	11.5	2 (2, 2)	11.5 (11.4, 11.5)	1.6 (1.5, 2.1)	10.5	2 (2, 2)	10 (10, 10)	0 (0, 0)
Yoghurt, cow milk, plain	37.2	38.4 (34.8, 43)	-	41.7 (41.7, 41.7)	42.2	41.8 (37.5, 53.5)	-	41.7 (41.7, 57.9)

*Reference diet in North-Rhine Westphalia (RD); diet recommended by the German Nutrition Society (DD); vegan diet (VD); Mediterranean diet (MD). Average food consumption intake results from quadratic optimisation algorithms based on dietary recommendations to constrain food intake quantities of individual food items by each of the dietary scenarios (see Table S3 in ESM). Nutritional property constraints were defined according to EFSA and D-A-CH reference dietary values (DGE, 2021b; EFSA, 2019). The sensitivity range is given in brackets minimum and maximum values, respectively. Scenario uncertainties are based on 100 Monte Carlo simulations.

S2. Life cycle inventory data

Table S5. Life cycle inventory data sources for agricultural production and processing.

Life Cycle Stage	Sub-stage	Parameters and assumptions	Inventory data sources of Optimeal®
Agricultural production	*Crop and livestock production*	Crop yields, seedling, fertiliser inputs (N-P-K and lime) and emissions, soil management and emissions, manure inputs and emissions, energy inputs and emissions, water use in crop irrigation, land use and emissions, capital goods (e.g. tractors), methane emissions of enteric digestion, manure management and storage Excl. Pesticides application and production, feed and animal products carbon storage	Agri-footprint 4.0 methodology (Durlinger et al., 2017b) IPCC data sources (IPCC, 2006)
	Market mixes of raw materials	Market mix and transport of raw materials (global exports) (2009-2013) Exceptions: almonds, hazelnuts, peppermint, groundnuts, sugar, assumed as global production (2009-2013), and rice, assumed as global exports (2013-2017), within the European market share	(Eurostat, 2017; FAOSTAT, 2013)
Transport of raw materials	*Road*	Load capacity, load factor, fuel consumption, distances in km, truck sizes, European emissions (EURO1-EURO5)	(Klein et al., 2012)
	Water	Load capacity for bulk, barge and containers, emissions of fuel and fuel consumption	(Boer et al., 2011; Klein et al., 2012)
	Sea	Load capacity, load factor and, fuel consumption, travel distance using the "Dead Weight Tonnage" method	(Hellinga, 2002)
	Rail	Diesel and electricity trains, terrain, bulk products and containers, emissions	(Boer et al., 2011; Klein et al., 2012)
	Air	Boeing and Fokker aeroplanes, distance in tkm, load capacity, kerosene fuel consumption, emissions	(European Environment Agency, 2006; Klein et al., 2012)
Processing into food products	*Processing of raw material to product & co-product*	A) Processing of fruits and vegetables	(Lehto et al., 2014; Sanjuán et al., 2014)
		B) Milling (oat and wheat)	(McDevitt and Milà i Canals, 2009; Welch, 1995)
		C) Tree nuts (drying and deshelling)	(Anıl et al., 2018; Jekayinfa and Bamgboye, 2006; Kendall et al., 2015; Klonsky et al., 2009)
		D) Black and herbal tea processing	(Tarhan et al., 2011; Taulo and Sebitosi, 2016)
		E) Fish processing	(Broekema et al., 2015a)
		F) Meat processing	(Broekema et al., 2015b)
		G) Milk pasteurisation	(Sheane et al., 2011)
		H) Honey processing	(Arena et al., 2014).
	Processing of products	A) Baked products	(Therkelsen et al., 2014)
		B) Pasta	(Technical Secretariat of the PEF dry pasta Pilot., 2004)

		C) French fries	(Broekema et al., 2016; Ponsioen and Blonk, 2011)
		D) Jam, fruit compote, ready-to-eat-meals	(Andersson et al., 1998)
		E) Margarine	(Broekema et al., 2016)
		F) Tomato puree	(Manfredi and Vignali, 2014)
		G) Soups	(Milà I Canals et al., 2011)
		H) Chocolate	(Konstantas et al., 2018; Recanati et al., 2018)
		I) Soft drinks	(Ercin et al., 2011; Pluimers et al., 2011)
		J) Coffee	(Humbert et al., 2009)
		K) Beer	(Broekema and Scholten, 2015)
		L) Wine	(Technical Secretariat of the PEF pilot on wine, 2015)
		M) Cider	(Iannone et al., 2016)
		N) Spirits	(Broekema et al., 2016)
		O) Fish products	(Broekema et al., 2015a)
		P) Cheese	(Broekema et al., 2015b)
		Q) Yogurt, ice cream, pudding and custard production	(Sheane et al., 2011)
		R) Evaporated milk	(Fox et al., 2010)
		S) Butter and buttermilk production	(JRC and European Commission, 2015)
Packaging	*Packaging materials*	Cardboard, polypropylene (PP), paper 50%, chromium steel, modified starch, polystyrene (EPS), glass, polyethylene terephthalate (PET), low-density polyethylene (LDPE), high-density polyethylene (HDPE), liquid packing board (LPB)	Ecoinvent 3 database (Wernet et al., 2016)
		Aluminum	ELCD (JCR-IES, 2012)
	Transport distances	All materials: 230 km by truck, 280 km by train, 360 km by ship For glass: 350 km by truck, 39 km by train and 87 km by ship	PEF Guidance document 6.3 (European Commission, 2018)
Distribution	*Transport and storage*	Distribution distance: 150 km; losses at distribution assumed as 0%; energy use for cooling, freezing, lighting, heating, water use, R404a emissions per product density, according to volume and time of storage (for ambient, cooled and frozen products)	(Charrondiere et al., 2012; European Commission, 2018)
Retail	*Supermarket*	Retail distance: 50 km Energy use for cooling, freezing, lighting, water use, R404 emissions per product density, according to volume and time of storage (for ambient, cooled and frozen products); heating not included Food losses accounted for the final stage	PEF Guidance document 6.3 (European Commission, 2018)
	Food losses	Retail: 10% fruit and vegetables, 4% meat products, 0.5% dairy products; 2% grains;	PEF Guidance document 6.3

		1% oils, prepared meals 0.6-5%; 5% sweets, other items 1%	(European Commission, 2018)
Consumption	*Food preparation*	Cooking techniques (deep-frying, pan-frying, boiling, water boiling, baking, microwaving, chilling and freezing, or no preparation Product characteristics: mass, time of preparation, inedible parts, raw-to-cooked ratio Energy use: electricity, natural gas, oil used for frying Water use: in cooking, brewing or addition of water to beverages following product ratio g/ml of water added	Optimeal assumptions (Broekema et al., 2019); Additional assumptions based on PEF data (European Commission, 2018)
	Packaging disposal	Disposal scenarios assumed: Paper: Europe w/o CH paper waste treatment, incineration with energy recovery Plastic: Europe w/o CH mixture plastic waste treatment, incineration with energy recovery Steel: CH scrap steel waste treatment: incineration with energy recovery Aluminium: CH scrap aluminium waste treatment: incineration with energy recovery Glass: Europe w/o CH glass waste treatment, incineration with energy recovery	Ecoinvent 3.4. (Wernet et al., 2016)
	Food losses	Consumption: 19% fruit and vegetables, 11% meat products, 7% dairy products; 25% grains; 4% oils, prepared meals 0.5-10%; 2% sweets, other items 2%	PEF Guidance document 6.3 (European Commission, 2018)

Source of data: Optimeal® dataset and Agri-footprint 4.0 (Broekema et al., 2019; Durlinger et al., 2017a, 2017b)

S3. Life cycle impact indicators of human health and animal welfare

Table S6. Data sources and assumptions for space allowance and quality of life of animal welfare indicators.

Animal	Data & assumptions	Calculation	Data source
Cattle (beef)	Days of pasture/year before fattening: assumed as summer pasture from 16 May to 15 October in NRW	I =100*(153/365) $Q = (6.8136 + 1.9435 * I - 0.016979 * I^2 + 0.000068633 * I^3) /100$	(BMEL, 2020c; MULNV.NRW, 2020)
Cattle (milk)	Days of pasture/year assumed as summer pasture from 16 May to 15 October in NRW	I =100*(153/365) $Q = (1.7756 * I - 0.00093197 * I^2 - 0.00010556 * I^3)/100$	(BMEL, 2020c; MULNV.NRW, 2020)
Cattle (calf)	Days of pasture/year for calves from six to nine months assumed as summer pasture from 16 May to 15 October in NRW)	Same as beef	(BMEL, 2020c; MULNV.NRW, 2020)
Pig	Legal minimum standard: surface area of $0.75m^2$ per pig (weighting 50-110kg)	I = (10.3*0.75) - 3.09 $Q = (12.306*I - 0.5837*I^2 + 0.0096231 * I^3)/100$	(BMEL, 2020a, 2020d)
Broiler chicken	Maximum allowed stocking density for broiler chicken: 39	I =2.5*(44-39)	(BMEL, 2020b)

	kg/m^2 (16-18 birds per m^2 at the end of the fattening period)	Q = (2.6077* I - 0.051672*I^2 + 0.00050863* I^3)/100	
Turkey	Maximum allowed stocking density for turkey: 5 hens (max 52 kg/m^2) or 3 cocks (max 58 kg/m^2)	I = 2.5*(58-52) [adapted from chicken] Q = (2.6077* I - 0.051672*I^2 + 0.00050863* I^3)/100	(BMEL, 2020d)
Laying hens (eggs)	EU egg coding: [0] organic: max. 6 animals/m^2 + outdoor area 4 m^2/animal, market share 11%; [1] free-range: max. 9 animals/m^2 + outdoor area 4 m^2/animal, market share 19%; [2] floor-keeping. 18 animals/m^2, no outdoor area, market share 63%; [3] cage keeping: max. 18 animals/m^2, no outdoor area, market share 7%;	Stocking density = (animals/m^2 * kg/animal) + (1.5/4)/2 I & Q calculated as broiler chicken multiplied by the market share percentage.	Animal Welfare Ordinance (BMJV, 2016)
Fish	FishEthoBase fish stock density *Sd* range for farmed fish for salmon 10-22 kg/m^3; trout 10-25 kg/m^3	Q = 4.67- 0.17*Sd	Salmon (Studer, 2018); Trout (Castanheira, 2020)
Shrimp	Stocking density *Sd* ranges from several cultured shrimp farms based on the growth rate, stocking density and survival	Q = 0.8457*Sd - 0.0054	(Suriya et al., 2016; Wyban et al., 1987)
Honeybees	Assumed stocking density as 3 bees/cm^2, two times worse than chickens (space factor), with 63.5 times lower sentience than chickens (sentience factor)	Q = 1- (space factor/ sentience factor) = 0.969 Sentience factor = (total neurons chicken/ total neurons humans) ÷ (total neurons bees/ total neurons humans)	Stocking density data (Litmann et al., 2016); sentience data (Menzel and Eckoldt, 2016); assumptions, calculation (Scherer et al., 2018)

Note Q = quality of life calculated over the stocking density or space allowance index *I. Equations retrieved and adapted from:* (Scherer et al., 2018).

Table S7. Data sources and assumptions for animal welfare parameters involving lifetime and conversion efficiencies.

Animal	Parameter, data, and assumptions				Data source
	Life duration	Slaughter age	Weight/yield	Slaughter duration	
Cattle	Fattening breeds (2 years) Dairy cows: 4 lactation periods of 90 months (7.5 years)	Fattening breeds (18-19 months); Dual-purpose breeds (18-19 months); Calf (6-8 months); For dairy cows, it is assumed the decrease in milk	Live weight after fattening (kg), slaughter weight of the carcass (kg), when not available, slaughter yield (%) for young bulls, cows, oxen, calves, older bulls	12 hours without fed before travel Transport: limit of 8 hours Slaughtering upon arrival (no waiting time), Electric stunning 8 seconds electrostimulation during bleeding max. 60 seconds	(BLE, 2021; BZfE, 2020; Ernst and Kalm, 1994; Litmann et al., 2016) "TierSchTrV" and "TierSchlV" (BMJV, 2013, 2009)

		production after the third lactation period (6.25 years)	For milk: milk performance (kg/cow) for dual-purpose breeds, dairy cows	Dairy cows suffer during milking. Time milking "Holstein" = [(milk performance)/ (liters/day)]* time to milk per day	
Pig	Pigs (8-10 years)	Average slaughter age Deutsche Landrasse (DL), Deutsche Edelschwein (DE) 188-202 days after the fattening period	Yield weight of the carcass, pork belly weight, ham weight, and loin weight	12 hours without fed before travel Transport: limit of 8 hours Waiting hours in the slaughterhouse: 1.5-3 hours Electric stunning 4 seconds, bleeding 30 seconds 100 seconds with carbon dioxide	(BLE, 2021; Litmann et al., 2016) "TierSchTrV" and "TierSchlV" (BMJV, 2013, 2009)
Poultry	Chicken 5 years; Turkey 7 years	Broilers 28-37 days Turkey: 111-145 days Laying hens: 16 months	Laying hens: laying rate unit/hen year, egg size classification weight Broilers: 1500-2100kg final live weight Turkey 11-21kg	Max. 60 hours for one-day-chicks after hatching 8 hours limit transport to slaughtering Electric stunning in a water tank (10 seconds) or with carbon dioxide	(BLE, 2021; BMEL, 2020b; Litmann et al., 2016) "TierSchTrV" and "TierSchlV" (BMJV, 2013, 2009)
Fish	Atlantic Salmon: 13 years wild Trout (Rainbow trout): 6 years	Production duration of trout "Forelle": 12 months Atlantic salmon 3.3 years captive	Atlantic salmon 3.5-5.5kg Trout 350g/piece	Transport 8 hours Electric stunning in a water tank (10 seconds)	Lifetime (Castanheira, 2020; Litmann et al., 2016; Wilhelm, 2008; Studer, 2018; U.S. Fish and Wildlife Service, 2020; World Life Expectancy, 2020) Fish welfare (EC Directorate - General for Health and Food Safety, 2017; Sampaio and Freire, 2016)
Shrimp	Shrimp: 2.5 years	120 days	Shrimp body weight from different body sizes in aquaculture	8 hours of transport Electrically stunned or killed (no time defined)	Lifetime (Suriya et al., 2016; Wyban et al., 1987) Welfare (BMJV, 2009)
Honeybee	8 months in winter (lower honey production)	6 weeks in summer (higher honey production); there is about 6% bee loss in winter	Honey yield per colony year, number of bees per colony to estimate honey yield per bee	No time accounted for; bees die naturally (can be premature death due to chemical diseases, but these are not assumed in slaughter time)	(Litmann et al., 2016; Scherer et al., 2018; Schroeder, 2014)

It was adapted from: (Scherer et al., 2018).

Table S8. Calculation of moral value and underlying data sources.

Animal	Cortical neurons	Total neurons	Brain weight (g)	Body weight (g)	EQ	Moral value	Proxy animal	Reference
Human	1.60E+10	8.60E+10	1508	70000	7.129	1.000	*Homo sapiens*	(Azevedo et al., 2009; Herculano-Houzel, 2009)
Cattle		3.00E+09	480.54	597050	0.540	0.055	*Bos Taurus*	(Ballarin et al., 2016; Herculano-Houzel, 2016)
Pig	3.07E+08	2.22E+09	64.18	110000	0.224	0.025	*Sus scrofa domesticus*	(Hof et al., 2015)
Chicken	6.10E+07	2.21E+08	2.9529	1199.605	0.213	0.012	*Gallus gallus; Gallus gallus domesticus*	(Henriksen et al., 2016; Olkowicz et al., 2016)
Turkey			6.9933	11157.2	0.113	0.016	*Meleagris gallopavo L*	(Ebinger et al., 1989)
Salmon			1.0598	2633.89	0.045	0.006	*Oncorhynchus tshawytscha*	(Wiper et al., 2017)
Shrimp		6.55E+05				0.00001	*Crustacean - Panulirus argus*	(Meinertzhagen, 2019; Schmidt and Ache, 1996)
Bees		9.60E+05	0.001	0.08	0.045	0.003	*Apis Mellifera*	(Menzel and Eckoldt, 2016; Menzel and Giurfa, 2001)

Sources of calculations and conceptualisation: (Jerison, 1975; Scherer et al., 2018).

Table S9. Data sources and assumptions for estimating animal welfare impacts from processed food and food preparations.

Food Category	Conversion base and assumptions	Data sources
Dairy products	Based on product yield kg per100 L milk: • Cheeses (hard, soft, fresh, semi-soft), cream, butter, buttermilk • Milk density: 1.034g/mL • Cocoa preparation: 250ml milk, 15g cocoa, 5g sugar; • Evaporated milk: concentration of 7.5 fat + 31% milk solids	Dairy product yields (Belloin, 1988) Cocoa recipe (GuteKueche, 2020a) Yoghurt yield (Sumarmono et al., n.d.) Evaporated milk (Nieuwenhuijse, 2016) Milk density (Watson and Tittsler, 1961)
Meat products	Based on meat content and animal type • Sausages: the proportion of beef and pork meat and fat content. • Cooked smoked sausages: data from Wiener, Frankfurter, Bologna • Dry sausages: salami (Italian), salami (German) • Minced meat: 55% pork and 45% beef (packaging product	Meat processing (FAO, 1985; Heinz and Hautzinger, 2007) Recipes: Goulash (Essen & Trinken, 2020a); meatballs (Chefkoch, 2021a); "Wiener Schnitzel" (GuteKueche, 2020b) Pork slaughter yield (Litmann et al., 2016)

	reference from REWE) • Ham and bacon are based on pork slaughter yield • Meat stew: 125g Goulash mixed beef & pork (one portion) • Meatballs: typical German meatball recipe 125g mixed minced meat (one portion) • Meat-based meal: "Wiener Schnitzel" using calf fillet 160g	
Cocoa products	Based on the milk content: • Bitter chocolate 0% • White chocolate 26% • Milk chocolate 22%	(Universität zu Köln, 2020)
Gelatin content food	Based on the gelatin content • Gelatine proportion of 6.9 protein content (100g of candy "gummi bear") • Gelatine assumed as fish gelatine 30% of the animal (skin, bones and organs) with 17.21% yield	Gummi candies (Haribo, 2020) Gelatin (Jakhar et al., 2014)
Other food preparations	Recipes and assumptions: • Custard (as vanilla sauce), • Egg-based dishes (as Omelette), • Fish products (such as fish fingers), • Ice cream (as vanilla ice cream), • Dessert (as rice pudding), • Pasta assumed as egg pasta, • Pastries & cakes (cheesecake typical German recipe) • Pizza (as pizza Margherita "homemade") • Ready-to-eat soups (such as potato soup with sausages) • Starchy pudding (as vanilla pudding) • Biscuits (as butter biscuits)	**Sources of the recipes**: vanilla sauce (Essen & Trinken, 2020b); omelette (GuteKueche, 2020c); fish fingers (Jamie Oliver, 2020); Ice cream (Chefkoch, 2021b); milk rice (Chefkoch, 2021c); egg pasta (Alamprese, 2017); German cheesecake (Chefkoch, 2021d); pizza (Einfach-Backen, 2020), potato soup with sausages (Essen & Trinken, 2020c), biscuits (Rewe, 2020).
Other meat	Treated as "other meat", including veal meat, mutton/lamb meat, as • 1.50E-04 ALYS/g • 2.22E-02 AL/g • 5.14E-05 MAL/g	(Scherer et al., 2019)

Table S10. Data sources and assumptions on nutrition epidemiological risk factors.

Dietary risk factor	Threshold	Food/nutrient data (LCI)	Calculation
High intake of processed meat	Any intake of processed meat	Daily intake (DI) in g/day Data: bacon, cooked smoked sausage, dry sausage; fresh and lightly cooked sausage, ham (pork), and sausages	Total DI of processed meat, If DI > than 0 g/day; Then, % of DALYs is attributed to sex
High intake of red meat	Less than 113.4 grams (4 ounces) per week or 16.2 grams per day	Daily intake (DI) in g/day Data: beef meat, meat and meat products, meatballs, meat burger, meat stew; meat-based meals, mixed beef and pork meat, mutton/lamb meat; pork/piglet meat, veal meat Excl. processed meat, poultry, eggs, and fish	Total DI of red meat, If DI > than 16.2 g/day; Then, % of DALYs is attributed to sex
High intake of sodium	Less than 1000 mg sodium per day	Daily intake (DI) of sodium in g/day of the whole diet	Total DI of sodium, If DI > than 1000 mg/day; Then, % of DALYs is attributed to sex
High intake of sugar-sweetened beverages	50 kcal of sugars from sweetened beverages	Total daily energy intake (kcal) of mono- and disaccharides derived from sweetened beverages Data: sugar-sweetened beverages: cola beverages (caffeinic), soft drinks (flavoured), soft drinks (fruit content), fruit nectar Excl. fruit and vegetable juices	Total energy (in kcal) of sugars from sweetened beverages, E = DI*4 kcal If E > than 50 kcal; Then, % of DALYs is attributed to sex
High intake of trans-fatty-acids	Higher than 0.5% of total energy intake	Percentage of daily intake to the total energy intake (E%) of trans-fatty-acids in g/day of the whole diet	E% of total DI of trans-fatty-acids, E% = DI*9/Total E (kcal)*100 If E% > than 0.5% Then, % of DALYs is attributed to sex
Low intake of polyunsaturated fatty acids (PUFA)	Less than 12% of total energy intake (E%)	Percentage of daily intake to the total energy intake (E%) of PUFA in g/day of the whole diet	E% of total DI of PUFA, E% = DI*9/Total E (kcal)*100 If E% < than 12% Then, % of DALYs is attributed to sex
Low intake of seafood omega-3 fatty acids	Less than 250 milligrams per day EPA and DHA	Daily intake (DI) of omega-3 fatty acids (EPA + DHA[1]) in mg/day of the whole diet	Total DI of omega-3 fatty acids (EPA + DHA), If DI < than 250 mg/day; Then, % of DALYs is attributed to sex
Low intake of vegetables	Less than 397 grams (14 ounces) of vegetables per day	Daily intake (DI) in g/day Data: beetroot, carrots, tomatoes, head cabbage, iceberg-type lettuce, lettuce (excl. ice-berg type), parsley (herb), tomato purée, leafy vegetables, cucumbers, leek, onions (bulb), peppers (paprika), spinach (fresh), cultivated mushroom, melons Excl. Tree nuts, legumes, vegetable juices, starchy roots and tuber, e.g.	Total DI of vegetables, If DI < than 397 g/day; Then, % of DALYs is attributed to sex

		potatoes and ready-to-eat meals	
Low intake of legumes	Less than 50 grams per day	Daily intake (DI) in g/day Data: peas, peas (green, without pods), beans, beans (green, without pods), beans (with pods), lentils Excl. nuts and oilseeds	Total DI of legumes, If DI < than 50 g/day; Then, % of DALYs is attributed to sex
Low intake of fruits	Less than 312 grams (11 ounces) per day	Daily intake (DI) in g/day: Data: apple, bananas, strawberries, peaches, oranges, pear, mandarins, fruit compote, fruit sauce kiwi, jam Excl. fruit juices	Total DI of fruits, If DI < than 312 g/day; Then, % of DALYs is attributed to sex
Low intake of whole grains	Less than 113.4 grams (4 ounces) of whole grains per day	Daily intake (DI) in g/day Data: mixed wheat and rye bread and rolls, rye bread and rolls, multigrain bread and rolls, cereal flakes	Total DI of whole grains, If DI < than 113.4 g/day; Then, % of DALYs is attributed to sex
Low intake of fibre	Less than 30 grams per day	Daily intake (DI) of fibre in g/day of the whole diet	Total DI of fibre, If DI < than 30g/day; Then, % of DALYs is attributed to sex
Low intake of nuts and seeds	Less than 113.4 grams (4 ounces) per week or 16.2 grams per day	Daily intake (DI) in g/day: Data: almond (sweet), cashew nuts, hazelnuts, peanuts, peanut butter, sunflower seeds, tree nuts, walnuts	Total DI of nuts, If DI < than 16.2 g/day; Then, % of DALYs is attributed to sex
Low intake of calcium	Less than 1200 milligrams per day	Daily intake (DI) of calcium in mg/day of the whole diet	Total DI of calcium, If DI < than 1200 mg; Then, % of DALYs is attributed to sex
Low intake of milk	Less than two serving cups (490 grams) of milk per day	Daily intake (DI) in g/day: Data: cow milk, flavoured milk	Total DI of milk, If DI < than 490g/day; Then, % of DALYs is attributed to sex

[1] Seafood Omega-3 fatty acids: Eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA)
Equations are based on the (GBD 2019, 2020) database. DALYs values are gender standardised by country. Available at the GBD 2019 database.

S4. Supplementary results

Table S11. Parameters are estimated to calculate animal welfare impacts per animal and kg of product.

Animal	Slaughter age (years)	Yield (kg/ animal)	Moral value	Life fraction (years)	Life duration (years)	Slaughter fraction (years)	Slaughter duration (years)	Number affected	Life quality (Q)
Cattle (beef)	1.4E+00	2.6E+02	5.5E-02	6.8E-01	2.0E+00	6.8E-04	1.4E-03	3.9E-03	6.4E-01
Cattle (milk)	6.3E+00	8.2E+03	5.5E-02	8.3E-01	7.5E+00	3.7E-02	2.8E-01	1.2E-04	6.5E-01
Pig	5.3E-01	1.1E+02	2.5E-02	5.9E-02	9.0E+00	1.9E-04	1.7E-03	9.3E-03	4.5E-01
Broiler chicken	8.9E-02	1.9E+00	2.1E-01	1.8E-02	5.0E+00	2.7E-04	1.4E-03	5.2E-01	2.6E-01
Turkey	3.5E-01	1.6E+01	1.6E-02	5.0E-02	7.0E+00	2.0E-04	1.4E-03	6.3E-02	2.9E-01
Laying hen (egg)	1.3E+00	1.5E+01	1.2E-02	2.7E-01	5.0E+00	2.7E-04	1.4E-03	6.7E-02	7.0E-01
Fish (salmon & trout)	2.2E+00	4.5E-01	6.3E-03	2.7E-01	8.0E+00	1.4E-05	1.1E-04	2.2E+00	8.4E-01
Shrimp	3.3E-01	1.9E-02	7.6E-06	1.3E-01	2.5E+00	4.6E-05	1.1E-04	5.2E+01	4.6E-01
Bees (honey)	1.2E-01	2.1E-03	3.2E-03	1.7E-01	6.7E-01	2.9E-05	1.9E-05	4.8E+02	9.6E-01
Calf	5.8E-01	2.9E+02	5.5E-02	2.9E-01	2.0E+00	6.8E-04	1.4E-03	3.5E-03	6.4E-01

Note: see assumptions and equations in Section S3

Table S12. Animal welfare impacts derived from processed food items and food preparations

Milk-based Products	Yield (kg/100l milk)	Yield (g/ml)	Yield (g/g milk)	ALYS/g	AL/g	MAL/g
Fresh cheese	19.00	0.19	0.18	6.32E-08	6.89E-06	2.08E-10
Soft cheese	14.00	0.14	0.14	4.66E-08	5.08E-06	1.53E-10
Semi-soft cheese	11.50	0.12	0.11	3.82E-08	4.17E-06	1.26E-10
Hard cheese	10.50	0.11	0.10	3.49E-08	3.81E-06	1.15E-10
Cheese all	13.75	0.14	0.13	4.57E-08	4.99E-06	1.50E-10
Cream	1.50	0.02	0.01	4.99E-09	5.44E-07	1.64E-11
Butter	1.80	0.02	0.02	5.99E-09	6.53E-07	1.97E-11
Buttermilk	0.63	0.01	0.01	2.10E-09	2.29E-07	6.89E-12
Evaporated milk	39.81	0.40	0.39	1.32E-07	1.44E-05	4.35E-10
Fermented milk	57.26	0.57	0.55	1.90E-07	2.08E-05	6.26E-10
Flavored milk	95.69	0.96	0.93	3.18E-07	3.47E-05	1.05E-09
Cocoa products	0.16 milk content			5.50E-08	6.00E-06	1.81E-10

Meat-based products	**Yield kg/animal**	**pork***	**beef***	**ALYS/g**	**AL/g**	**MAL/g**
Bacon	0.54 (pork belly) 0.18 (ham) 0.07 (pork loin) 0.6 (beef meat)	0.54	-	2.46E-05	4.98E-06	1.2E-07
Cooked smoked sausage And		0.35	0.17	1.62E-05	3.66E-06	8.8E-08
Fresh and lightly Cooked sausage		0.35	0.17	1.62E-05	3.66E-06	8.8E-08
Dry sausage		0.26	0.09	1.62E-05	3.66E-06	8.8E-08
Ham, pork		0.18	-	8.09E-06	1.64E-06	3.95E-08
Mixed minced meat		0.55	0.45	2.63E-05	6.35E-06	1.53E-07
Food preparations	**Ingredients**	**quantity/ portion**	**proportion**	**ALYS/g**	**AL/g**	**MAL/g**
Custard	Egg	63.0	0.39	3.86E-05	2.13E-05	2.31E-07
	Cream	41.7	0.26	1.29E-09	1.41E-07	4.25E-12
	Milk	41.7	0.26	8.91E-08	3.34E-12	3.78E-21
	Sugar	13.3	0.08	-	-	-
	Vanilla	1.0	0.01	-	-	-
	Salt	0.2	0.00	-	-	-
	Total	**160.8**		**3.87E-05**	**2.14E-05**	**2.31E-07**
Omelet	Egg	189.0	0.83	8.21E-05	4.52E-05	4.91E-07
	Butter	7.0	0.03	1.85E-10	2.01E-08	6.07E-13
	Milk	30.0	0.13	4.54E-08	4.96E-06	1.49E-10
	Salt	0.5	0.00	-	-	-
	Pepper	0.5	0.00	-	-	-
	Total	**227.0**		**8.21E-05**	**5.02E-05**	**4.91E-07**
Fish finger	Fish	112.5	0.61	1.77E-03	1.05E-03	6.29E-06
	Egg	31.5	0.17	1.69E-05	9.30E-06	1.01E-07
	Flour	12.5	0.07	-	-	-
	Bread crumb	25.0	0.14	-	-	-
	Paprika	2.5	0.01	-	-	-
	Total	**184.0**		**1.78E-03**	**1.06E-03**	**6.39E-06**
Ice cream	Egg	10.5	0.20	1.97E-05	1.09E-05	1.18E-07

	Milk	15.0	0.29	9.82E-08	1.07E-05	3.23E-10
	Cream	15.0	0.29	1.43E-09	1.55E-07	4.68E-12
	Vanilla	2.0	0.04	-	-	-
	Sugar	10.0	0.19	-	-	-
	Total	**52.5**		**1.98E-05**	**2.17E-05**	**1.18E-07**
Milk rice pudding	Milk	250.0	0.76	2.62E-07	2.86E-05	8.63E-10
	Butter	2.5	0.01	4.57E-11	4.98E-09	1.50E-13
	Rice	62.5	0.19	-	-	-
	Sugar	10.0	0.03	-	-	-
	Vanilla sugar	2.5	0.01	-	-	-
	Total	**327.5**		**2.63E-07**	**2.86E-05**	**8.63E-10**
Egg pasta	Egg	100.0	0.09	8.96E-06	4.94E-06	5.36E-08
	Flour	1000.0	0.91	-	-	-
	Total	**1100.0**		**8.96E-06**	**4.94E-06**	**5.36E-08**
Cheesecake	Flour	200.0	0.11	-	-	-
	Sugar	300.0	0.16	-	-	-
	Margarine	200.0	0.11	-	-	-
	Egg	252.0	0.13	1.32E-05	7.28E-06	7.90E-08
	Backing powder	7.0	0.00	-	-	-
	Vanilla sugar	10.0	0.01	-	-	-
	Vanilla pudding	10.0	0.01	-	-	-
	Quark	500.0	0.27	5.07E-08	5.53E-06	1.67E-10
	Cream	400.0	0.21	1.06E-09	1.16E-07	3.49E-12
	Total	**1879.0**		**1.33E-05**	**1.29E-05**	**7.92E-08**
Pizza	Pizza dough	400.0	0.57	-	-	-
	Mozzarella	200.0	0.29	1.09E-08	1.19E-06	3.59E-11
	Tomato	100.0	0.14	-	-	-
	Total	**700.0**		**1.09E-08**	**1.19E-06**	**3.59E-11**
Potato soup with sausages	Onion	340.0	0.19	-	-	-

	Herbs	30.0	0.02	-	-	-
	Potato	1000.0	0.56	-	-	-
	Butter	20.0	0.01	6.65E-11	7.26E-09	2.19E-13
	Spices	10.0	0.01	-	-	-
	Dry fermented sausage	400.0	0.22	2.68E-06	5.89E-07	1.42E-08
	Total	**1800.0**		**2.68E-06**	**5.96E-07**	**1.42E-08**
Vanilla pudding	Vanilla	10.0	0.02	-	-	-
	Milk	500.0	0.82	2.80E-07	3.06E-05	9.22E-10
	Sugar	70.0	0.11	-	-	-
	Egg	3.0	0.00	4.83E-07	2.66E-07	2.88E-09
	Starch	30.0	0.05	-	-	-
	Total	**613.0**		**7.63E-07**	**3.09E-05**	**3.81E-09**
Butter biscuits	Lemon	10.0	0.02	-	-	-
	Flour	250.0	0.40	-	-	-
	Sugar	150.0	0.24	-	-	-
	Butter	125.0	0.20	1.19E-09	1.30E-07	3.91E-12
	Egg	84.0	0.13	1.32E-05	7.25E-06	7.87E-08
	Milk	10.0	0.02	5.47E-09	5.96E-07	1.80E-11
	Total	**629.0**		**1.32E-05**	**7.98E-06**	**7.87E-08**

*Based on the carcass yield and ingredient proportion to the final product, see assumptions in section S3

Table S13. Nutrient properties, nutrient constraints as dietary reference values per day, and mean, minimum and maximum nutrient values1 per day across the different dietary scenarios2 for men.

Nutrient	Unit	Men (values per day)											
ALA[3]	g	DRV[1]	UL[1]	RD	DD mean	min	max	VD mean	min	max	MD mean	min	max
Alcohol	g	1.26	-	1.74	1.79	1.63	1.99	2.20	1.86	2.52	1.71	1.71	1.92
Calcium	mg	-	-	13.01	0.88	0.81	0.97	13.01	12.39	15.52	5.37	5.07	7.11
Carbohydrates total	g	950	2500	1073.9	1163.5	1099.7	1189.9	613.4	573.2	637.0	950.0	954.7	991.7
Cholesterol	mg	246.2	335.3	324.90	273.82	265.04	300.45	337.14	312.62	346.16	313.35	292.12	340.53
Copper	mg	-	-	338.27	239.50	222.19	256.11	6.43	4.97	9.51	212.92	178.09	231.83
Cystine	mg	1.6	5	3.31	2.92	2.65	2.96	4.16	3.78	4.31	2.87	2.77	3.06
DHA[3]	mg	-	-	1298.0	1265.6	1196.3	1297.5	1077.2	1018.3	1160.8	1447.2	1291.7	1447.9
DHA+EPA[3]	mg	-	-	473.63	474.74	392.34	495.88	45.35	40.15	53.91	677.68	509.88	812.15
Dry matter	g	250	-	841.2	1167.4	1059.6	1296.7	530.2	495.6	690.8	2418.7	2078.9	3008.1
Energy	kcal	-	-	571.48	512.31	498.89	545.73	536.39	503.87	551.63	551.63	520.42	584.31
EPA[3]	g	2231	2279	2643.4	2236.0	2236.0	2279.5	2231.2	2221.6	2221.6	2279.2	2257.5	2257.5
Fat total	g	-	-	0.37	0.69	0.55	0.73	0.48	0.46	0.63	1.74	1.56	2.09
Fatty acids n-3	g	50.27	89.86	109.76	94.23	94.23	94.23	69.14	56.79	77.34	71.64	69.59	81.00
Fatty acids n-6	g	-	-	3.01	2.77	2.60	3.20	2.31	2.02	2.68	4.17	3.68	4.76
Fibre	g	-	-	15.38	14.91	13.59	15.95	18.53	15.11	24.04	10.76	10.18	12.59
Fluoride	mg	25		27.47	35.52	33.49	36.81	44.40	42.41	46.95	41.75	40.28	45.73
Folate eq.	µg	-	7.00	0.70	0.78	0.75	0.82	0.68	0.67	0.74	0.92	0.84	0.96
Grams	g	330	1000	336.40	498.10	475.66	518.25	545.59	511.10	561.04	561.53	567.68	627.80
Haem iron	mg	-	-	4147.9	3787.3	3336.5	3779.6	4028.7	4206.9	4650.8	3535.6	3471.3	3853.6
Histidine	mg	-	-	1.26	0.65	0.63	0.72	0.00	0.00	0.01	0.97	0.71	1.07
Iodine	µg	-	-	2524.8	2316.9	2275.3	2455.9	1297.1	1228.3	1371.9	2356.7	2335.2	2640.2
Iron total	mg	150	600	163.56	155.31	145.47	156.49	95.13	90.15	99.94	213.71	172.98	221.61
Isoleucine	mg	11.0	-	14.98	17.18	16.51	17.93	19.22	17.77	19.59	20.89	19.93	22.52
Lactose	g	-	-	4444.3	4214.63	4093.4	4404.1	2390.8	2469.1	2738.6	4410.7	4230.1	4844.7
Leucine	mg	-	-	12.86	10.50	9.91	11.60	0.16	0.05	0.21	8.80	7.85	10.65
Linoleic acid	g	-	-	7318.3	7022.3	6931.5	7483.8	3976.8	3731.0	4084.1	7286.3	6820.8	7716.6

Lysine	**mg**	10.05	-	12.77	14.18	12.99	15.90	17.74	13.59	25.03	10.05	10.19	10.95
Magnesium	**mg**	-	-	6049.8	5436.6	5227.7	5562.2	2314.2	2217.1	2456.4	5785.5	5682.7	6628.3
Manganese	**mg**	350	600	494.59	565.82	521.61	584.35	596.83	570.73	607.53	549.60	541.81	589.23
Methionine	**mg**	3		5.84	7.01	6.85	7.58	9.72	9.30	10.48	8.81	8.37	9.89
Mono- and disaccharides	**g**	-	-	2018.89	1778.96	1701.21	1829.46	822.07	720.89	807.85	1981.84	1917.80	2252.13
MUFA[3]	**g**	-	-	120.84	95.24	87.30	97.96	102.24	95.65	104.70	98.70	94.54	107.54
Niacin	**mg**	-	-	56.59	47.07	42.13	47.75	39.55	32.56	40.17	43.77	42.09	51.95
Phosphorus	**mg**	15.04	-	40.49	38.69	36.89	40.15	31.65	29.58	33.14	41.23	39.44	43.69
Polysaccharides	**g**	550	-	1697.47	1724.96	1654.40	1800.27	1212.17	1169.33	1307.12	1707.69	1671.18	1844.81
Potassium	**mg**	-	-	150.46	166.84	153.21	181.50	210.62	204.19	233.76	197.84	174.83	209.18
Protein animal	**g**	3500	-	4252.7	4704.1	4566.3	4919.7	4834.1	4602.1	5079.4	5015.5	4553.0	5009.0
Protein total	**g**	-	-	54.38	40.42	39.23	43.26	0.08	0.03	0.10	43.54	41.05	54.14
Protein vegetable	**g**	56.52	-	91.06	87.00	83.52	90.19	54.93	51.11	56.70	94.10	91.12	103.98
PUFA[3]	**g**	-	-	36.57	46.47	42.70	46.72	54.85	52.96	59.91	50.06	44.94	53.11
Retinol eq.	**µg**	-	-	17.96	17.14	16.14	19.04	21.27	17.67	29.92	14.90	14.09	16.10
SAFA	**g**	750	3000	1333.1	2047.3	1878.2	2116.7	1978.7	1707.0	2028.3	2186.6	2141.2	2496.0
Selenium	**µg**	-	-	43.76	32.39	32.28	37.22	11.06	9.78	13.21	16.51	15.08	18.45
Sodium	**mg**	70	300	96.57	111.67	101.13	119.75	93.08	82.36	100.17	109.43	103.15	118.67
Threonine	**mg**	-	-	3369.3	2722.4	2627.1	2947.1	2000.0	1920.9	1923.6	3232.9	2566.0	3330.7
Trans fatty acids	**g**	-	-	374.8	3489.3	3268.6	3499.5	2007.5	1793.2	2005.6	3833.7	3673.7	4111.3
Tryptophan	**mg**	-	-	2.19	1.84	1.69	2.02	0.17	0.06	0.34	0.37	0.31	0.49
Valine	**mg**	-	-	1109.8	1055.2	1016.2	1088.2	673.3	619.5	701.0	1094.0	1015.2	1155.7
Vitamin B1	**mg**	-	-	5190.3	4926.9	4892.7	5232.5	2869.2	2653.5	2943.7	5136.1	4795.4	5399.4
Vitamin B12	**µg**	0.1	-	1.69	1.89	1.82	2.05	1.91	1.75	1.98	2.10	1.95	2.22
Vitamin B2	**mg**	4.0	-	5.61	4.50	4.13	4.68	0.34	0.30	0.40	10.38	10.23	14.67
Vitamin B5	**mg**	1.6	-	2.13	2.16	2.12	2.29	1.72	1.60	1.81	2.28	2.12	2.32
Vitamin B6	**mg**	5.0	-	6.77	6.80	6.73	7.27	6.59	6.40	7.03	7.93	7.40	8.19
Vitamin B7	**µg**	1.7	25	2.10	2.33	2.20	2.37	2.38	2.35	2.58	2.73	2.61	2.87
Vitamin C	**µg**	40	-	63.46	70.69	65.89	73.77	68.03	61.40	71.99	68.07	61.56	69.66
Vitamin D	**µg**	110	-	179.67	209.10	196.14	219.66	252.04	236.98	262.79	244.78	240.32	273.25

Vitamin E	**mg**	-	50	4.41	4.41	4.30	5.17	0.29	0.15	0.67	15.00	18.29	18.29
Vitamin K	**mg**	13	300	13.15	17.58	16.06	18.81	22.98	19.41	29.37	17.78	16.64	18.21
Water	**g**	70	-	167.76	443.15	405.28	495.25	543.88	472.17	583.15	557.96	504.25	591.30
Zinc	**mg**	2500	-	3575.60	3274.98	3264.82	3771.98	3492.29	3209.89	3628.43	2984.01	2726.83	3101.08
Zinc	**mg**	12.9	25	13.19	12.90	12.94	12.94	9.44	8.58	9.78	12.90	12.61	12.61

*See notes after Table S14

Table S14. Nutrient properties, nutrient constraints as dietary reference values per day, and mean, minimum and maximum nutrient values1 per day across the different dietary scenarios2 for women.

Nutrient	**Unit**	**Women (values per day)**											
		DRV[1]	**UL[1]**	**RD mean**	**DD mean**	**min**	**max**	**VD mean**	**min**	**max**	**MD mean**	**min**	**max**
ALA[3]	**g**	1.01	-	1.27	1.50	1.43	1.76	2.26	1.98	2.37	1.42	1.32	1.49
Alcohol	**g**	-	-	5.15	0.59	0.56	0.69	2.62	2.25	2.80	3.80	2.93	4.57
Calcium	**mg**	950	2500	945.1	950.0	1021.5	1031.6	583.4	541.9	586.7	950.0	929.5	929.5
Carbohydrates total	**g**	198.5	268.2	251.18	268.24	270.44	270.44	267.03	256.05	284.61	253.05	235.41	274.71
Cholesterol	**mg**	-	-	246.25	174.67	142.63	179.98	10.92	9.04	12.06	149.39	142.14	174.66
Copper	**mg**	1.3	5.0	2.03	2.82	2.64	3.12	2.90	2.75	3.02	2.47	2.27	2.53
Cystine	**mg**	-	-	987.2	1105.2	1042.7	1162.8	851.8	859.7	950.7	1126.4	1059.3	1174.5
DHA[3]	**mg**	-	-	355.13	275.93	249.41	378.22	51.30	44.74	56.17	324.28	294.05	362.21
DHA+EPA[3]	**mg**	250	-	708.7	855.1	773.8	1078.7	543.0	431.6	605.4	1266.8	1092.9	1338.1
Dry matter	**g**	-	-	446.98	455.80	415.21	460.97	433.29	416.95	449.01	444.34	420.29	469.62
Energy	**kcal**	1799	1823	1999.2	1823.4	1824.8	1824.8	1800	1854.2	1854.2	1823.4	1776.4	1776.4
EPA[3]	**g**	-	-	0.35	0.58	0.44	0.71	0.49	0.55	0.81	0.94	0.73	0.95
Fat total	**g**	40.54	71.89	79.73	53.46	45.40	63.39	66.34	58.23	70.44	58.23	52.42	61.57
Fatty acids n-3	**g**	-	-	2.27	1.73	1.52	2.01	2.33	2.18	2.66	2.33	2.20	2.58
Fatty acids n-6	**g**	-	-	11.69	8.11	6.44	9.61	19.10	16.93	20.99	8.92	8.23	9.99
Fibre	**g**	25.0	-	23.40	32.47	30.65	34.68	38.08	36.08	39.49	35.77	33.69	37.71
Fluoride	**mg**	-	7.0	0.59	0.71	0.65	0.73	0.59	0.59	0.65	0.72	0.69	0.76
Folate eq.	**µg**	330	1000	286.15	443.52	416.89	456.35	466.96	445.28	483.27	489.09	491.00	542.24
Grams	**g**	-	-	3663.1	3897.0	3859.0	4420.8	3543.7	3303.1	3742.3	3399.1	3062.4	3512.4

Haem iron	**mg**	-	-	0.71	0.56	0.37	0.63	0.00	0.00	0.01	0.27	0.24	0.30
Histidine	**mg**	-	-	1931.2	1943.7	1784.4	2032.7	1189.8	1127.0	1223.9	1800.0	1718.6	1912.7
Iodine	**µg**	150	600	138.00	150.00	153.11	156.42	82.62	78.01	86.96	181.55	173.59	198.41
Iron total	**mg**	16.00		11.99	16.00	16.18	16.18	15.35	14.21	15.51	17.41	16.37	18.22
Isoleucine	**mg**	-	-	3459.6	3562.1	3354.1	3762.6	2074.7	2037.6	2214.5	3319.8	3015.7	3460.0
Lactose	**g**	-	-	11.51	8.47	8.14	10.42	0.08	0.07	0.10	8.44	8.88	12.24
Leucine	**mg**	-	-	5735.5	5893.7	5940.9	6695.6	3424.4	3076.8	3392.2	5580.7	5338.2	5923.9
Linoleic acid	**g**	8.11	-	8.89	9.50	8.41	13.21	19.42	16.38	21.91	8.52	8.10	9.01
Lysine	**mg**	-	-	4678.5	4628.2	4343.5	4958.4	2240.2	2140.8	2333.4	4217.3	3911.5	4478.9
Magnesium	**mg**	300	550	411.73	499.31	458.40	525.21	527.18	475.64	520.57	469.56	456.05	503.75
Manganese	**mg**	3.0	-	4.95	6.78	6.63	7.65	7.59	7.30	7.96	7.74	6.82	7.74
Methionine	**mg**	-	-	1557.04	1544.25	1407.81	1632.25	654.03	626.69	691.27	1424.30	1361.11	1531.45
Mono- and disaccharides	**g**	-	-	104.65	69.04	62.48	71.80	97.68	90.61	98.50	76.91	70.52	87.37
MUFA[3]	**g**	-	-	41.31	27.00	22.24	30.44	30.73	27.79	33.11	33.41	32.54	39.72
Niacin	**mg**	12.08	-	31.27	34.19	31.71	35.63	25.24	24.32	26.58	30.50	28.14	31.67
Phosphorus	**mg**	550	-	1340.76	1472.93	1408.14	1609.27	977.59	966.32	1052.23	1353.83	1330.77	1459.96
Polysaccharides	**g**	-	-	119.54	156.71	145.63	176.95	153.86	144.07	163.33	170.23	165.28	186.87
Potassium	**mg**	3500	-	3668.8	4248.8	4064.6	4442.6	4086.5	3940.8	4262.1	4105.9	3979.2	4425.3
Protein animal	**g**	-	-	39.43	33.19	28.74	37.16	0.00	0.00	0.00	26.55	24.57	28.62
Protein total	**g**	48.60	-	68.72	74.64	71.59	80.56	45.87	44.37	49.00	69.16	63.92	70.27
Protein vegetable	**g**	-	-	29.20	41.35	40.15	45.65	45.87	43.28	47.48	42.61	39.83	44.10
PUFA[3]	**g**	-	-	13.61	11.50	10.00	14.06	21.83	19.20	24.42	11.43	10.61	12.63
Retinol eq.	**µg**	650	3000	1091.7	1490.6	1370.3	1554.3	1566.9	1439.8	1659.0	1928.8	1822.8	2136.8
SAFA	**g**	-	-	31.96	18.00	15.46	20.96	11.94	10.66	13.15	14.32	12.63	15.16
Selenium	**µg**	70	300	90.07	102.08	95.91	113.50	75.21	65.39	82.48	77.05	71.33	82.23
Sodium	**mg**	-	-	2608.7	2558.0	2216.9	2575.0	1797.2	1563.0	1820.1	2822.8	2443.6	2882.8
Threonine	**mg**	-	-	2884.7	2964.4	2771.6	3117.6	1745.7	1662.1	1793.1	2818.5	2645.9	2957.7
Trans fatty acids	**g**	-	-	1.59	0.75	0.61	0.98	0.37	0.30	0.41	0.33	0.25	0.36
Tryptophan	**mg**	-	-	8512.0	900.1	826.3	929.6	544.9	514.3	564.1	832.4	796.8	887.1

Valine	**mg**	-	-	4043.3	4179.7	3962.1	4454.4	2484.7	2422.8	2682.4	3945.3	3577.3	4024.8
Vitamin B1	**mg**	0.1	-	1.32	1.68	1.58	1.84	1.55	1.48	1.62	1.82	1.70	1.94
Vitamin B12	**µg**	4.0	-	4.19	4.27	4.14	5.43	0.20	0.18	0.22	4.67	4.26	5.10
Vitamin B2	**mg**	1.6	-	1.76	1.90	1.76	1.96	1.26	1.21	1.33	1.94	1.86	2.08
Vitamin B5	**mg**	5.0	-	5.54	6.03	6.16	6.69	4.98	4.78	5.18	6.20	5.96	6.53
Vitamin B6	**mg**	1.6	25	1.69	2.14	2.03	2.26	1.81	1.73	1.87	2.10	1.98	2.24
Vitamin B7	**µg**	40	-	52.93	57.89	53.45	60.92	55.92	53.17	58.89	56.27	53.18	59.37
Vitamin C	**µg**	95	-	163.35	182.42	171.42	189.15	224.03	213.55	233.15	195.58	173.70	216.20
Vitamin D	**µg**	-	50	3.50	4.19	4.21	6.96	0.53	0.47	0.59	7.14	6.30	8.05
Vitamin E	**mg**	11	300	10.78	12.51	11.29	15.90	22.72	20.61	24.95	15.95	14.99	16.79
Vitamin K	**mg**	70	-	161.25	394.01	341.33	410.86	598.57	524.07	664.33	520.96	456.52	587.17
Water	**g**	2000	-	3216.1	3441.3	3238.5	3788.3	3271.2	3037.6	3502.6	3157.5	2934.9	3388.9
Zinc	**mg**	10.2	25	10.07	11.58	10.36	11.87	8.31	7.93	8.76	10.34	9.88	10.86

[1] Nutritional property constraints were defined according to dietary reference values (DRV) as minimum intake per day and upper tolerable intake level (UL) as maximum intake, according to EFSA and D-A-CH reference dietary values (DGE, 2021b; EFSA, 2019). During the optimisation process, constraint limits were determined more than the mean values, as variations - minimum and maximum changes occurred during Monte Carlo simulations.

2 Dietary scenarios are defined as reference diet in North-Rhine Westphalia (RD), diet recommended by the German Nutrition Society (DD), vegan diet (VD), and Mediterranean diet (MD). The sensitivity range is given in minimum and maximum values, respectively. Scenario uncertainties are based on 100 Monte Carlo simulations.

3 ALA: α-Linolenic acid; EPA: Eicosapentaenoic acid; DHA: Docosahexaenoic acid; PUFA: Polyunsaturated fatty acids; SAFA: Saturated fatty acids; MUFA: Monounsaturated fatty acids

Table S15. Human health impact means upper and lower values in disability-adjusted life years for men and women's dietary scenarios.

NCDs	Men				Women			
	RD	DD	VD	MD	RD	DD	VD	MD
Cardiovascular diseases	0.503	0.359	0.174	0.278	0.348	0.221	0.149	0.159
lower	0.153	0.098	0.037	0.072	0.120	0.077	0.049	0.043
upper	0.840	0.633	0.355	0.527	0.590	0.408	0.296	0.322
Ischemic heart disease	0.802	0.558	0.278	0.434	0.666	0.395	0.280	0.318
lower	0.203	0.120	0.066	0.095	0.173	0.097	0.081	0.078
upper	1.344	0.982	0.531	0.815	1.128	0.736	0.526	0.605
Hypertensive heart disease	0.102	0.102	0.102	0.102	0.047	0.047	0.047	0.047
lower	0.004	0.004	0.004	0.004	0.002	0.002	0.002	0.002
upper	0.356	0.356	0.356	0.356	0.233	0.233	0.233	0.233
Stroke	0.304	0.244	0.062	0.168	0.246	0.189	0.095	0.072
lower	0.122	0.107	0.003	0.077	0.106	0.093	0.030	0.023
upper	0.536	0.435	0.175	0.307	0.433	0.336	0.218	0.177
Diabetes and kidney diseases	0.325	0.230	0.048	0.242	0.271	0.213	0.039	0.148
lower	0.167	0.136	0.015	0.141	0.144	0.128	0.012	0.080
upper	0.498	0.342	0.095	0.359	0.419	0.319	0.087	0.240
Diabetes mellitus	0.437	0.303	0.046	0.319	0.394	0.307	0.045	0.210
lower	0.237	0.193	0.020	0.201	0.219	0.194	0.016	0.121
upper	0.629	0.413	0.067	0.436	0.565	0.419	0.077	0.302
Diabetes mellitus type 2	0.463	0.322	0.048	0.339	0.412	0.321	0.047	0.219
lower	0.252	0.205	0.021	0.213	0.229	0.203	0.017	0.126
upper	0.667	0.438	0.072	0.462	0.591	0.439	0.080	0.316
Neoplasms	0.076	0.055	0.022	0.039	0.074	0.053	0.026	0.034
lower	0.026	0.018	0.008	0.013	0.030	0.022	0.009	0.012
upper	0.131	0.101	0.045	0.074	0.119	0.090	0.050	0.061
Colon and rectum cancer	0.464	0.290	0.151	0.290	0.438	0.268	0.131	0.200
lower	0.171	0.107	0.062	0.107	0.156	0.094	0.050	0.076
upper	0.723	0.478	0.245	0.478	0.692	0.447	0.216	0.323
Esophageal cancer	0.144	0.144	0.000	0.000	0.146	0.146	0.146	0.084
lower	0.011	0.011	0.000	0.000	0.013	0.013	0.013	0.011
upper	0.365	0.365	0.000	0.000	0.372	0.372	0.372	0.240
Stomach cancer	0.074	0.074	0.074	0.074	0.050	0.050	0.050	0.050
lower	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
upper	0.308	0.308	0.308	0.308	0.257	0.257	0.257	0.257
Breast cancer	0.051	0.051	0.000	0.051	0.052	0.052	0.000	0.000
lower	0.026	0.026	0.000	0.026	0.026	0.026	0.000	0.000
upper	0.069	0.069	0.000	0.069	0.070	0.070	0.000	0.000

Note: RD: reference diet in NRW (baseline scenario); DD: DGE diet scenario; VD: Vegan diet scenario; MD: Mediterranean diet scenario

Table S16. Environmental and animal welfare impacts mean, minimum and maximum values per person and day for the alternative diet scenarios.

	RD		DD diet						VD						MD					
LCA impacts	**men**	**women**	**men**			**women**			**men**			**women**			**men**			**women**		
	mean	**mean**	**mean**	**min**	**max**	**mean**	**min**	**max**	**mean**	**min**	**max**	**mean**	**min**	**max**	**mean**	**min**	**max**	**mean**	**min**	**max**
loss of Animal Lives (AL)	6.8E-01	6.3E-01	5.4E-01	4.3E-01	5.6E-01	8.4E-02	7.4E-02	1.0E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	5.7E-01	1.9E-01	8.9E-01	7.1E-02	6.3E-02	8.2E-02
Animal Life Years Suffered (ALYS)	2.1E-01	1.8E-01	2.1E-01	1.9E-01	2.5E-01	8.4E-02	6.6E-02	1.1E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	7.2E-01	2.5E-01	1.3E+00	1.2E-01	1.1E-01	1.4E-01
loss of Morally Adjusted Animal Lives (MAL)	3.0E-03	2.6E-03	2.1E-03	1.7E-03	2.2E-03	7.8E-04	6.3E-04	9.2E-04	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.1E-03	1.8E-03	2.6E-03	1.2E-03	8.9E-04	1.2E-03
Fine particulate matter formation (kg PM2.5 eq)	1.9E-02	1.3E-02	1.2E-02	1.2E-02	1.3E-02	9.9E-03	8.6E-03	1.0E-02	5.9E-03	5.6E-03	6.1E-03	4.6E-03	4.6E-03	5.0E-03	1.1E-02	1.0E-02	1.2E-02	7.8E-03	7.4E-03	8.3E-03
Fossil resource scarcity (kg oil eq)	1.10	0.78	0.82	0.80	0.85	0.69	0.68	0.75	0.76	0.72	0.78	0.59	0.55	0.59	0.94	0.86	0.98	0.71	0.67	0.76
Freshwater eutrophication (kg P eq)	2.0E-03	1.3E-03	1.2E-03	1.2E-03	1.3E-03	9.9E-04	8.5E-04	1.1E-03	6.5E-04	6.0E-04	6.7E-04	5.6E-04	5.4E-04	5.9E-04	1.1E-03	9.5E-04	1.2E-03	7.7E-04	7.3E-04	8.2E-04
Global warming - excl LUC (kg CO_2eq)	8.24	5.55	5.61	5.33	5.77	4.56	4.01	4.80	3.48	3.31	3.54	2.78	2.68	2.87	5.53	5.22	6.03	3.94	3.84	4.31
Land use (m^2a crop eq)	6.23	4.27	4.70	4.54	4.90	3.75	3.34	4.16	3.87	3.47	3.98	3.44	3.34	3.67	4.77	4.31	4.93	3.59	3.37	3.72
Marine eutrophication (kg N eq)	1.4E-02	9.6E-03	9.9E-03	9.6E-03	1.1E-02	7.8E-03	6.8E-03	8.6E-03	5.1E-03	4.7E-03	5.2E-03	4.5E-03	4.4E-03	4.8E-03	8.5E-03	7.7E-03	9.3E-03	6.0E-03	5.6E-03	6.3E-03
Terrestrial acidification (kg SO_2 eq)	1.3E-01	8.1E-02	7.7E-02	7.3E-02	8.1E-02	6.0E-02	5.1E-02	6.6E-02	2.5E-02	2.5E-02	2.7E-02	2.1E-02	2.0E-02	2.2E-02	6.3E-02	5.5E-02	7.0E-02	4.2E-02	3.9E-02	4.5E-02
Water consumption (m3)	0.22	0.17	0.22	0.20	0.24	0.17	0.12	0.19	0.32	0.29	0.34	0.31	0.29	0.33	0.29	0.28	0.31	0.25	0.24	0.28

Note: RD: reference diet in NRW (baseline scenario); DD: DGE diet scenario; VD: Vegan diet scenario; MD: Mediterranean diet scenario

ii. Chapter 4 Appendices: Supplementary Information: "Optimised diets for improving human, animal, and environmental health in the Rhine-Ruhr Metropolis in Germany"

This material was submitted as electronic supplementary material and can be downloaded as a Word file at https://doi.org/10.1016/j.eiar.2024.107529.

S1. Demographic data

Table S1. Demographic characteristics of the study population.

Variable	Categories	Frequencies/ mean values
Gender	Female Male	76.9% 23.1%
Age	25% percentile 32 y 50% percentile 44 y 75% percentile 56 y	Mean 44.8 y ± 1.2
Education	Secondary education or lower Higher education entrance qualification (*Abitur*) Advanced technical college Graduation or higher (Bachelor, Master, Doctorate) Not responded	6.56% 27.32% 2.19% 63.39% 0.55%
Marital status	Married Single Living with a partner or in an official civil partnership Divorced Not responded	46.99% 27.32% 19.67% 5.46% 0.55%
Nationality	German nationality German with other nationality European nationality Other nationality Undeclared	89.07% 4.37% 2.19% 3.28% 1.09%
Monthly median income (PPP Int$)	25% percentile $ 3,190.01 50% percentile $ 4,299.58 75% percentile $ 5,963.58	Mean $ 5,956.14 ± 370.32
Location	**Rhine-Ruhr Metropolis**	**92.97%**
	Ruhrgebiet	70.81%
	Bergisch Triangle	0.54%
	Cologne/Bonn	2.16%
	Düsseldorf	2.70%
	Ennepe-Ruhr-Kreis	3.24%
	Kreis Mettmann	0.54%
	Kreis Recklinghausen	5.95%
	Kreis Unna	3.24%
	Kreis Viersen	0.54%
	Kreis Wesel	1.08%
	Märkischer Kreis	1.62%
	Rheinisch-Bergischer Kreis	0.54%
	outside Rhine-Ruhr Metropolis	**4.32%**
	Not within a metropolis	**1.08%**
	Not responded	1.62%

Note: mean values at 95% Confidence Interval

S2. Dietary data

We classified the food items obtained from the EPIC FFQ according to the EPICSOFT food group classification (Harttig, 2021). The raw data from the FFQ served to identify food item quantities within each food category. Food items were further reallocated to fit into the EFSA FoodEx classification (EFSA, 2018) to match the food consumption foreground data with the food item LCA background data, as shown in **Table S2.**

Table S2. Food groups and subgroups are mapped from the EPICSOFT FFQ2 to the EFSA (2018) database.

EPICSOFT		EPIC FFQ2 questionnaire	Re-categorization & reallocation			Remarks
Group	**Subgroup**	**Food items**	**Group (EFSA)**	**Subgroup (EFSA)**	**Food items (EFSA)**	
alcoholic beverages	aniseed drinks (absinth)	-	alcoholic beverages	spirits	spirits	Reallocated to proxy “spirits”
	beer, cider	beer, wheat beer, strong beer	alcoholic beverages	beer and beer-like beverage	beer, regular	-
		light beer, low-alcohol beer	alcoholic beverages	beer and beer-like beverage	beer and beer-like beverage	-
		malt beer, non-alcoholic beer	alcoholic beverages	beer and beer-like beverage	beer and beer-like beverage	Assumed as “beer”
	cocktails, punches	mixed drinks (e.g., cocktails, *Radler*, mulled wine and other wine-based drinks)	alcoholic beverages	alcoholic mixed drinks	spirits	Assumed as 1/3 spirit, 2/3 soft drink
	liqueurs	liqueur (e.g., amaretto, cream liqueur, egg liqueur, *Jenever*)	alcoholic beverages	liqueur	spirits	Reallocated to proxy “spirits”
	spirits, brandy	spirits (e.g., brandy, whiskey, grain, vodka, fruit liqueur, rum)	alcoholic beverages	spirits	spirits	-
	wine	red wine	alcoholic beverages	wine	wine, red	-
		white wine, rosé wine	alcoholic beverages	wine	wine, white	-
		sparkling wine, champagne, prosecco	alcoholic beverages	wine	wine, white	Assumed as “white wine”
cakes	cakes, pies, pastries, puddings	fruit cake	grains and grain-based products	fine bakery wares	pastries and cakes	Reallocated to proxy “pastries and cakes”

		cheesecake, cream or custard cake	grains and grain-based products	fine bakery wares	pastries and cakes	Reallocated to proxy “pastries and cakes”
		sponge cake (e.g., marble cake, cupcake, muffin)	grains and grain-based products	fine bakery wares	pastries and cakes	Reallocated to proxy “pastries and cakes”
	dry cakes, biscuits	biscuits (e.g., butter biscuits, cookies, double biscuits)	grains and grain-based products	fine bakery wares	biscuits	-
cereals	bread (1 slice), bun (1 piece)	whole-grain bread, rolls and toast bread	grains and grain-based products	bread and rolls	mixed wheat and rye bread and rolls	-
		grey bread, rye bread, spelt bread, mixed bread or rolls	grains and grain-based products	bread and rolls	rye bread and rolls	-
		wheat bread, rolls, baguette, toast, flatbread, pretzel pastries	grains and grain-based products	bread and rolls	wheat bread and rolls	-
		croissant, sliver roll	grains and grain-based products	fine bakery wares	pastries and cakes	Reallocated to proxy “pastries and cakes”
	breakfast cereals	muesli, cereals (e.g. cereal flakes, cereal meal, cornflakes, puffed rice)	grains and grain-based products	breakfast cereals	cereal flakes	-
	crisp bread, rusk	-	grains and grain-based products	bread and rolls	wheat bread and rolls	Assumed as “wheat bread and rolls”
	dough and pastry	egg pancakes, waffles	grains and grain-based products	grain milling products	wheat milling products	Assumed as “wheat milling products”
		pastries, cakes (e.g., cinnamon bun, filled cake)	grains and grain-based products	fine bakery wares	pastries and cakes	Reallocated to proxy “pastries and cakes”
	flour, flakes, starches, semolina	-	grains and grain-based products	grain milling products	wheat milling products	Allocated to food group “wheat milling products”. Rice and pasta are in the same FFQ question, making individual quantification impossible.
	pasta, rice, and other grain	rice, noodles, whole-grain pasta, pearl barley, cereals	grains and grain-based products	grain milling products	wheat milling products	

	salty biscuits, aperitif biscuits	salty biscuits, snacks (e.g., crisps, pretzels, salt sticks, crackers)	snacks, desserts, and other foods	snack food	pretzels	Assumed as “pretzels”
condiments, spices and flavourings	condiments	mustard	herbs, sauces and condiments	condiment	mustard, mild	-
		tomato ketchup, curry ketchup	herbs, spices and condiments	condiment	tomato ketchup	-
	dessert sauces	-	snacks, desserts, and other foods	ices and desserts	custard	Assumed as “custard”
	dressing sauces	salad dressings (diverse)	herbs, spices and condiments	dressing	dressing	-
	mayonnaise and similar	mayonnaise, tartar sauce	herbs, spices and condiments	dressing	mayonnaise, > 50% oil	-
	spices, herbs and flavourings	-	herbs, spices and condiments	spices	pepper, black and white	Assumed as “black pepper”
	tomato sauces	tomato sauce (made from fresh or canned tomatoes)	vegetables and vegetable products	savoury sauces	savoury sauces	Assumed as “savoury sauce”
	unclassified other sauces	-	herbs, spices and condiments	savoury sauces	savoury sauces	
dairy products	cheeses	soft cheese (e.g., Camembert, mozzarella, feta)	milk and dairy products	cheese	cheese, Camembert	Assumed as “Camembert”
		sour milk cheese (e.g., *Harz* cheese)	milk and dairy products	cheese	cheese	Put into the "cheese" group, as no proxy was identified.
		semi-hard cheese, hard cheese (e.g., *Gouda*, parmesan, *Emmental*)	milk and dairy products	cheese	cheese, *Gouda*	Assumed as “*Gouda”*
	cream desserts, puddings	desserts (e.g., ice cream, chocolate mousse, pudding, tiramisu, fruit curd, red fruit jelly)	snacks, desserts, and other foods	ices and desserts	ices and desserts	-
	dairy creams	whipped cream	milk and dairy products	cream and cream products	cream	-
		cream, crème Fraiche	milk and dairy products	cream and cream products	cream	-
	fromage blanc, petit Suisse’s	cream cheese, granular cream cheese	milk and dairy products	cheese	cheese, processed spreadable	-
		quark, herb quark	milk and dairy products	cheese	quark	-

	milk	milk	milk and dairy products	liquid milk	cow milk	-
	milk beverages	buttermilk	milk and dairy products	fermented milk products	buttermilk	-
		cocoa, milkshake, mixed milk drink	milk and dairy products	milk-based beverages	flavoured milk	-
	yoghurt	fruit yoghurt and flavoured yoghurt	milk and dairy products	fermented milk products	yoghurt, cow milk, plain	Assumed as "plain yoghurt"
		natural yoghurt, soured milk, kefir	milk and dairy products	fermented milk products	yoghurt, cow milk, plain	-
	milk for coffee creamer	as coffee/tea additions	milk and dairy products	concentrated milk	evaporated milk	-
egg and egg products	egg	egg, fried (e.g., omelette, fried or scrambled)	composite food	egg-based meal (e.g., omelette)	egg-based meal	-
		egg, cooked	eggs and egg products	eggs, fresh	chicken egg	-
oils and fats	butter	butter	animal and vegetable fats and oils	animal fat	butter	-
	deep frying fats	other vegetable oil	animal and vegetable fats and oils	vegetable oil	vegetable oil	-
	fat (unclassified)	animal cooking fat	animal and vegetable fats and oils	animal fat	butter	Assumed as "butter"
	margarine	margarine	animal and vegetable fats and oils	margarine and similar products	margarine, normal fat	-
	other animal fat	other fat-lard	animal and vegetable fats and oils	fats of mixed origin	fats of mixed origin	Reallocated to proxy "fats of mixed origin"
	vegetable oils	olive oil, rapeseed oil	animal and vegetable fats and oils	vegetable oil	vegetable oil	
fish and shellfish	fish	fish, fresh, canned (e.g., herring, tuna, salmon, Pollock, trout)	fish and other seafood	fish meat	salmon and trout	Assumed as "salmon and trout"
	fish products, fish in crumbs	fish dishes (e.g., fish fingers, gourmet fillets)	fish and other seafood	fish products	fish fingers	-
	crustaceans, molluscs	seafood (e.g., shrimps, squid, mussels)	fish and other seafood	crustaceans	shrimps	Assumed as "shrimps"
fruits	fruits	apple, pear	fruit and fruit products	pome fruits	apple	-

		orange, *Mandarine*	fruit and fruit products	citrus fruits	oranges	-
		kiwi, pineapple	fruit and fruit products	miscellaneous fruits	kiwi	-
		banana	fruit and fruit products	miscellaneous fruits	bananas	-
		fig, *physalis*, pomegranate	fruit and fruit products	miscellaneous fruits	fig	Item added
		cherries, plums, *Mirabelle*, apricot	fruit and fruit products	stone fruits	cherries	Item added
		grape	fruit and fruit products	berries and small fruits	grape	Item added
		peach, nectarine	fruit and fruit products	stone fruits	peaches	-
		soft fruit (strawberry, gooseberry, blueberry)	fruit and fruit products	berries and small fruits	strawberries	-
		melon	vegetables and vegetable products	fruiting vegetables	melons	-
		avocado	fruit and fruit products	oil fruits	avocado	Item added
	mixed fruits	fruit compote	fruit and fruit products	other fruit products	fruit compote	-
		fresh fruit salad	fruit and fruit products	fruit and fruit products	a mix of apples, oranges, and bananas (1:3)	Assumed as a mix of apples, oranges, and bananas (1:3)
		dried fruit	fruit and fruit products	dried fruits	dried fruits	Item added
	nuts and seeds	nuts, fresh, roasted, salted (including peanuts, almonds, pistachios, trail mix)	legumes, nuts and oilseeds	tree nuts	tree nuts	A blend of almonds, cashews, hazelnuts and walnuts
		seeds (e.g. sunflower or pumpkin seeds, linseeds)	legumes, nuts and oilseeds	oilseeds	sunflower seed	Assumed as “sunflower seed”
	olives	olives		oil fruits	olives	Item added
legumes	legumes	legumes (beans, peas, chickpeas, lentils)	legumes, nuts and oilseeds	legumes, beans, dried	lentils	-
		As an ingredient of vegetarian stew (e.g., vegetable, lentil, or bean stew without meat), or stew with meat (e.g., vegetable, lentil, or bean stew with meat).	-	-	-	No identifiable individual intake quantified within other food groups
	beef	beef	meat and meat products	livestock meat	beef meat	-

meat and meat products	chicken, hen	poultry meat	meat and meat products	poultry	chicken meat	-
	game	veal, lamb, rabbit, game	meat and meat products	game mammals	red deer	Item added
	mutton, lamb	veal, lamb, rabbit, game	meat and meat products	livestock meat	mutton/lamb meat	-
	offal	offal (e.g., liver, kidney, stomach)	meat and meat products	edible offal-farmed animals	pork liver	Item added
	other poultry	poultry meat	meat and meat products	poultry	turkey meat	-
	pork	pork	meat and meat products	livestock meat	pork/piglet meat	-
	processed meat	liver sausage	meat and meat products	sausages	sausages	Reallocated to major food category
		salami, pork sausage, *cabanossi*	meat and meat products	sausages	dry sausage	-
		meat sausage, ham sausage	meat and meat products	sausages	fresh and lightly cooked sausage	Reallocated to proxy
		poultry sausage	meat and meat products	sausages	fresh and lightly cooked sausage	Reallocated to proxy
		red sausage, black pudding, aspic, head cheese	meat and meat products	sausages	sausages	Reallocated to proxy
		raw ham, cooked ham	meat and meat products	preserved meat	ham, pork	-
		bratwurst (1 whole), liver loaf, meatloaf (1 slice)	meat and meat products	sausages	fresh and lightly cooked sausage	Assumed as "bratwurst" -fresh and lightly cooked sausage
		boiled sausage (*Wiener, Frankfurter, bock, knack, Weißwurst*)	meat and meat products	sausages	cooked smoked sausage	-
	rabbit (domestic)	veal, lamb, rabbit, game	meat and meat products	livestock meat	rabbit meat	Item added
	red meat (unclassified)	-	meat and meat products	meat and meat products (including edible offal)	meat and meat products (including edible offal)	-
	where meat was an ingredient (not possible to	*Frikadelle*, *Boulette*	composite food	meat-based meals	meatballs	No identifiable individual intake quantified within other food groups
		delicatessen salad (e.g. meat, egg, herring, poultry salad)	-	-	-	

	quantify individually), already quantified within several meat food groups	stew with meat (e.g. vegetable, lentil, bean stew with meat)	composite food	meat-based meals	meat stew	
		meat-based dishes (e.g. casseroles, lasagne, pizza, kebab, filled puff pastry)	composite food	meat-based meals	meat-based meals	
	veal	veal, lamb, rabbit, game	meat and meat products	livestock meat	veal meat	-
miscellaneous	artificial sweeteners	as coffee/tea additions	-	-	-	Assumed as sugar
	miscellaneous (unclassified)	-	-	-	-	Assumed as unclassified sugars
	soya products	soymilk	animal protein substitutes		soymilk	Item added
		soy sauce			salt, iodised	Assumed as salt, iodised
		Tofu	animal protein substitutes		Tofu	Item added
	sweeteners unclassified	-	-	-	-	Assumed as unclassified sugars
non-alcoholic beverages	carbonated/soft/isotonic drinks	lemonade, cola	non-alcoholic beverages	soft drinks	soft drink, flavoured	-
		diet lemonade, diet cola	non-alcoholic beverages	soft drinks	soft drink, flavoured	It is assumed to be a soft drink
	chicory, substitutes	coffee without caffeine	non-alcoholic beverages	coffee (beverage)	decaffeinated coffee	Item added
	coffee	coffee, espresso (also cappuccino, café latte, then tick "with milk")	non-alcoholic beverages	coffee (beverage)	coffee	-
	fruit and vegetable juices	orange juice	fruit and vegetable juices	fruit juice	juice, orange	-
		apple juice	fruit and vegetable juices	fruit juice	juice, apple	-
		multivitamin juice	fruit and vegetable juices	fruit juice	fruit juice	Assumed as "fruit juice"
		other fruit juices	fruit and vegetable juices	fruit juice	fruit juice	Assumed as "fruit juice"
		vegetable juice	fruit and vegetable juices	vegetable juice	vegetable juice	-
	water	mineral water, tap water	drinking water	bottled water tap water	bottled water tap water	-

	tea	herbal tea	non-alcoholic beverages	tea (infusion)	herbal tea, infusion	-
		fruit tea, herbal tea	non-alcoholic beverages	tea (infusion)	herbal tea, infusion	Assumed as "herbal tea"
		tea, black or green	non-alcoholic beverages	tea (infusion)	black tea, infusion	-
	non-alcoholic beverages (unclassified)	-	non-alcoholic beverages	-	-	Assumed as tap water
potatoes and other tubers	potatoes	potato preparations (e.g., fried potatoes, French fries, potato pancakes, potato salad)	starchy roots and tubers	potatoes and potato products	potatoes and potato products	-
soups, bouillon	bouillon	clear soups (e.g., vegetable broth, noodle soup)	composite food	ready-to-eat soups	ready-to-eat soups	-
	soups	cream soups (e.g., from pumpkin, asparagus, broccoli)	composite food	ready-to-eat soups	vegetable/her b soup	-
sugar and confectione ry	chocolate, candy bars, paste	chocolate, sweets with chocolate (e.g., chocolate bars, chocolates, dried fruits with chocolate coating)	sugar and confectionery	chocolate (cocoa) products	chocolate (cocoa) products	-
	confectionery non-chocolate	confectionery without chocolate (e.g., gummy bears, sweets, liquorice confectionery)	sugar and confectionery	confectionery (non-chocolate)	confectionery (non-chocolate)	-
	ice cream	inside "desserts (e.g., ice cream, chocolate mousse, pudding, tiramisu, fruit curd, red fruit jelly)"	snacks, desserts, and other foods	ices and desserts	ices and desserts	-
	sugar, honey, jam	jam, honey, sugar, syrup	sugar and confectionery	sugars	white sugar (proxy)	Reallocated to “white sugar”
	syrup	jam, honey, sugar, syrup	sugar and confectionery	molasses and other syrups	molasses and other syrups	-
	unclassified	-	sugar and confectionery	-	-	No identifiable intake or respective food item
vegetable	cabbages	sauerkraut	vegetables and vegetable products	Brassica vegetables	head cabbage (proxy)	Reallocated to representative “head cabbage”
		cabbage (white, green, pink, purple)	vegetables and vegetable products	Brassica vegetables	head cabbage	-
		broccoli, cauliflower	vegetables and vegetable products	Brassica vegetables	head cabbage	Reallocated to proxy

	fruiting vegetables	tomato, pepper cooked	vegetables and vegetable products	fruiting vegetables	tomatoes	Assumed as tomatoes
		cucumber, gherkin	vegetables and vegetable products	fruiting vegetables	cucumbers	-
		aubergine, courgette	vegetables and vegetable products	fruiting vegetables	zucchini	Item added
		tomato, pepper, raw	vegetables and vegetable products	fruiting vegetables	tomatoes	Assumed as tomatoes
	grain and pod vegetables	legumes (beans, peas, chickpeas, lentils)	vegetables and vegetable products	legume vegetables	beans with pods	Assumed as beans, with pods
	leafy vegetables	spinach	vegetables and vegetable products	leafy vegetables	spinach (fresh)	-
		green salad, leaf vegetables	vegetables and vegetable products	leafy vegetables	lettuce, excluding iceberg-type lettuce	-
	mixed salad, mixed vegetables	vegetable mix	composite food	prepared salads	prepared mixed vegetable salad	-
	mushrooms	mushrooms	vegetables and vegetable products	fungi, cultivated	cultivated mushroom	-
	onion, garlic	onion, garlic	vegetables and vegetable products	bulb vegetables	onions, bulb	-
	root vegetables	carrot cooked	vegetables and vegetable products	root vegetables	carrots	-
		carrot, kohlrabi (raw)	vegetables and vegetable products	root vegetables	carrots	-
	stalk vegetables, sprouts	asparagus	vegetables and vegetable products	stem vegetables (fresh)	leek (proxy)	Assumed as "stem vegetables" and reallocated to “leeks”

unclassified (other)	where vegetables are ingredients (not possible to quantify individually)	"vegetarian dishes (e.g. vegetable casserole, cereal or vegetable fritters, filled puff pastry without meat"	vegetable-based meals	vegetable-based meals	vegetable-based meals	No identifiable individual intake. Food items are quantified among other food groups

Table S3. Average intake in grams per day by each dietary pattern.

Food Category	Food Item	WT1*		WT2		PRU	
		average	SE**	average	SE	average	SE
Alcoholic beverages	Beer and beer-like beverage	88.6	± 54.2	67.2	± 15.3	29.0	± 6.0
	Beer, regular	74.7	± 45.7	56.6	± 12.9	24.4	± 5.0
	Spirits	4.7	± 1.4	8.1	± 1.6	3.3	± 0.7
	Wine, red	23.6	± 5.9	34.6	± 6.1	24.2	± 4.8
	Wine, white	41.3	± 10.2	60.7	± 10.8	42.4	± 8.5
Animal and vegetable fats and oils	Butter	10.9	± 1.7	11.1	± 1.4	6.8	± 0.9
	Fats of mixed origin	0.1	± 0.0	0.1	± 0.0	0.0	± 0.0
	Margarine, normal fat	6.3	± 1.3	4.0	± 0.8	5.2	± 0.8
	Olive oil	12.3	± 1.3	13.5	± 1.0	22.4	± 1.9
	Vegetable oil	0.2	± 0.0	0.3	± 0.0	0.2	± 0.0
Animal protein substitutes	Soy milk	2.9	± 1.0	8.2	± 2.1	27.5	± 5.2
	Tofu	1.2	± 0.4	3.5	± 0.9	11.7	± 2.2
Composite food	Egg-based meal	4.7	± 0.6	7.5	± 0.6	3.7	± 0.5
	Prepared mixed vegetable salad	7.1	± 0.8	7.2	± 0.8	13.4	± 1.3
	Ready-to-eat soups	7.6	± 1.1	17.0	± 2.1	12.2	± 1.3
	Vegetable/herb soup	22.2	± 4.3	45.6	± 4.6	41.2	± 4.2
Drinking water	Bottle water	11.3	± 3.0	36.6	± 14.5	17.5	± 5.3
	Tap water	1033.3	± 95.5	1431.4	± 83.8	1300.6	± 79.1
Eggs and egg products	Chicken egg	0.1	± 0.0	0.1	± 0.0	0.1	± 0.0
Fish and other seafood	Fish fingers	2.3	± 0.4	4.7	± 0.6	1.8	± 0.3
	Salmon and trout	6.7	± 1.1	12.8	± 1.5	5.7	± 0.9
	Shrimps	0.9	± 0.2	1.1	± 0.3	0.6	± 0.2
Fruit and fruit products	Apple	17.1	± 1.4	25.8	± 1.6	53.8	± 4.5
	Avocado	1.5	± 0.1	2.3	± 0.1	4.7	± 0.4
	Bananas	8.4	± 0.7	12.7	± 0.8	26.4	± 2.2
	Cherries	7.4	± 0.6	11.1	± 0.7	23.1	± 2.0
	Dried fruits	1.8	± 0.2	2.5	± 0.3	4.8	± 0.7
	Figs	1.7	± 0.1	2.5	± 0.2	5.2	± 0.4

	Fruit compote	0.3	± 0.0	0.5	± 0.0	0.9	± 0.1
	Grapes	7.4	± 0.6	11.2	± 0.7	23.4	± 2.0
	Kiwi	3.6	± 0.3	5.3	± 0.3	11.2	± 0.9
	Olives	0.4	± 0.1	0.4	± 0.1	0.6	± 0.1
	Oranges	11.0	± 0.9	16.5	± 1.0	34.4	± 2.8
	Peaches	7.9	± 0.6	11.9	± 0.8	24.9	± 2.1
	Strawberries	15.2	± 1.2	22.9	± 1.5	47.9	± 4.0
Fruit and vegetable juices	Fruit and vegetable juices	2.1	± 0.5	5.7	± 1.2	3.1	± 0.5
	Fruit juice	14.1	± 3.4	37.3	± 7.6	20.6	± 3.4
	Juice, Apple	9.1	± 2.2	24.1	± 4.9	13.3	± 2.2
	Juice, Orange	15.0	± 3.6	39.8	± 8.1	21.9	± 3.6
Grains and grain-based products	Biscuits	7.0	± 2.4	8.6	± 1.2	5.5	± 0.9
	Cereal flakes	3.8	± 0.7	10.6	± 1.4	9.6	± 1.0
	Multigrain bread and rolls	51.0	± 5.9	33.6	± 4.2	33.2	± 2.3
	Pasta, wheat flour, without eggs	60.2	± 6.4	80.6	± 6.4	70.0	± 5.5
	Pastries and cakes	48.3	± 5.9	57.5	± 4.5	44.8	± 3.1
	Rye bread and rolls	44.0	± 5.1	28.9	± 3.6	28.6	± 2.0
	Wheat bread and rolls	25.5	± 2.7	17.7	± 1.9	17.4	± 1.0
	Wheat milling products	3.6	± 0.4	7.6	± 0.7	5.4	± 0.4
Herbs, spices and condiments	Dressing	3.5	± 0.6	4.4	± 1.0	3.9	± 0.7
	Mayonnaise	1.3	± 0.2	2.8	± 0.3	1.1	± 0.1
	Mustard, mild	2.6	± 0.4	2.8	± 0.3	6.9	± 0.7
	Pepper, black and white	0.0	± 0.0	0.0	± 0.0	0.1	± 0.1
	Salt, iodised	1.7	± 0.6	4.8	± 1.2	16.2	± 3.0
	Savoury sauces	61.1	± 5.3	93.1	± 5.6	59.8	± 4.0
	Tomato ketchup	1.3	± 0.2	1.4	± 0.2	3.5	± 0.4
Legumes, nuts and oilseeds	Lentils	3.9	± 0.5	5.5	± 0.6	10.6	± 1.0
	Sunflower seed	1.4	± 0.3	3.3	± 0.5	3.6	± 0.3
	Tree nuts	1.5	± 0.3	3.7	± 0.5	4.0	± 0.4
Meat and meat products	Beef meat	15.1	± 6.8	10.2	± 1.9	3.9	± 0.7
	Chicken meat	5.4	± 0.7	8.6	± 0.7	4.3	± 0.5

	Cooked smoked sausage	2.1	± 0.4	1.7	± 0.2	0.9	± 0.1
	Dry sausage	7.3	± 1.3	5.7	± 0.7	3.0	± 0.4
	Fresh and lightly cooked sausage	12.9	± 2.2	10.1	± 1.2	5.3	± 0.8
	Game meat	1.1	± 0.2	0.6	± 0.1	0.4	± 0.1
	Ham, pork	10.3	± 1.8	8.1	± 1.0	4.3	± 0.6
	Other meat and meat products	0.1	± 0.0	0.2	± 0.0	0.1	± 0.0
	Mutton/lamb meat	0.7	± 0.2	0.4	± 0.1	0.2	± 0.0
	Pork/piglet meat	26.9	± 11.0	17.3	± 4.7	4.7	± 1.0
	Pork liver	0.2	± 0.1	0.6	± 0.2	0.2	± 0.1
	Rabbit meat	0.2	± 0.1	0.1	± 0.0	0.1	± 0.0
	Sausages	5.3	± 0.9	4.1	± 0.5	2.2	± 0.3
	Turkey meat	18.3	± 7.4	10.7	± 1.7	5.5	± 1.5
	Veal meat	1.1	± 0.7	0.5	± 0.1	0.2	± 0.0
Milk and dairy products	Buttermilk	0.9	± 0.3	2.9	± 0.7	1.1	± 0.3
	Cheese	1.2	± 0.1	1.6	± 0.1	1.5	± 0.2
	Cheese, Camembert	7.4	± 0.7	10.0	± 0.7	9.4	± 1.5
	Cheese, Gouda	14.5	± 1.3	19.5	± 1.4	18.4	± 2.9
	Cheese, processed spreadable	2.6	± 0.5	8.5	± 0.8	5.7	± 0.9
	Cow milk	79.1	± 12.5	157.8	± 17.1	86.1	± 11.3
	Cream	2.7	± 0.3	5.1	± 0.5	3.1	± 0.3
	Evaporated milk	0.4	± 0.2	0.1	± 0.0	0.5	± 0.4
	Flavoured milk	1.4	± 0.4	4.5	± 1.1	1.7	± 0.5
	Quark	2.7	± 0.5	9.0	± 0.9	6.0	± 0.9
	Yoghurt, cow milk, plain	16.1	± 2.9	49.1	± 9.0	24.6	± 3.3
Non-alcoholic beverages	Black tea, infusion	71.0	± 19.0	125.1	± 26.9	122.8	± 21.6
	Coffee	195.0	± 32.6	229.6	± 29.0	276.8	± 32.4
	Coffee, decaffeinated	5.3	± 0.2	5.6	± 0.1	5.3	± 0.0

	Herbal tea, infusion	96.8	± 29.7	112.8	± 23.1	270.9	± 43.7
	Soft drink, flavoured	142.3	± 49.4	61.2	± 15.2	33.5	± 11.4
Snacks, desserts, and other foods	Custard	0.5	± 0.0	0.9	± 0.1	0.6	± 0.0
	Ice cream, milk-based	2.1	± 0.4	14.1	± 1.8	4.7	± 1.1
	Ices and desserts	2.4	± 0.5	16.2	± 2.1	5.4	± 1.2
	Pretzels	3.1	± 0.6	6.5	± 1.0	3.0	± 0.5
Starchy roots and tubers	Potatoes and potato products	40.5	± 4.7	60.1	± 4.4	47.9	± 4.2
Sugar and confectionery	Chocolate (Cocoa) products	6.7	± 0.9	13.2	± 1.3	11.2	± 1.7
	Confectionery (non-chocolate)	3.0	± 0.6	4.7	± 0.7	2.6	± 0.5
	Molasses and other syrups	1.1	± 0.1	1.5	± 0.1	1.9	± 0.1
	White sugar	14.0	± 2.5	22.9	± 2.8	17.0	± 1.8
Vegetables and vegetable products	Beans with pods	3.3	± 0.4	4.2	± 0.4	9.3	± 0.9
	Broccoli	6.9	± 0.6	6.8	± 0.5	13.7	± 1.4
	Carrots	11.2	± 0.8	12.9	± 0.8	21.6	± 1.6
	Cucumbers	15.1	± 1.2	18.7	± 1.1	30.4	± 1.9
	Cultivated mushroom	2.0	± 0.3	2.5	± 0.3	4.1	± 0.6
	Head cabbage	5.8	± 0.5	5.7	± 0.5	11.4	± 1.2
	Leek	2.9	± 0.3	3.0	± 0.2	4.3	± 0.5
	Lettuce	7.6	± 0.8	7.0	± 0.7	14.6	± 1.3
	Melons	5.2	± 0.4	7.8	± 0.5	16.4	± 1.4
	Onions, bulb	5.5	± 0.4	6.9	± 0.4	5.0	± 0.2
	Peppers, paprika	7.8	± 0.6	9.7	± 0.6	15.8	± 1.0
	Spinach (fresh)	1.8	± 0.2	1.7	± 0.2	3.5	± 0.3
	Tomatoes	19.1	± 1.5	23.7	± 1.4	38.5	± 2.4
	Zucchini	6.0	± 0.5	7.4	± 0.4	12.0	± 0.7

*WT1 = Western-type 1; WT2 = Western-type 2; PRU = Prudent

**Standard error of the average intake, considering the number of observations within each dietary pattern at 95% confidence interval

S3. Life Cycle Assessment

The method based on our previous study framework to integrate One Health into the LCA (Paris et al., 2022), where more information can be found. The system boundaries, the LCI for environmental impacts and animal welfare indicators for the added food items are available in **Figure 5, Chapter 3, and Chapter 3, Appendices S2**.

Table S4. Life cycle inventory data sources and assumptions used to estimate environmental impact categories for food items added.

Food item	Life Cycle (sub) stage	Parameters and assumptions	Data source
Olives	Green olive Spanish style (agricultural and processing stages) Ripe olive Californian style (only processing stage)	Agricultural phase, primary packaging (jar), pasteurisation secondary packaging (box), different processing methods (green and ripe olives); • Eutrophication [kg P eq.] • Global warming [kg CO_2 eq.] • energy use [MJ/100 kg or FU]	For green olives (Cappelletti et al., 2010); for Californian-style olives (Russo et al., 2010); conversion to kilograms of oil equivalent (kgoe) (Eurostat, 2022)
Decaffeinated coffee	Agricultural, transportation and processing (steaming, extraction, washing, degassing, evaporation, crystallisation	blend coffee (60% Arabica, 40% Robusta); Supercritical CO_2 extraction of caffeine from coffee beans; Emissions to water, air and soil; • climate change [kg CO_2 eq] • terrestrial acidification [kg SO_2 eq] • freshwater eutrophication [kg P eq] • Marine eutrophication [kg N eq] • agricultural land occupation [m^2 x yr.] • water depletion [m^3] • fossil fuel depletion [kg oil eq]	Caffeine extraction (De Marco et al., 2018)
Rabbit meat	Feed cultivation stage, feed processing stage, breeding stage, slaughtering stage, manure treatment, biogas generation	The standard weight of 2.6 kg after 140 days of breeding adult rex rabbits with an output of 1.5 kg meat and 1kg fur; • Acidification [kg SO_2 eq] • climate change [kg CO_2 eq] • Land occupation [m^2yr]	Rex rabbit LCA (Wang et al., 2022)
Game meat	Census of wild red deer, bullets used, hunting trips, hunting	Wild red deer standard mass at the Control Centre (i.e. carcass weight already eviscerated);	Red deer hunting (Fiala et al., 2020);

	activity, transportation to the Control Centre (culling and evisceration)	Allocation is given to the carcass as offal is not a commercial product; • Global warming [kg CO_2 eq] • Particulate matter formation [kg $PM_{2.5}$ eq] • Acidification potential conversion [mol H^+ eq] 1 kg sulphur oxides = 1.31 mol H^+ eq • Freshwater eutrophication [kg P eq] • Marine eutrophication [kg N eq]	Conversion of units (EPD International, 2022)
Tofu	Soybean cultivation, transport, processing (washing, soaking, grinding, curd boiling, filtering, clumping, forming, frying)	Tofu is produced in Jakarta (Indonesia) and Grobogan (Java); • Global warming [kg CO_2 eq] • Acidification [kg SO_2 eq] • Eutrophication [PO_4 eq] • Fine dust [kg $PM_{2.5}$ eq] • Oil & gas depletion [kg oil eq]	Processing (Hartini et al., 2021) Cradle to gate (Sari et al., 2021)
Soymilk	Agricultural production, transportation to the processing plant and retail, processing, retail	Soybean produced in Illinois (USA); Processing: steaming, boiling, grinding, sterilisation, homogenisation and cooling; • GWP [kgCO_2 eq/ kg] • Eutrophication [kg N eq/L milk] • Fossil fuel depletion [MJ/kg] • Water [L/kg] • Fossil fuel depletion [kg oil eq/kg] • Water [m^3/kg]	Soymilk LCA (Grant and Hicks, 2018)
Cherries	Nursery, orchard infrastructure, orchard full life cycle, packing, waste (cradle to grave) Transports, storage, retail	Fruit cultivation to consumption in Norway; Different fruit grades are not split; • Climate change [kg CO_2 eq] • Acidification [g SO_2 eq] • Eutrophication [g PO_4 eq] • Depletion potential fossil [MJ]	LCA of fruits (Svanes and Johnsen, 2019); Unit conversion (Eurostat, 2022)
Grapes	Manufacturing of fertiliser, machinery, plant protection and fuel; vineyard cultivation, transport to the winery	Red and white grapes; Conventional, low input and organic vineyards in Cyprus; • Acidification [mol H^+ eq] • Climate change [kg CO_2 eq]	LCA of vineyards (Litskas et al., 2020); conversion of units (EPD International, 2022; Eurostat, 2022)

		• Eutrophication freshwater [kg P eq] • Eutrophication marine [kg N eq] • Resource use, energy [MJ] • Water scarcity [m^3 depriv.]	
Avocado	Raw materials (fertilisers, fuel), Agricultural production, post-harvest, transportation to the sailing point, packaging waste management (bio-waste)	Origin Tampico, Mexico; Sale point in Europe; The consumption stage is not included; • Climate change [kgCO_2-eq] • Land occupation [m^2∗a] • Water depletion [m^3]	Avocado LCA (Hadjian et al., 2019)
Broccoli	Cradle to grave, including production of fertilisers and pesticides, agricultural production, distribution (retail), home preparation, consumption, sewage system and food waste	Origin countries UK and Spain; Producing, processing, packaging on the farm, distribution directly to supermarkets; • LU [m^2·yr] • PEU [MJ] • WU [L] • AP [kg SO_2-eq] • EP [kg Phosphate-eq.] • GWP [kg CO_2-eq]	LCA of broccoli (Canals et al., 2008), conversion of units (Eurostat, 2022)
Zucchini	Carbon footprint of selected food items	GWP values (kg CO_2 eq./kg produced)	Source: (Clune, 2019)
Dried fruits	Agricultural production, dry fruit processing (selection, sorting, washing, peeling, cutting, drying, packaging and labelling), and waste generation.	Pineapple and sweet bananas are produced in Uganda as packed dried fruit, including non-edible parts; Package (poly-ethylene 0.00370 kg and poly-vinyl chloride 0.00159 kg); Included: energy use, raw materials, emissions and other releases; • Global warming [kg CO_2 eq.] • Energy [MJ]	LCA (Mfitumukiza et al., 2019); conversion of units (Eurostat, 2022)

Table S5. Criteria, parameters, data sources, and assumptions used in estimating animal welfare indicators for the food items added.

Animal	criteria	Parameter, data and assumptions	Data source
Rabbit	Slaughter age	Weight of 2.6 kg after 140 days of breeding	(Wang et al., 2022)
	Life duration (years)	Life expectancy is ten years Life expectancy fattening rabbits ten weeks	(Tier im Fokus, 2010)
	Yield (kg/animal)	Weight of 2.6 kg after 140 days of breeding 1.5 meat, 1 fur	(Wang et al., 2022)
	Moral value	Domestic rabbit (*Oryctolagus cuniculus*); body mass g (4,600); brain mass g (9.132); brain neurons (494.20E +06); cortical neurons (71.45E +06)	(Herculano-Houzel et al., 2011)
	Slaughter duration (years)	Electro stunning of warm-blooded animals 10 (prone bleeding) 20 (for hanging bleeding), Max 12 hours of transportation for rabbits (EU regulation)	(BMJV, 2013; EPRS, 2018)
	Space Allowance Index/ Life Quality	Floor area for each animal (fattening rabbit) at least 300 cm^2 In the case of breeding rabbits, the number increases to 600 cm^2 Space allowance index in kg/m^2: $I = 2.5*(16-8)$ Life Quality: $Q = (2.6077*I - 0.051672*I^2 + 0.00050863*I^3)/100$	(BMJV, 2016) (Scherer et al., 2018)
Red deer (game meat)	Slaughter age	Calves (age <12 months), yearlings (12–23 months), sub-adults (2–4 yrs.), and adults (≥ 5 yrs.) for males; calves, yearlings, and adults (≥ 2 yrs.) for females	(Becciolini et al., 2016)
	Life duration (years)	The sample includes hinds and stags aged up to 15 and 12 years	(Becciolini et al., 2016)
	Yield (kg/animal)	Eviscerated weight red deer male: adult (130kg), sub-adult (102.2 kg), yearling (69.7 kg), calf (40 kg); Eviscerated weight red deer female: adult (72.6 kg), yearling (56.7 kg); calf (37.6 kg)	(Becciolini et al., 2016)
	Moral value	*Cervus elaphus*; mean brain mass 409.3g, mean body mass 200 kg	(Burger et al., 2019)

	Slaughter duration (years)	13 days of hunting; 4 deer per hunter	(Fiala et al., 2020)
	Space Allowance Index/ Life Quality	2.60 to 2.05 deer/100 ha (population density) Assumed as maximum space allowance index as animals live in the wild; Q = 1	(Burger et al., 2019)
Sheep (mutton/lamb)	Slaughter age	Lifespan sheep 5 years Lifespan lamb 4 to 12 months	(Tier im Fokus, 2010)
	Life duration (years)	Life expectancy 12 years	(Tier im Fokus, 2010)
	Slaughter duration (years)	15 seconds stunning; transport must not exceed eight hours of travel time	(BMJV, 2013; EPRS, 2018)
	Yield (kg/animal)	Extensive breeds 30kg; semi-extensive breeds 38 kg; intensive breeds 42kg	(Landwirtschaftskammer NRW, 2014)
	Moral value	Sheep 140 g brain mass; 0.8 Encephalization Quotient (EQ)	(Roth, 2013)
	Space Allowance Index/ Life Quality	0.75 m^2 per sheep/ pasture year-round, winter months in steel Space allowance index in days of pasture I = 100*(8*30/365) $Q = (-37.324 + 4.0151*I - 0.045721*I^2+0.00019303*I^3)/100$	(Burau and Kivelitz, 2018) (Scherer et al., 2018)
Shrimp (crustaceans)	Life Quality	Different stocking densities and yield/m2, including survival rate in survived kg shrimp/m2, with the equation: $Q = 0.8047*I - 0.523$ Q=>1, then Q=1	(Towers, 2016; Wyban et al., 1987)
	Yield (kg/animal)	Several sizes and densities ranging from 0.091 to 2.6 kg shrimp/m^2	(Towers, 2016; Wyban et al., 1987)
Custard	Proportion of eggs	Assumed as vanilla sauce: 250 ml cream, 250 ml milk, 6 eggs (yolk), 80g sugar, vanilla 6g, salt 1g	(Essen & Trinken, 2020)
Mayonnaise	Proportion of eggs	Ingredients for processing mayonnaise: Egg yolk, vinegar, egg albumen, salt, sugar, water, rapeseed/ soy oil	(Olsson et al., 2018; Shariful et al., 2018)

Pork liver	Pork yield	Liver weight of crossbred pigs and mini-pigs Carcass yield of breeds commonly in Germany	(Ernst and Kalm, 1994; Litmann et al., 2016; Niehues et al., 2010)
Fats of mixed origin	Proportion of butter	Assumed as ½ butter and ½ other vegetable oil	(Broekema et al., 2019)
Dressing	Proportion of mayonnaise	Mayonnaise-based, assumed as 1/3 mayonnaise proportion	(Broekema et al., 2019)

*Original calculations of animal welfare criteria and parameters are found in Paris et al. 2022 and Scherer et al. 2018

S4. Health Nutritional Index (HENI)

Diet exposure

The mean intake of the 15 dietary risks and associated non-communicable diseases (NCDs) was obtained from the Institute of Health Metrics and Evaluation website and stratified by age-sex group. (IHME, 2019)Table S6 contains all NCDs associated with the studied DRFs, the DRF definition, and exposure risk.

Table S6. Dietary risk factors, risk exposure level, life cycle inventory (LCI) related to food/nutrients used and non-communicable diseases.

Dietary risk factor	Risk exposure[1]	Food/nutrient intake (LCI[2])	Non-communicable diseases
processed meat	>2 g/day	daily intake of cooked smoked sausage, dry sausage, fresh and lightly cooked sausage, ham (pork), and sausages	colon and rectum cancer, diabetes mellitus type 2, ischemic heart disease
red meat	>22.5 g/day	daily intake of beef meat, meat and meat products, mutton/lamb meat, pork/piglet meat, veal meat, game meat and rabbit meat	colon and rectum cancer, diabetes mellitus type 2, ischemic heart disease, intracerebral haemorrhage, ischemic stroke, subarachnoid haemorrhage, breast cancer
sodium[3]	>3.49 g/day	daily intake of sodium in g/day of the whole diet	aortic aneurism, atrial fibrillation and flutter, chronic kidney disease (due to diabetes mellitus type 1 and 2, glomerulonephritis, hypertension and unspecified causes), endocarditis, hypertensive heart disease, intracerebral haemorrhage, heart disease, ischemic stroke, non-rheumatic calcific aortic valve disease, other cardiomyopathies, peripheral artery disease, rheumatic heart disease,

			stomach cancer, subarachnoid haemorrhage
sugar-sweetened beverages	>2.5 g/day	daily intake of sugar-sweetened beverages: soft drinks (flavoured)	diabetes mellitus type 2, ischemic heart disease
trans-fatty-acids	>0.5% total energy intake	percentage of daily intake to the total energy intake (e%) of trans-fatty-acids in g/day of the whole diet	ischemic heart disease
polyunsaturated fatty acids (PUFA)	<11% total energy intake	percentage of daily intake to the total energy intake (e%) of PUFA in g/day of the whole diet	ischemic heart disease
omega-3 fatty acids	<250 mg/day	daily intake of omega-3 fatty acids (EPA + DHA[4]) in mg/day of the whole diet	ischemic heart disease
vegetables	<360 g/day	daily intake of broccoli, carrots, tomatoes, head cabbage, lettuce (excl. ice-berg type), leafy vegetables, cucumbers, leek, onions, peppers (paprika), spinach (fresh), cultivated mushroom, zucchini	intracerebral haemorrhage, ischemic heart disease, ischemic stroke, subarachnoid haemorrhage, oesophageal cancer
legumes	<60 g/day	daily intake of beans (green, without pods), beans (with pods), lentils	ischemic heart disease
fruits	< 250 g/day	daily intake of apples, bananas, strawberries, peaches, oranges, pears, fruit compote, fruit sauce kiwi, figs, grapes, cherries	intracerebral haemorrhage, ischemic heart disease, ischemic stroke, subarachnoid haemorrhage, diabetes mellitus type 2, tracheal, bronchus, and lung cancer
whole grains	<125 g/day	daily intake of mixed wheat and rye bread and rolls, rye bread and rolls, multigrain bread and rolls, cereal flakes	diabetes mellitus type 2, ischemic heart disease, ischemic stroke
fibre	<23.5 g/day	daily intake of fibre in g/day of the whole diet	colon and rectum cancer, diabetes mellitus type 2, ischemic heart disease, intracerebral haemorrhage, ischemic stroke, subarachnoid haemorrhage,

nuts and seeds	<20.5 g/day	daily intake of sunflower seeds, tree nuts	diabetes mellitus type 2, ischemic heart disease
calcium	<1.25 g/day	daily intake of calcium in mg/day of the whole diet	colon and rectum cancer
milk	<435 g/day	cow milk, flavoured milk, evaporated milk	colon and rectum cancer

[1] Risk exposure retrieved from (Stylianou et al., 2021); DRF are listed in the GBD database (GBD 2019, 2020)

[2] Life cycle inventories: EFSA food and nutrient database available as background data in Optimeal® (EFSA, 2019), complemented by the food composition data (EFSA, 2022), output nutrient intake in g/day acquired through the FFQ EPICSOFT and the Dutch food and nutrient database (RIVM, 2021).

[3] Sodium dietary risk factor represents both direct effects from the daily intake of sodium and the mediated effect of systolic blood pressure (Mozaffarian et al., 2014)

[4] Seafood Omega-3 fatty acids: Eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA)

Dietary Risk Factors (DRFs)

The Comparative Risk Assessment approach was used to estimate the DRFs for each age-sex-outcome-disease pair. The intake distribution followed a gamma function (we assumed a coefficient of variation of 70%). The general equation to calculate the DRFs is as follows:

$$DRF = \frac{\ln(RR)}{Ref} \cdot \frac{BR}{\sum_x P_x RR^{X/Ref}}$$

Where:

$\Delta x \rightarrow 0$: assumed log-linear dose-response association;
RR: population-weighted relative risk;
Ref: reference exposure in grams per day;
BR: health burden in µDALYs per person and day;
P_x: population fraction exposed to a daily x level of the risk intake;
Note: morbidity (YDLs) and mortality (YLL) are reported separately and further summed to estimate DALYs.

DRFs were aggregated by summing the DRFs for different outcomes calculated for the same dietary risk and averaging the DRFs over the age-sex group weighted by population size. The characterised and standardised DRFs for the German population expressed in µDALYs are in Table S7. We performed sensitivity analysis by varying DRFs using a wider range of coefficients of variation from 35% to 140%, as seen in **Table S8.**

Table S7. Characterised and population-standardised dietary risk factors in µDALYs.

GBD Dietary risk factors	Characterised DRF (µDALYs)
vegetables	-0.0489
calcium	-10.7879
fruits	-0.0722
legumes	-0.1901
milk	-0.0144
processed meat	0.4197
red meat	0.323
whole grains	-0.2699
trans-fatty-acids	13.2458
nuts and seeds	-2.5343
polyunsaturated fatty acids (PUFA)	-0.7821
omega-3 fatty acids	-13.567
sugar-sweetened beverages (ssbs)	0.0398
sodium direct effect	0.4063
sodium mediated by systolic blood pressure	10.9694
sodium total effect	11.3758

Table S8. Dietary Risk factor variation by different coefficients of variation in µDALYs.

GBD Dietary risk factors	**DRF 35%**	**DRF 49%**	**DRF 70%**	**DRF 105%**	**DRF 140%**
vegetables	-0,057	-0,054	-0,049	-0,039	-0,031
calcium	-11,263	-11,068	-10,788	-10,430	-10,126
fibre	-1,932	-1,647	-1,234	-0,774	-0,542
fruits	-0,083	-0,079	-0,072	-0,062	-0,055
legumes	-0,174	-0,178	-0,190	-0,204	-0,209
milk	-0,015	-0,015	-0,014	-0,014	-0,014
processed meat	0,429	0,442	0,420	0,316	0,252
red meat	0,411	0,389	0,323	0,271	0,232
whole grains	-0,297	-0,286	-0,270	-0,235	-0,194
trans-fatty-acids	15,168	15,293	13,246	9,840	7,820
nuts and seeds	-2,289	-2,370	-2,534	-1,904	-1,492
polyunsaturated fatty acids (PUFA)	-1,117	-0,992	-0,782	-0,521	-0,366
omega-3 fatty acids	-12,556	-13,077	-13,567	-12,251	-11,628
sugar-sweetened beverages (ssbs)	0,040	0,040	0,040	0,040	0,040
sodium total effect	11,643	11,557	11,376	11,150	10,936

Sodium mediated by systolic blood pressure

Sodium is mediated by systolic blood pressure, which depends on ethnicity and the prevalence of hypertension in the population. The prevalence of hypertension in Germany (31.6%) was based on epidemiological studies in Germany (Diederichs & Neuhauser, 2014; Neuhauser et al., 2015). The more vulnerable population to hypertension was taken as the percentage of blacks in the population (0.65%), assumed to be proportional to the number of foreigners in Germany from African countries (Destatis, 2022a). Sodium has a direct effect on health (stomach cancer) and an indirect effect, mediated by increase in the systolic blood pressure (SBP). Age, race, and hypertension status are found to be effect modifiers (Mozaffarian et al., 2014).

$$DRF_{d.sodium,o,b}^{a,g,m} = \frac{lnRR_{SBP,o,b}^{a,g}}{Ref_{SBP}} \cdot \frac{\Delta SBP^{a,g,m}}{\Delta u.sodium} \cdot f_{u.sodium \to d.sodium} \cdot BR_{\widehat{d.sodium,o,b}}^{\widehat{a,g}}$$

$$BR_{\widehat{d.sodium,o,b}}^{\widehat{a,g}} = \frac{BR_{o,b}^{a,g}}{\sum x\, P_{x\ d.sodium}^{a,g} \cdot RR_{SBP,o,b}^{a,g(\frac{x_{d.sodium}}{Ref_{SBP}} \cdot \frac{\Delta SBP^{a,g}}{\Delta u.sodium} \cdot f_{u.sodium \to d.sodium})}}$$

Where: $RR_{SBP,o,b}^{a,g}$ is the relative risk for the systolic blood pressure and the outcomes for the age group *a,* sex *g,* and disease burden *b,* corresponding to a reference exposure Ref_{SBP} of 10mmHg. The age-sex-specific-modifier conversion coefficient is given by $\frac{\Delta SBP^{a,g,m}}{\Delta u.sodium}$, characterises the change in SBP levels in mmHg for each change in the urinary sodium. This value was assumed to be 4.64, obtained using the equation proposed by Mozaffarian et al. (2014) (Mozaffarian et al., 2014). The parameters used were: mean German population age: 53 years old (Destatis, 2022b), prevalence of hypertense: 31.6%, prevalence of blacks: 0.65%. The conversion factor $f_{u.sodium \to d.sodium}$ was assumed 86%, i.e., for 1 g of sodium consumed (*d.sodium*) 0,86g are excreted in the urine (*u.sodium*) (Rhodes et al., 2013). $BR_{\widehat{d.sodium,o,b}}^{\widehat{a,g}}$ is the age-sex-burden rate of the outcome *o* adjusted for the background dietary sodium population exposure (*x d.sodium*) in µDALYs/person/day.

S5. Optimisation sensitivity analysis results (quadratic and linear programming)

We conducted linear and quadratic programming and performed a robust regression analysis to predict the marginal variation of impacts by optimisation and dietary pattern. Apart from water consumption, no significant differences between linear and quadratic were observed via linear regression.

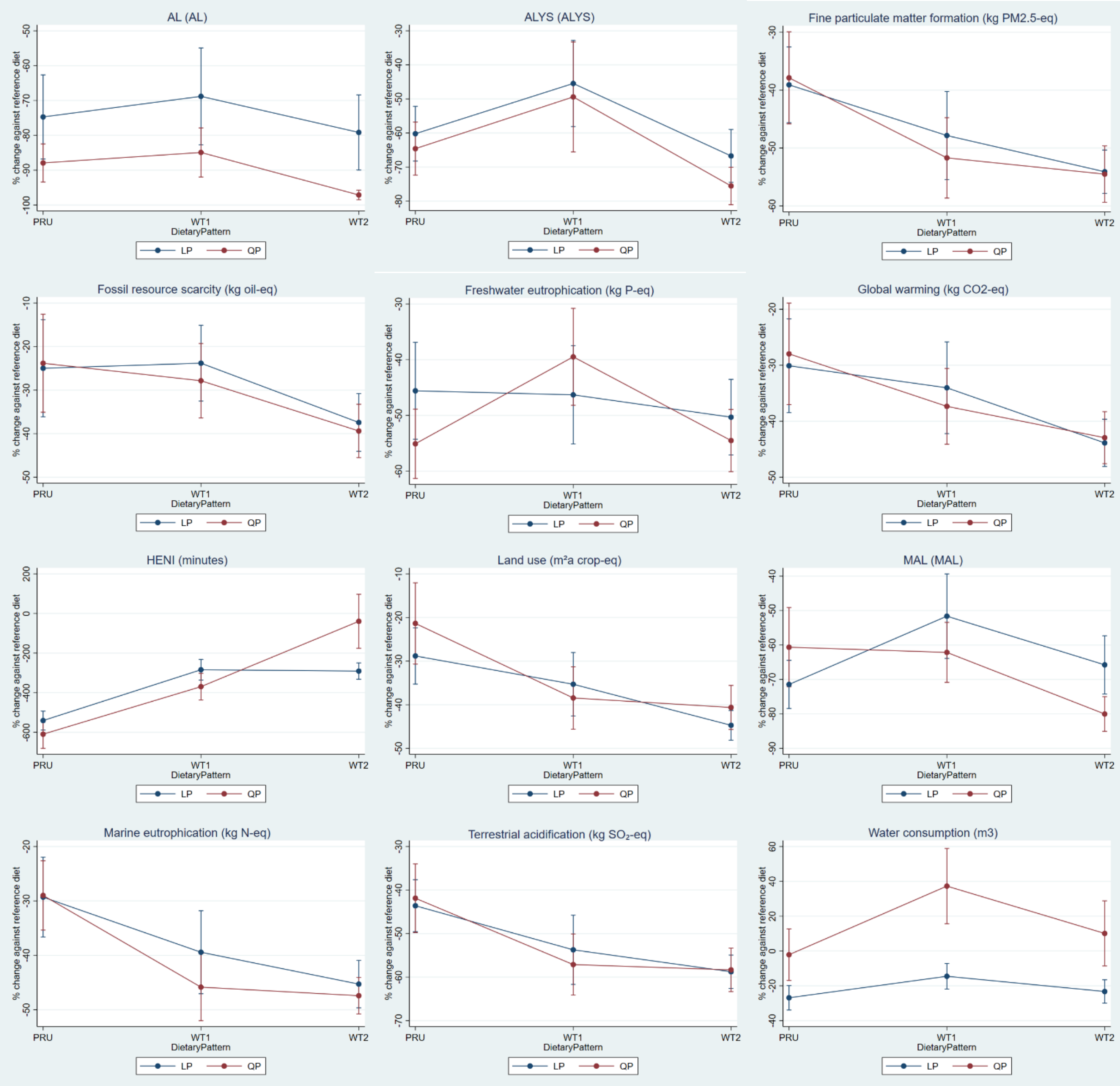

Figure S1. Quadratic and Linear programming optimisation of observed dietary patterns.

Dots represent the plot of predicted margins resulting from robust regression analysis of the correlations between dietary patterns and optimisation changes against the baseline diet. Standard error bars are present when $p < 0.05$. WT1: Western-type 1; WT2: Western-type 2; PRU: Prudent; HENI: Health nutritional index; LP: linear programming; QP: quadratic programming.

iii. Chapter 5 Appendices: Supplementary Information: "Self-reported changes in eating habits and lifestyle during the first year of the COVID-19 pandemic across metropolitan regions in Brazil and Germany: a survey-based cross-sectional study"

This material was submitted as electronic supplementary material and can be downloaded as a Word file at https://doi.org/10.1002/fsn3.3960.

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Supplementary Results

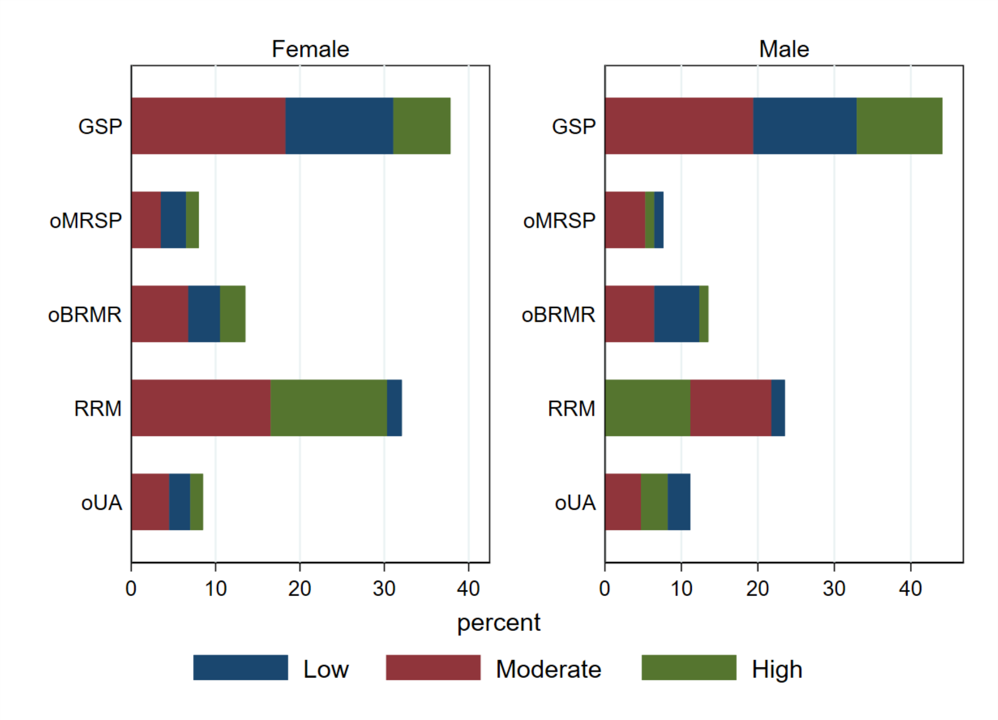

Figure S1. Self-reported Physical Activity Level (PAL) during COVID-19.

Legend: GSP: Great São Paulo; oMRSP: other metropolitan regions in São Paulo state; oBRMR: other Brazilian metropolitan regions; RRM: Rhine-Ruhr Metropolis; oUA: other urban areas.

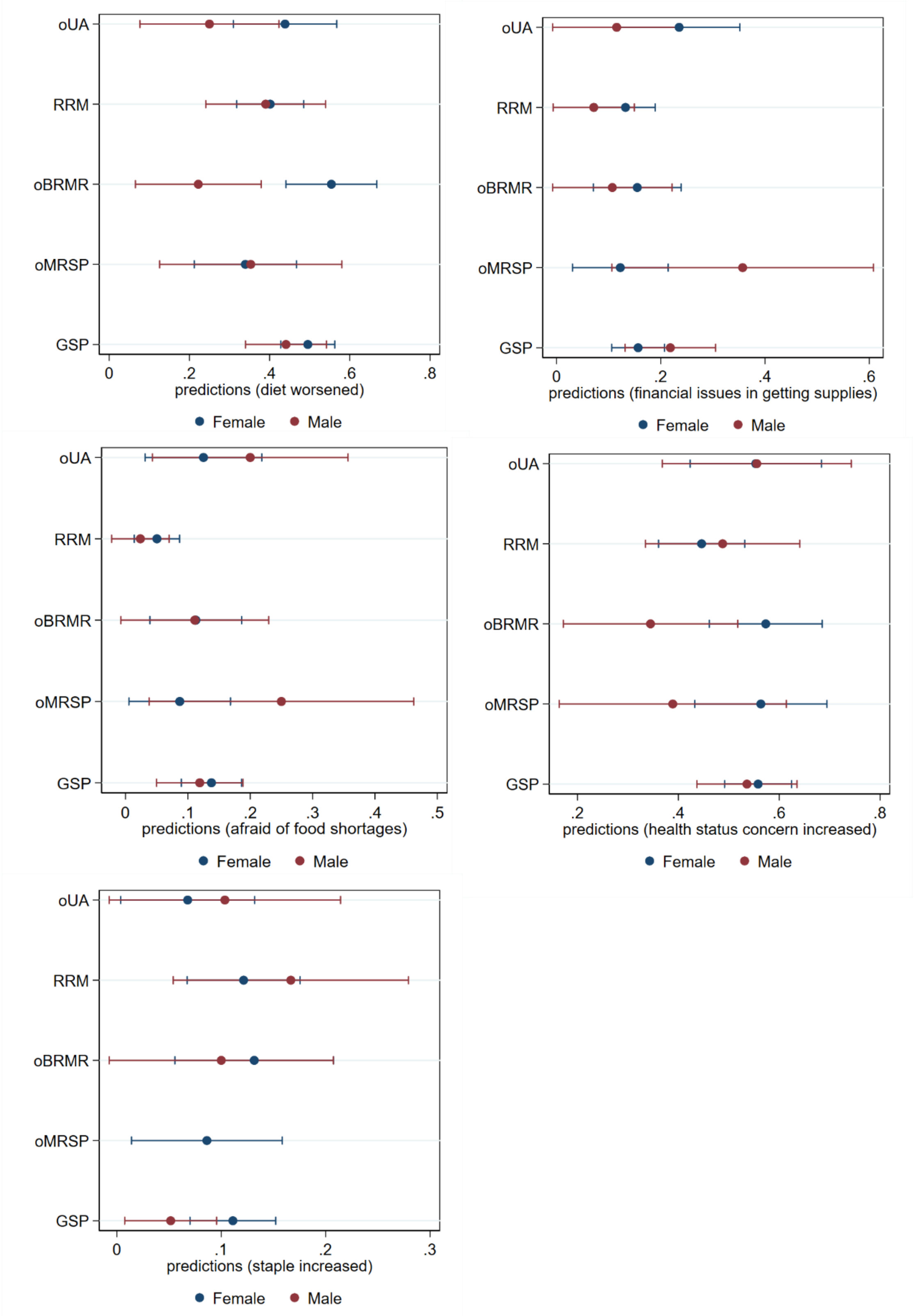

Figure S2. Supplementary results on self-reported changes in eating habits and buying groceries between sex and the different metropolitan regions.

Dots represent adjusted predictions from no change (0) to change (1) of the logistic regression correlations between sex and metropolitan areas. Error bars represent the 95% confidence intervals. Legend: GSP: Great São Paulo; oMRSP: other metropolitan regions in São Paulo state; oBRMR: other Brazilian metropolitan regions; RRM: Rhine-Ruhr Metropolis; oUA: other urban areas.

Publication list

A. Peer-reviewed journal articles

Paris, J.M.G., Escobar, N., Falkenberg, T., Gupta, S., Heizel, C., Verly, E. Jr., Jolliet, O., Borgemeister, C., Nöthlings, U. (2024). Optimised diets for achieving One Health: A pilot study in the Rhine-Ruhr Metropolis in Germany. *Environmental Impact Assessment Review, 106*, 107529, https://doi.org/10.1016/j.eiar.2024.107529

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Paris, J. M. G., Lima, E. M. F., Finger, J. d. A. F. F., Isidorio, W. R., Heinzel, C., Falkenberg, T., Borgemeister, C., Pinto, U. M., & Nöthlings, U. (2024). Changes in eating habits and lifestyle during the first year of the COVID-19 pandemic across metropolitan regions in Brazil and Germany: A survey-based cross-sectional study. *Food Science & Nutrition*, *12*, 2783–2798. https://doi.org/10.1002/fsn3.3960

Paris, J. M. G., Falkenberg, T., Nöthlings, U., Heinzel, C., Borgemeister, C., & Escobar, N. (2022a). Changing dietary patterns is necessary to improve the sustainability of Western diets from a One Health perspective. *Science of the Total Environment*, *811*, 151437. https://doi.org/10.1016/j.scitotenv.2021.151437

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Schmiege, D., Arredondo, A. M. P., Ntajal, J., **Paris, J. M. G.**, Savi, M. K., Patel, K., Yasobant, S., & Falkenberg, T. (2020). One Health in the context of coronavirus outbreaks: A systematic literature review. *One Health*, *10*, 100170. https://doi.org/10.1016/j.onehlt.2020.100170

B. Book chapters

Yasobant, S., Arredondo, A. M. P., Felappi, J. F., Ntajal, J., **Paris, J. M. G.**, Patel, K., Savi, M. K., Schmiege, D., & Falkenberg, T. (2023). One Health as an Integrated

Approach: Perspectives from Public Services for Mitigation of Future Epidemics. In *Integrated Science* (pp. 47–72). https://doi.org/10.1007/978-3-031-17778-1_3

Falkenberg, T., **Paris, J. M. G.**, Patel, K., Arredondo, A. M. P., Schmiege, D., & Yasobant, S. (2022). Operationalizing the One Health Approach in a Context of Urban Transformations. In *Urban Health and Wellbeing Programme. Urban Health and Wellbeing* (pp. 95–102). Springer, Singapore. https://doi.org/10.1007/978-981-19-2523-8_14

C. Conference contributions

Paris, J. M. G. (2024). *Improving Human, Animal and Environmental Health through Optimized Diets in the Rhine-Ruhr Metropolis, Germany*. [Poster presentation]. Inaugural Symposium Hertz-Chair Innovation for Planetary Health 2024, Bonn, Germany

Paris, J. M. G., Escobar, N., Falkenberg, T., Beuchelt, T., Borgemeister, C., & Nöthlings, U. (2020). *Sustainability of food consumption in the Ruhr Metropolis (Germany) under the One Health approach* [Poster presentation]. LCAFOOD2020.

Paris, J. M. G., Escobar, N., Falkenberg, T., Borgemeister, C., & Nöthlings, U. (2020). *Sustainability of diets under the One Health in the Ruhr area during COVID-19* [Poster presentation]. Symposium on One Health and Urban Transformation 2020, Bonn, Germany. https://www.zef.de/project-homepages/one-health/template-following/events/symposium-2020.html

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D. Other publications

Paris, J. M. G. (2024). From a 'one health' perspective, our food systems are not healthy. April 2024 - Global theories vs local realities, ZEF News No. 48, pp. 10. https://www.zef.de/publications/non-scientific-publications/zef-news.html

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