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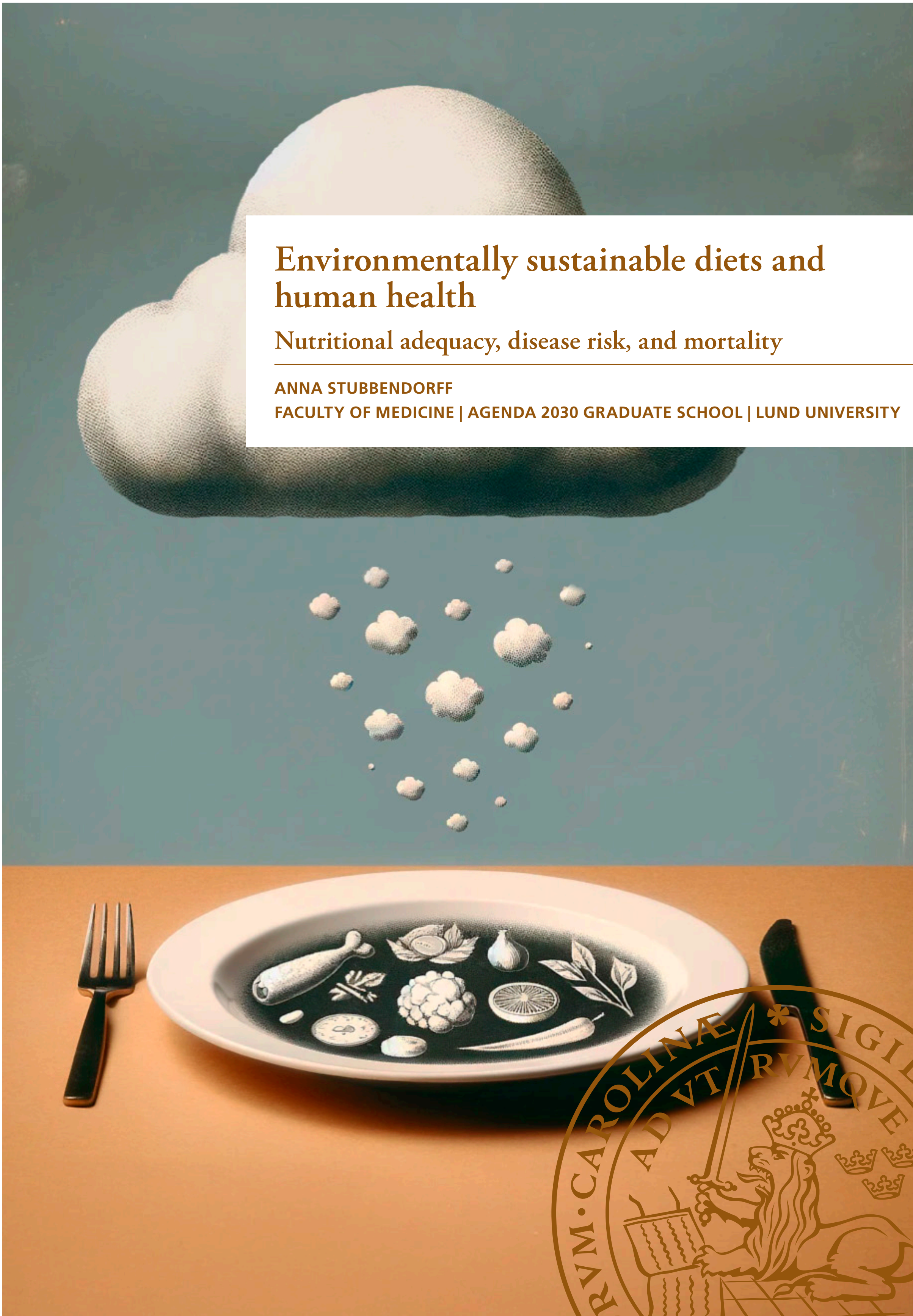

Environmentally sustainable diets and human health

Nutritional adequacy, disease risk, and mortality

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ANNA STUBBENDORFF has carried out her doctoral studies at Lund University, ranked as the leading university in sustainability in 2026 (QS World University Rankings). Her PhD work has been based at the Faculty of Medicine and the Agenda 2030 Graduate School.

Her research is grounded in nutritional epidemiology, focusing on how environmentally responsible dietary patterns relate to nutrient intake, nutrient status, and long-term health outcomes. Using large population-based cohorts, she examines how dietary greenhouse gas emissions and sustainable dietary patterns, including the EAT-Lancet diet, are associated with mortality, diabetes, cardiovascular disease, and micronutrient intake and status.

A central theme of this thesis is how dietary shifts toward more sustainable eating can support both human health and environmental objectives.

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Anna Stubbendorff

DOCTORAL DISSERTATION

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Abstract:

Introduction: Food systems strongly influence both human and planetary health. Unhealthy diets are major risk factors for chronic disease and mortality, while food production contributes substantially to greenhouse gas emissions (GHGE), and other negative environmental impacts. Adopting more sustainable dietary patterns, such as the EAT-Lancet diet, has been proposed as part of the solution, but uncertainties remain regarding their long-term health effects, nutri-tional adequacy, and optimal methods for assessment.

Aim: The aim of this thesis was to examine associations between environmentally sustainable diets, nutritional adequacy, and major health outcomes, with a focus on mortality, cardiovascular disease, diabetes, and micronutrient intake and status.

Methods: The analyses were mainly based on the Malmö Diet and Cancer Study, including about 26,000 adults followed for up to 30 years. Dietary intake was assessed using a validated diet history method combining a 7-day food diary, questionnaire, and interview. Health outcomes were retrieved from national registers. Nutrient adequacy was evaluated using both dietary data and blood biomarkers. Life cycle assessment (LCA) was used to estimate dietary GHGE, and adherence to the EAT-Lancet diet was assessed using dietary scores.

Results: Higher adherence to the EAT-Lancet diet was associated with lower risks of mortality, reduced stroke risk, and lower GHGE. Lower dietary GHGE were most consistently associated with decreased risk of diabetes, while associations with mortality were weaker and partly non-linear. Diets with lower environmental impact were generally compatible with adequate micronutrient intake and status and were sometimes linked to nutritional benefits, such as a reduced risk of folate deficiency, though a slightly higher risk of anaemia was observed.

Conclusion: Environmentally sustainable diets can promote health, reduce mor-tality, and do not substantially increase the risk of micronutrient deficiencies. These findings underscore the co-benefits of aligning nutrition and climate poli-cies and support the integration of sustainability into dietary guidelines.

Key words: Sustainable diets, climate friendly diets, nutrition, non-communicable diseases, micronutrients.

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List of publications

Papers included in the thesis

This doctoral thesis is based on the following five original papers:

Paper I **Stubbendorff, A.,** Sonestedt, E., Ramne, S., Drake, I., Hallström, E., Ericson, U. *Development of an Eat-Lancet Index and Its Relation to Mortality in a Swedish Population.* The American Journal of Clinical Nutrition, 2022. 115(3): p705–716. https://doi.org/10.1093/ajcn/nqab369

Paper II **Stubbendorff, A.**, Stern, D., Ericson, U., Sonestedt, E., Hallström, E., Borné, Y., Lajous, M., Forouhi, N. G., Olsen, A., Dahm, C. C., Ibsen, D. B. *A Systematic Evaluation of Seven Different Scores Representing the Eat-Lancet Reference Diet and Mortality, Stroke, and Greenhouse Gas Emissions in Three Cohorts.* The Lancet Planetary Health, 2024. 8(6): e391–401. https://doi.org/10.1016/S2542-5196(24)00094-9

Paper III **Stubbendorff, A.**, Ericson, U., Hallström, E., Samuelsson, J., Sonestedt, E., Ibsen, D. B. *Nutritional adequacy of the EAT-Lancet diet: a Swedish population-based cohort study*. Accepted in The Lancet Planetary Health.

Paper IV **Stubbendorff, A.,** Janzi, S., Borné, Y., Carlbaum, M., Jukkola, J., Ericson, U., Hallström, E., Sonestedt, E. *Associations between dietary greenhouse gas emissions, mortality, and chronic disease risk: a prospective cohort study in Sweden.* Environmental Challenges, 2025. 20: p101309. https://doi.org/10.1016/j.envc.2025.101309

Paper V **Stubbendorff, A.**, Ericson, U., Bengtsson, Y., Borné, Y., Sonestedt, E., Hallström, E. *Balancing Environmental Sustainability and Nutrition: Dietary Climate Impact in Relation to Micronutrient Intake and Status in a Swedish Cohort.* Current Developments in Nutrition, 2025. 9(8): p107501. https://doi.org/10.1016/j.cdnut.2025.107501

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1. **Stubbendorff, A.** and Elinder, L.S., *Matvanor för god hälsa och miljö - Förändrade matvanor kan förbättra folkhälsan, minska miljöpåverkan och bidra till en hållbar framtid*. Läkartidningen, 2025. 122: p.1–5. https://lakartidningen.se/vetenskap/matvanor-for-god-halsa-och-miljo/

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Populärvetenskaplig sammanfattning

Vad vi äter påverkar både vår hälsa och miljön. Matproduktionen i världen står för omkring en tredjedel av de globala utsläppen av växthusgaser och är den främsta drivkraften bakom omfattande markanvändning, hög vattenförbrukning och förlust av biologisk mångfald. Samtidigt är ohälsosamma matvanor en av de största riskfaktorerna för sjukdom och förtida död. Hur vi kan äta på ett sätt som både gynnar människor och miljö är därför en central framtidsfråga.

I denna avhandling har jag undersökt sambanden mellan miljömässigt hållbara kostmönster, näringsintag och hälsa. Studierna bygger främst på data från den svenska befolkningsstudien Malmö Kost och Cancer, där 26 000 personer har följts under upp till 30 år. Deltagarnas kostvanor har analyserats utifrån hur väl de följer den så kallade EAT-Lancet-kosten, en kost med mycket fullkorn, baljväxter, frukt och grönsaker, och endast små mängder av kött, kyckling och andra animaliska livsmedel. Förslaget till dessa kostråd publicerades 2019 och beskriver på vetenskaplig grund hur världen måste ställa om sin matproduktion för att jordens knappa resurser ska räcka till 10 miljarder människor år 2050, och samtidigt hålla sig inom de planetära gränserna. Dessutom har jag undersökt kostens hållbarhet genom att mäta kostens klimatpåverkan med hjälp av livscykelanalys, en metod som uppskattar utsläppen av växthusgaser från hela livscykeln för maten, från produktion till konsumtion.

När våra matvanor blir mer miljömässigt hållbara kan intaget av vissa näringsämnen förändras, och det är ännu oklart om detta kan leda till för låga nivåer hos vissa grupper. Samtidigt behöver vi förstå de långsiktiga hälsoeffekterna av att äta mer miljövänligt, såsom risken att drabbas av olika sjukdomar och förtida död.

Mitt arbete visar att miljömässigt hållbara koster har en positiv effekt på den långsiktiga hälsan. Personer som äter mer i linje med EAT-Lancet-kosten har lägre risk att dö i förtid, både i hjärt-kärlsjukdom och cancer. När vi istället mätte klimatpåverkan, såg vi att den grupp som hade lägst klimatutsläpp från maten hade minskad risk att drabbas av diabetes, medan sambanden med dödlighet var svagare och framför allt sågs vid mycket höga utsläppsnivåer.

Näringsmässigt visade sig kost med lägre klimatpåverkan, och högre följsamhet till EAT-Lancet-kosten, ge något lägre men i de flesta fall tillräckligt intag av vitaminer och mineraler. I vissa fall gav de till och med fördelar, som minskad risk för folatbrist. En något ökad risk för anemi hos kvinnor observerades, men inga tecken framkom på att mer miljövänliga koster generellt leder till näringsbrister.

Slutsatsen är att en omställning mot mer miljömässigt hållbara matvanor också kan ge positiva hälsoeffekter. Det är alltså möjligt att förena en miljömässigt hållbar kost med god hälsa. Sådana kostmönster kan minska risken för sjukdom och förtida död utan att kompromissa med näringsintaget hos majoriteten av befolkningen. Resultaten stärker argumenten för att det finns positiva synergier mellan hälsa och hållbarhet, och att dessa perspektiv bör integreras i framtida kostråd och folkhälsopolitik. Genom att belysa samspelet mellan mänsklig och planetär hälsa kan vi skapa matvanor som gagnar både mänsklig hälsa och miljömässig hållbarhet.

Abbreviations and key concepts

AR	Average Requirement
BMI	Body Mass Index
CO_2-eq	Carbon dioxide (CO_2) equivalents
CVD	Cardiovascular Disease
DCH	Danish Diet, Cancer and Health Cohort
FAO	Food and Agriculture Organization of the United Nations
FFQ	Food Frequency Questionnaire
GHGE	Greenhouse Gas Emissions
Hb	Haemoglobin
LCA	Life Cycle Assessment
MDC	Malmö Diet and Cancer Study
MTC	Mexican Teachers’ Cohort
NCDs	Non-Communicable Diseases
NIH	National Institutes of Health
NNR	Nordic Nutrition Recommendations
PAL	Physical Activity Level
RI	Recommended Intake
SDGs	Sustainable Development Goals
WHO	World Health Organization
UN	United Nations

Abstract

Introduction: Food systems strongly influence both human and planetary health. Unhealthy diets are major risk factors for chronic disease and mortality, while food production contributes substantially to greenhouse gas emissions (GHGE), and other negative environmental impacts. Adopting more sustainable dietary patterns, such as the EAT-Lancet diet, has been proposed as part of the solution, but uncertainties remain regarding their long-term health effects, nutritional adequacy, and optimal methods for assessment.

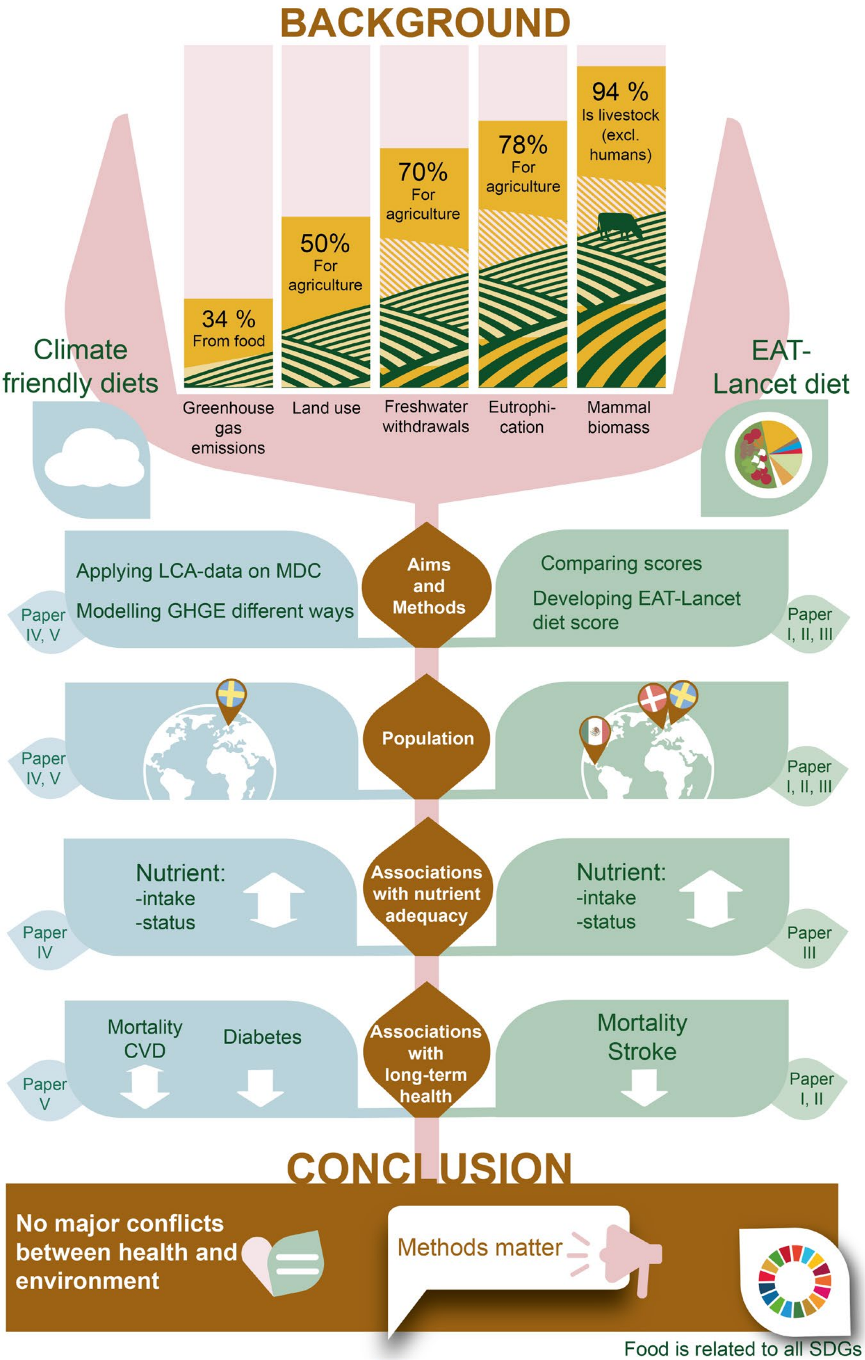
Aim: The aim of this thesis was to examine associations between environmentally sustainable diets, nutritional adequacy, and major health outcomes, with a focus on mortality, cardiovascular disease, diabetes, and micronutrient intake and status.

Methods: The analyses were mainly based on the Malmö Diet and Cancer Study, including about 26,000 adults followed for up to 30 years. Dietary intake was assessed using a validated diet history method combining a 7-day food diary, questionnaire, and interview. Health outcomes were retrieved from national registers. Nutrient adequacy was evaluated using both dietary data and blood biomarkers. Life cycle assessment (LCA) was used to estimate dietary GHGE, and adherence to the EAT-Lancet diet was assessed using dietary scores.

Results: Higher adherence to the EAT-Lancet diet was associated with lower risks of mortality, reduced stroke risk, and lower GHGE. Lower dietary GHGE were most consistently associated with decreased risk of diabetes, while associations with mortality were weaker and partly non-linear. Diets with lower environmental impact were generally compatible with adequate micronutrient intake and status and were sometimes linked to nutritional benefits, such as a reduced risk of folate deficiency, though a slightly higher risk of anaemia was observed.

Conclusion: Environmentally sustainable diets can promote health, reduce mortality, and do not substantially increase the risk of micronutrient deficiencies. These findings underscore the co-benefits of aligning nutrition and climate policies and support the integration of sustainability into dietary guidelines.

Graphical abstract



Background

Health impacts of food consumption

The impacts of unhealthy food consumption are wide-ranging, spanning from diet-related chronic diseases to conditions caused by under- and over nutrition (**Figure 1**). Non-communicable diseases (NCDs), including cardiovascular diseases (CVD), cancers, chronic respiratory conditions, and diabetes, remain the leading causes of death and disability globally [1]. Together, these conditions contribute significantly to mortality, accounting for approximately 75% of all deaths globally [2].

Worldwide, it is estimated that 80% of non-communicable disease cases are preventable [2]. For example, up to 95% of type 2 diabetes cases [3], 80% of cardiovascular disease cases [4], and 40% of all cancer cases [5] may be avoidable. In Europe, 1.8 million deaths from non-communicable diseases are considered avoidable every year through effective prevention strategies or timely, high-quality treatment [1].

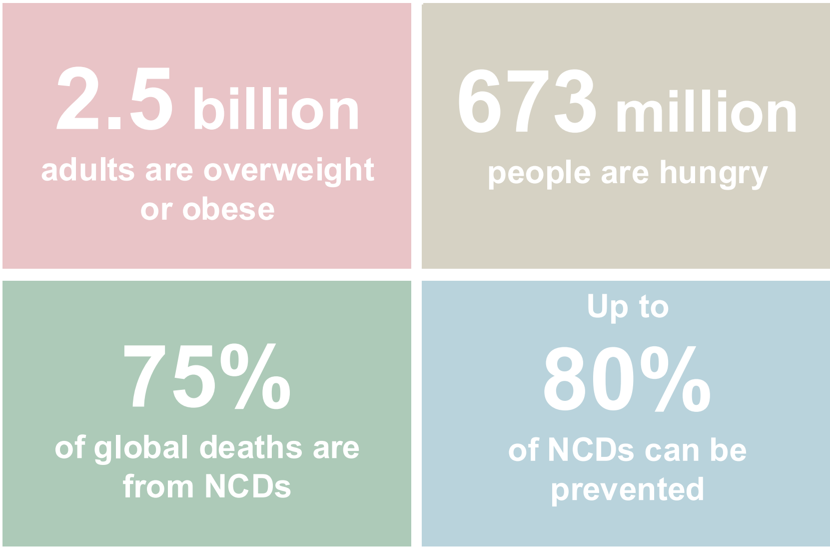


Figure 1. Global nutrition and health challenges.
Estimates from the World Health Organization (WHO) and the Food and Agriculture Organization of the United Nations (FAO) [2, 6].

According to the *Global Burden of Disease (GBD) studies*, unhealthy diets are the leading contributor to disease and mortality worldwide [7, 8] (**Figure 2**). Globally, approximately 12% of total deaths are attributed to dietary risks for non-communicable diseases, and 4% are attributable to malnutrition [9]. A healthy dietary pattern can substantially decrease the risk of morbidity and mortality associated with non-communicable diseases, while simultaneously addressing different forms of malnutrition. Such a diet provides essential nutrients without excess or insufficient energy intake. Currently, over 2.5 billion adults, approximately 40% of the global adult population, are classified as overweight or obese [10, 11].

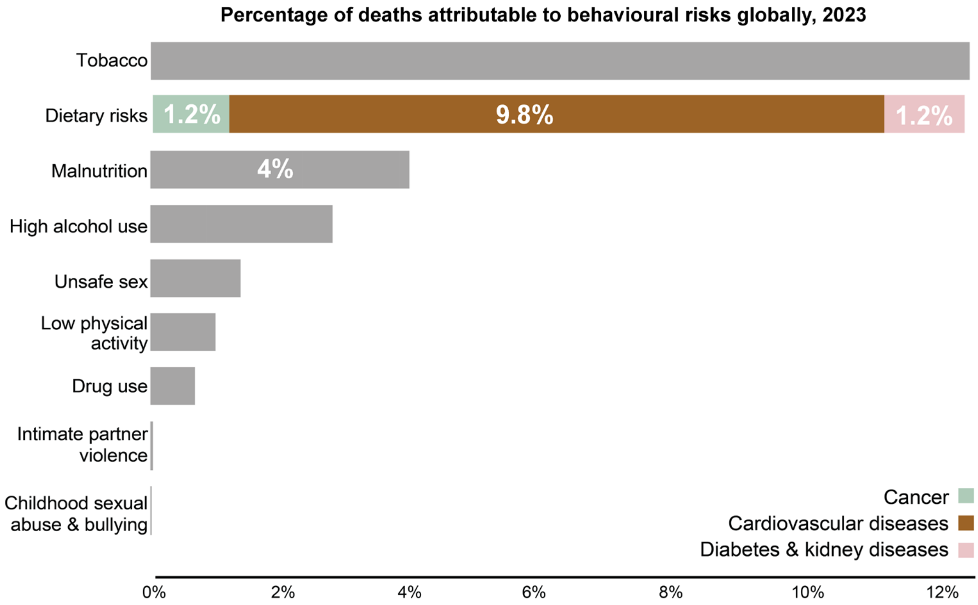


Figure 2. Lifestyle factors contributing to death globally, 2023.
Adapted from the Global Burden of Disease Compare VizHub, Institute for Health Metrics and Evaluation [9]. Licensed under CC BY 4.0.

Globally, insufficient intake of wholegrains, fruits and vegetables, legumes, as well as nuts and seeds, together with excessive consumption of sodium, red meat, and processed meat are among the most significant dietary risk factors for health [9] (**Figure 3**). Higher intakes of nuts, wholegrains, fruits, vegetables, legumes, and fish have been associated with lower mortality, whereas high consumption of red and processed meats and sugar-sweetened beverages has been linked to higher risk [12]. Overall, these risks reflect dietary patterns characterized by limited consumption of plant-based foods and excessive intake of animal-sourced products.

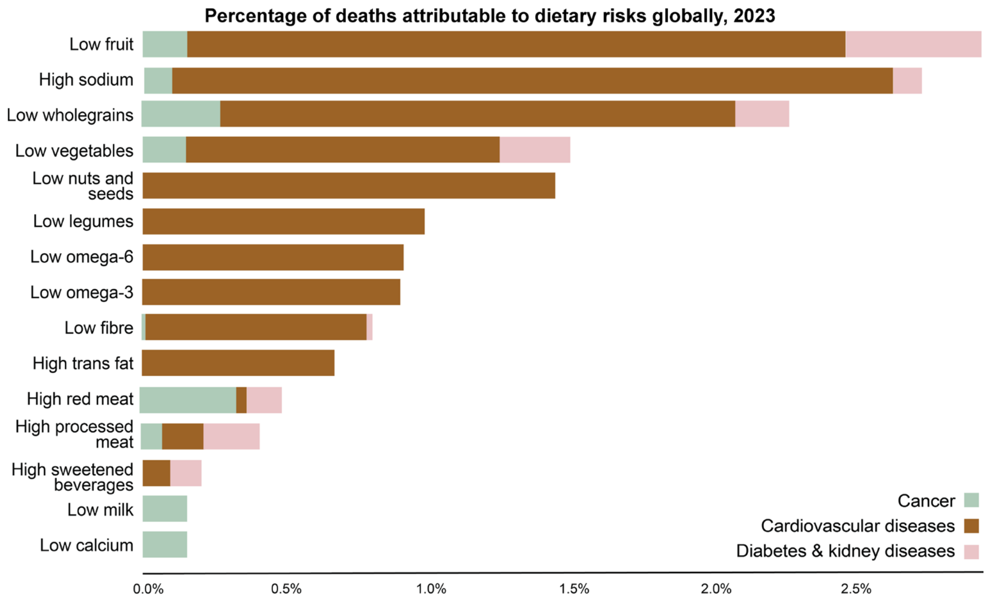


Figure 3. Dietary risks contributing to death globally, 2023.
Adapted from the Global Burden of Disease Compare VizHub, Institute for Health Metrics and Evaluation [9]. Licensed under CC BY 4.0.

Cardiovascular disease

Cardiovascular disease, is the leading cause of death globally, accounting for about 19.2 million deaths in 2023 [8]. In Sweden, cardiovascular disease is also the leading cause of death among both men and women, contributing substantially to premature mortality and healthcare burden [9]. Cardiovascular diseases include conditions such as coronary heart disease, myocardial infarction, stroke, atrial fibrillation, and peripheral artery disease, most of which arise from atherosclerosis.

The global burden of cardiovascular disease is increasingly concentrated in low- and middle-income countries [8]. Although cardiovascular mortality has declined in high-income countries such as Sweden due to advances in treatment and reductions in risk factors, including smoking and dietary habits, the overall prevalence remains high [8]. According to *the Global Burden of Disease 2023,* major drivers of cardiovascular diseases include dietary risks, high LDL cholesterol, high fasting plasma glucose, high BMI, and smoking [7]. The largest diet-related risks for cardiovascular mortality include low intake of wholegrains, fruits, vegetables, nuts and seeds, and high intake of sodium and processed meat. Together, these dietary factors account for an estimated 6–8 million cardiovascular disease deaths worldwide. About 80% of premature cardiovascular disease deaths could be prevented through addressing modifiable risks. Continued efforts in primary prevention through lifestyle modification are therefore essential and could prevent the majority of cases and deaths [13].

Diabetes

Diabetes is a chronic metabolic disease characterised by elevated blood glucose levels. Type 2 diabetes accounts for about 90–95% of all cases, while type 1 diabetes and other, rarer forms make up the remainder [14]. Type 2 diabetes is a major component of cardiovascular diseases and a rapidly growing global health concern. Its prevalence is now almost four times higher than in the year 2000, and continues to rise [14]. In 2024, an estimated 589 million adults, around 10% of the world's population, were living with diabetes, and this number is projected to reach 850 million by 2050. The largest increase has been observed in low- and middle-income countries and the burden is particularly high in South Asia, the Middle East, and sub-Saharan Africa [8]. The burden is increasing also in Sweden [9].

According to *the Global Burden of Disease 2023*, unhealthy dietary patterns are among the leading modifiable risk factors for type 2 diabetes, particularly low intake of wholegrains, fruits, vegetables, and nuts and seeds, and high intake of refined grains, processed meat, and sugar-sweetened beverages [7]. Deaths directly attributed to diabetes have more than doubled since 1990, reaching about 3.4 million in 2023 [14]. When considering deaths from other diseases to which high blood glucose contributes, such as cardiovascular disease, the total mortality attributable to high fasting plasma glucose is estimated at 6–7 million [7]. Although advances in care have improved outcomes, prevention through healthy lifestyle habits remains essential to curb the growing global burden.

Malnutrition and micronutrient deficiencies

Simultaneously to the increasing burden of non-communicable diseases, 673 million people are considered hungry, according to *The State of Food Security and Nutrition in the World 2025* [6]. Undernutrition and micronutrient deficiencies affect over two billion people globally [15, 16]. Micronutrient deficiencies result primarily from inadequate dietary intake of essential nutrients such as iron, zinc, vitamin A, iodine, and folate, with each of these deficiencies carrying specific and significant implications for public health [17]. In Sweden, iron deficiency [18, 19], and vitamin D deficiency [20, 21] has gained attention the recent years. Taken together, food and nutrition are central determinants of health, as they link the global burden of non-communicable diseases with persistent challenges of hunger and micronutrient deficiencies. These issues further interact with the accelerating impacts of climate change, forming what has been described as 'The global syndemic of obesity, undernutrition, and climate change' [22].

Affordability further compounds these challenges, with an estimated 2.6 billion people worldwide unable to afford a healthy diet worldwide [6]. This highlights the urgent need for food systems that provide equitable access to nutritious foods while simultaneously reducing environmental pressures.

Environmental impact of food

The global food system is a major driver of climate change and biodiversity loss, with current land and water use exceeding planetary boundaries for sustainability [23-25]. The food sector alone accounts for an estimated 26–34% of global greenhouse gas emissions (GHGE), 50% of global habitable land use, and 70% of freshwater use (**Figure 4**) [26, 27]. Agriculture is also a major driver of other adverse environmental effects, including biodiversity loss and eutrophication.

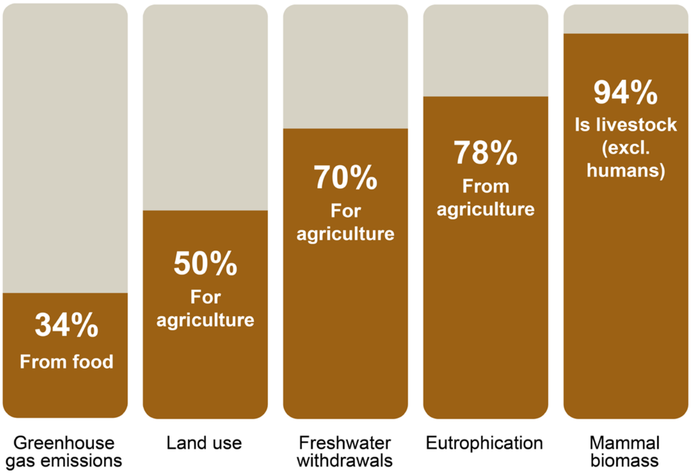


Figure 4. The environmental impacts of food production.
Adapted from Our World in Data [26], with updated estimates for climate impact from Crippa et al. [27]. Licensed under CC BY 4.0.

Today, 70% of the Earth's ice-free land surface is used by humans, while untouched natural land continues to shrink. Forests are cleared to create grazing areas and cropland, primarily for animal feed [28, 29], a practice that is less efficient than if crops such as soy and cereals were consumed directly by humans. Overall, around 80% of global agricultural land is linked to livestock production [30]. Data from *Our World in Data* further illustrate this imbalance, showing that while animal-sourced foods occupy most of the land, they contribute a relatively small share of global protein supply compared with plant-based foods (**Figure 5**). In Sweden, 68%

of cultivated cereals are used for animal feed, while only 16% are used for direct human consumption, according to the Swedish Board of Agriculture [31-33]. In general, animal-sourced foods require more land than plant-based foods, primarily because of the relatively lower efficiency of feed conversion in livestock production. In addition, animal-sourced foods generally use more nitrogen, phosphorus, and water, and contribute more greenhouse gas emissions per kilogram of product compared with plant-based foods. A diet high in meat is estimated to generate about four times higher GHGE and land use, nearly three times greater negative impacts on biodiversity, and roughly twice the water use compared to a vegan diet [34].

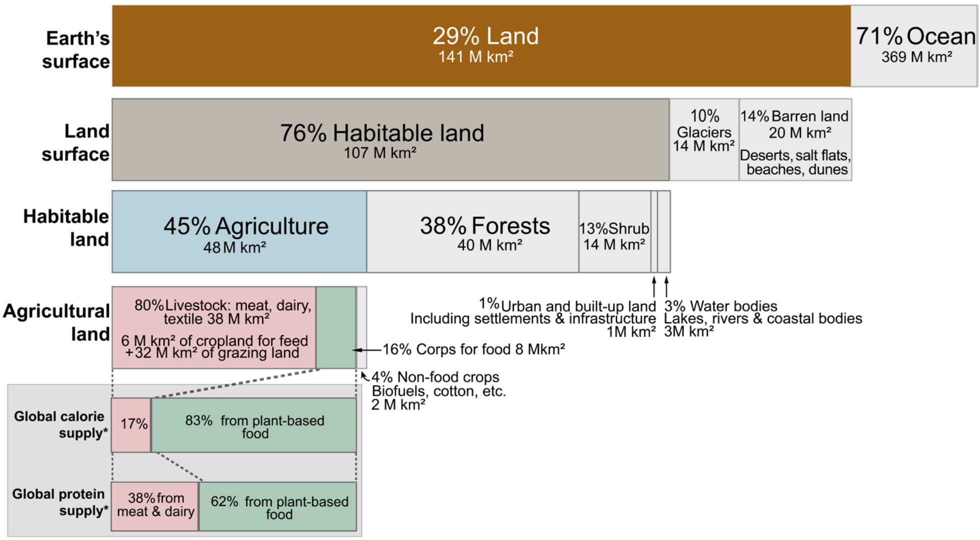


Figure 5. Global land use for food production[1].
Obtained from Our World in Data [30]. The global protein supply includes seafood from aquaculture production, which uses land for feed. *If wild fish catch is also included, animal products would provide 18% of calories and 40% of protein. Licensed under CC BY 4.0.

Quantifying the climate impact of food

To quantify and communicate the climate impact of food products, emissions of different greenhouse gases are often quantified as a single unit: carbon dioxide equivalents (CO_2-eq). This metric standardizes the global warming potential (GWP) of different greenhouse gases over a defined time period, usually 100, 20 or 500 years. The GWP values recommended by Intergovernmental Panel on Climate Change (IPCC) vary slightly between different IPCC assessment reports, partly due to whether

[1] In this figure, agricultural land use is based on 45% rather than 50%, as in **Figure 4**, although both figures are derived from the same publisher.

climate–carbon feedbacks are included. Carbon dioxide (CO_2) consistently serves as the baseline, assigned a GWP of 1 kg CO_2-eq per amount of emission over a 100-year period. Methane (CH_4) has been assigned values ranging from approximately 25 to 35, and nitrous oxide (N_2O) between 265 and 298 [35-37]. There is ongoing discussion regarding which GWP value should be applied for methane[2] [38]. In the IPCC *Fifth Assessment Report* from 2014[3], methane has the value of 34 (when including carbon feedbacks) and nitrous oxide the value of 298 (**Figure 6**).

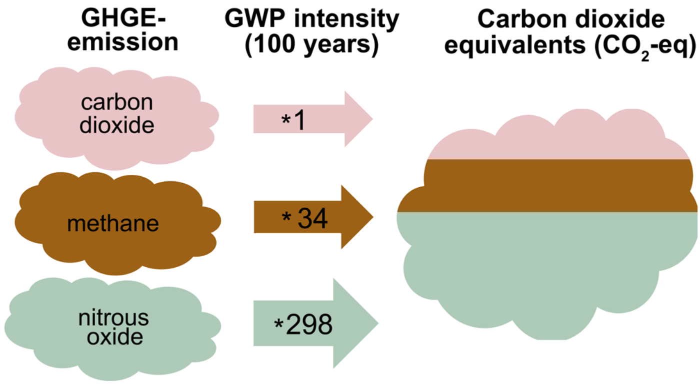


Figure 6. Global warming potential over a 100-year time frame (GWP100) of common GHGE from food production.
Based on data from the IPCC AR 5 [36].

Climate impact can sometimes serve as a proxy for broader environmental assessments. Previous research has shown that dietary GHGE strongly correlate with several other environmental impacts, such as use of land and nitrogen [39-42], but some modelling studies also show trade-offs [23, 43].

Life cycle assessment (LCA)

To estimate the environmental impact of a food product (or any product or process), a method called life cycle assessment (LCA) is commonly used [44]. An environmental LCA can focus on a single impact category, such as GHGE or water use, or incorporate multiple impact categories. The method is often described as assessing the impact throughout its life cycle 'from cradle to grave', but in practice, LCAs may apply different system boundaries including different stages of the product's

[2] In the most recent IPCC Assessment Report (AR6), methane is assigned three different global warming potential (GWP) values, presented under six labels, depending on the metric and time horizon applied. Because methane is a short-lived climate pollutant, there is ongoing debate about how its warming effect should be represented over a 100-year period. These methodological considerations are complex and fall beyond the scope of this thesis.

[3] The primary climate impact data is based on this report. Read more on page 79.

life cycle depending on the scope of the analysis **(Figure 7**). Many food-related LCAs begin with the impact from primary production and continue through storage, processing, packaging, and associated transports, often ending at the factory gate. Some studies go beyond this stage and also include impacts from distribution to, and losses within, retail or even further by including impacts from consumer transportation, cooking, waste management and impact associated with food losses and waste throughout the studied system. As the environmental impact of different foods may vary across production stages, substantial differences in LCA results can arise depending on the system boundaries applied. For example, bread often has a relatively low climate impact in the early stages of production, but due to substantial food waste at both the retail and consumer level, its total impact increases if the full life cycle is considered. Therefore, it is essential that LCA data are calculated based on similar system boundaries when comparing impacts from different foods.

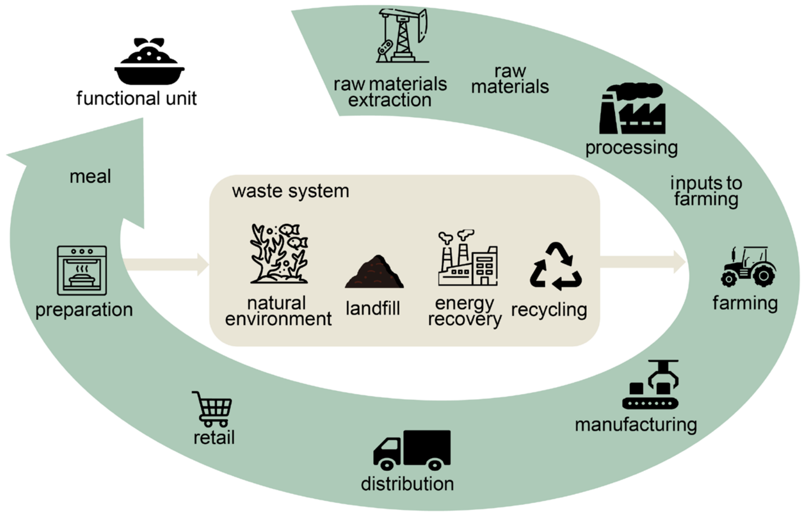


Figure 7. The life cycle of a meal.
Stages include raw material extraction, farming, processing, manufacturing, distribution, retail, and meal preparation, with waste and recycling possible at all steps. Adapted with permission from Currachi et al. [44]. Licensed under CC BY-NC-ND 4.0.

It is also critical to consider the chosen functional unit when assessing and comparing environmental impacts of foods, meals, and diets [44]. Frequently, environmental impacts are expressed using a mass-based functional unit, for example by expressing the environmental impact per kg of food. The functional unit should, according to the ISO standard, reflect the main function of the product or process assessed [45, 46]. Since the main function of food is generally perceived as providing energy and nutrients, alternative functional units may be relevant to capture variations in consumption amounts and nutrient contents among different foods. To reflect the foods nutritional value, environmental impact can therefore also be expressed in relation to nutrient quality of the food, meal or diet assessed. For example, comparisons can be made based on energy content, protein content, or overall nutrient density or quality (**Figure 8**) [47-50] based on specific micronutrient contributions or nutrient indices. An FAO report on nutritional life cycle assessment (nLCA) emphasizes that such nutrition-based functional units can provide a stronger link between environmental impacts and the nutritional value of foods [51]. A report from the Global Alliance for Improved Nutrition (GAIN) further highlights that these approaches can help guide policies and programs towards diets that nourish people while reducing environmental impacts [52].

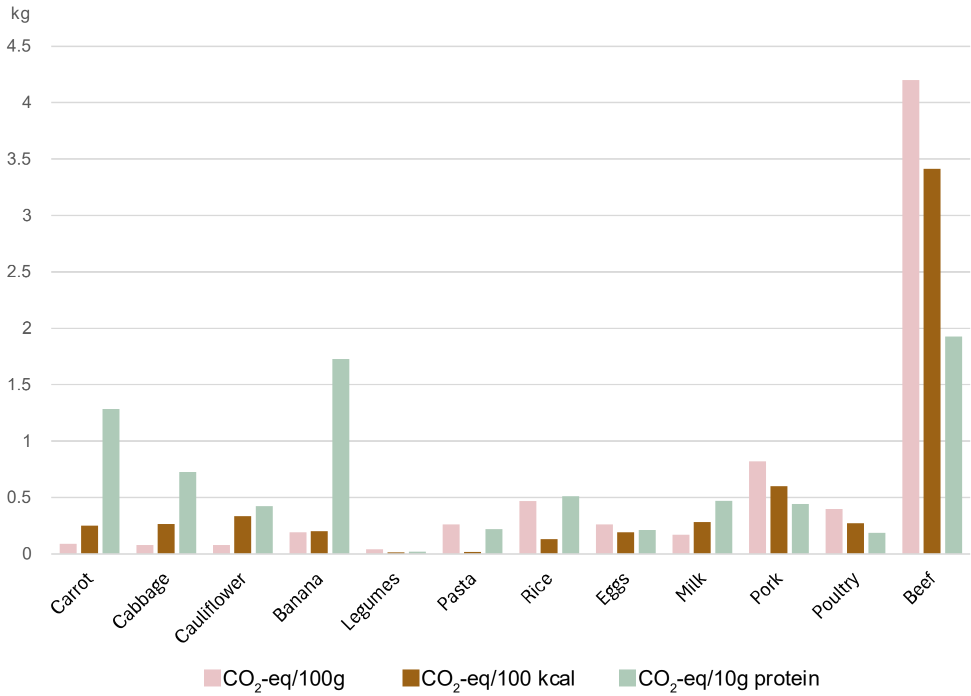


Figure 8. GHGE expressed using different functional units.
Emissions are estimated values and are presented as kg CO_2-eq per 100 g of product, per 100 kcal of food, and per 10 g of protein, based on Hallström et al. [53] and the Swedish Food Composition Database [54].

The chosen functional unit may impact the interpretation of results from a LCA considerably. As a theoretical example, using dietary fibre content as the functional unit would further accentuate the difference in climate impact per kg between animal-based and plant-based foods, since fibre levels are very low or absent in animal-based foods (**Figure 9**).

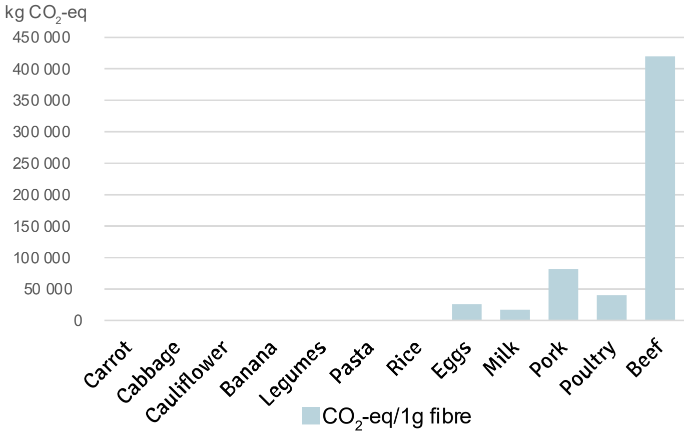


Figure 9. Example of GHGE of foods expressed using dietary fibre as the functional unit. Emissions are estimated values and are presented as kg CO_2-eq per 1 g of fibre, based on data from Hallström et al. [53] and the Swedish Food Composition Database [54].

Alternatively, environmental assessments of foods, meals and diets might be expressed per serving or per average daily intake. Accounting for cooking-related weight changes may influence GHGE estimates by up to 30%, and differences in assumptions such as raw versus cooked weight, inclusion of bones, or treatment of food losses may further alter results by up to 50% [55]. It is essential to clearly define the chosen functional unit to avoid misinterpretation of results. Different functional units can lead to varying conclusions regarding the relative environmental impact of food items and therefore it is essential that comparison of environmental impacts of foods, based on LCA results, are made based on results expressed in relation to the same functional unit [56].

Another method decision in LCA that might impact the estimates is the allocation method [44]. If the food system studied yields multiple products, the environmental impact is allocated between the main product and its by-products. For instance, environmental impact from a livestock production may be distributed across products such as milk, meat, leather, and manure. The allocation method varies between studies and can influence the results considerably. For example, a large share of the total impact from 'producing' a cow would be allocated to the meat and milk if the impact were allocated based on the products' economic value, while manure would get a relatively higher impact if using allocation based on the weight of products. In another example, if a potato producer is selling both peeled potatoes and potato chips processed from the peels, the environmental impact from the primary production can be shared between the two products, reducing the impact attributed to each. Another option is 'system expansion', where the system boundaries are broadened to include all co-products and their substituted functions. When this is not feasible, impacts are allocated between products, for example, between milk, meat, leather, and manure in livestock production. A recent review found major inconsistencies in allocation practices across agri-food LCAs, with many studies deviating from the ISO standards [57]. Economic allocation was most common, although physical allocation better reflects biophysical relationships. These methodological differences can substantially affect results, underscoring the need for transparency and adherence to ISO standards. Thus, how allocations are made should be considered carefully when interpreting or comparing LCA results.

Lastly, it is important to recognize that LCA results are influenced by uncertainty and variability in data, modelling assumptions, and regional production conditions [51]. Many food LCAs rely on European datasets, even when applied to products predominantly produced in other regions, which may limit representativeness. For nutrition-sensitive assessments, extending system boundaries to the consumption stage can be especially relevant, since cooking and storage affect both nutrient availability and environmental impacts. Moreover, assessments should also consider broader system dynamics, trade-offs, and spillover effects, acknowledging that no single metric can capture the full sustainability profile of foods [58]. Integrating multiple indicators and contextual factors is therefore essential for a comprehensive understanding of dietary environmental impacts.

Dietary climate impact from different foods

In general, most of the climate impact from food occurs during the primary production, i.e. the stage of farming, fishing, or aquaculture. This is making the ‘choice of food’ generally more significant for environmental impact, relative to other post-farm activities such as packaging or transportation (**Figure 10**) [59].

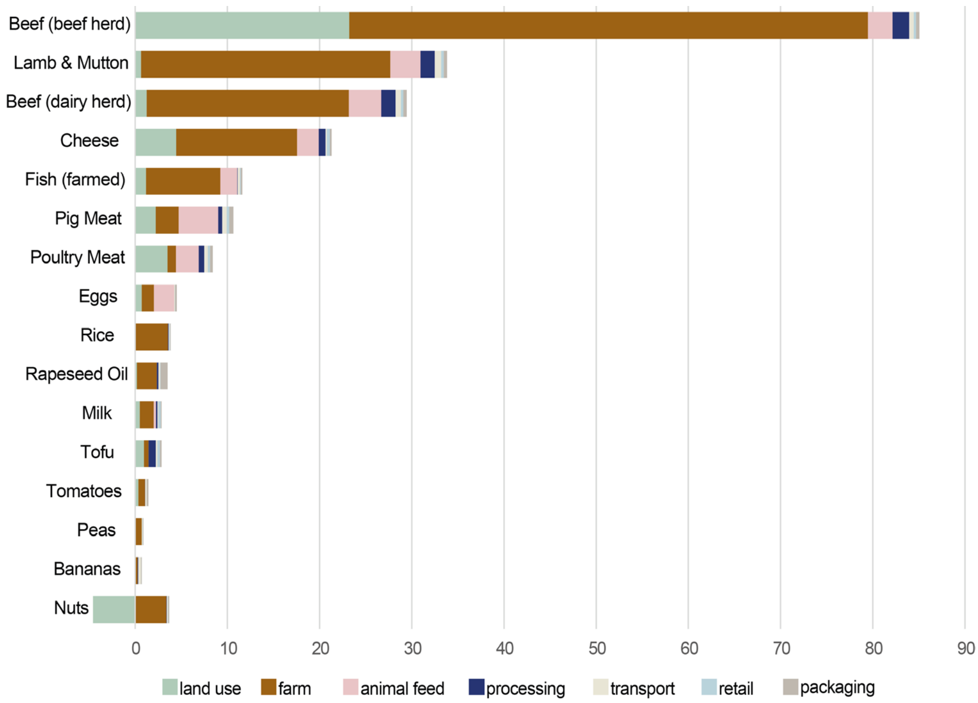


Figure 10. Dietary GHGE across the supply chain from farm to retail.
Values are expressed as kg CO_2-eq needed to produce 1 kg of food. Adapted from Our World in Data [59]. Licensed under CC BY 4.0.

Animal-based foods, particularly products from ruminant animals like cattle, sheep, and goats are associated high GHGE due relatively low feed-conversion rates and methane production during digestion. Since methane is a potent greenhouse gas with a higher (about 30-fold) global warming potential than carbon dioxide, this substantially increases the climate footprint of these foods compared to plant-based alternatives. Animal-based foods in general have a higher climate impact than plant-based foods [60, 61], but large differences in climate impact between products may exist both within and between product categories (**Figure 11**).

In countries with a high intake of animal-sourced foods, such as Sweden, their consumption dominates the impact [39, 62]. In the EU, animal-sourced foods contribute approximately 83% of the food system's total GHGE [63], with a similar figure of around 65–75% estimated for the Nordic region [53, 64]. This is partly explained by the low feed conversion efficiency in livestock production, as producing one kg of beef on a global average typically requires around 25 kg of feed, compared with about 6 kg for pork and 3 kg for poultry [65]. In addition, discretionary foods such as sweets, snacks, sugary drinks, and alcoholic beverages, which have low nutritional value, are often associated with negative health outcomes and are estimated to account for about 12% of food-related GHGE and 17% of total energy intake in Sweden [53]. In Australia, discretionary foods are estimated to stand for one third of dietary GHGE [66].

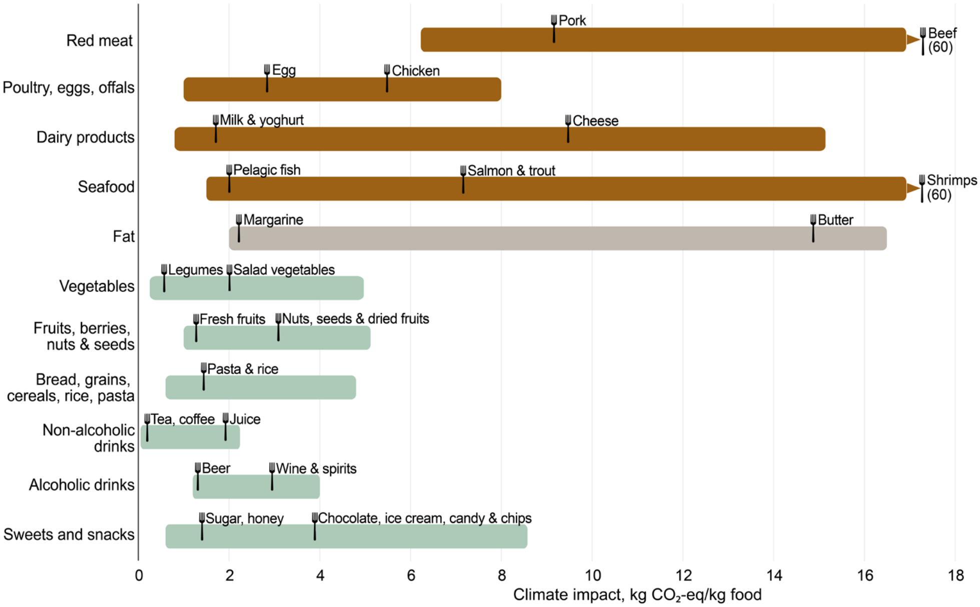


Figure 11. Variation in climate impact per kg of food produced, within and between food groups. Climate impact is expressed per edible weight at the consumer stage, using cooked weight for foods that require preparation, and includes GHGE from food loss and waste along the food chain. Bars indicate the minimum and maximum values for each food group, while forks represent the mean climate impact for selected foods to illustrate variation within groups. Maximum values for red meat (beef) and seafood (shrimps) are 60 kg CO_2-eq per kg of food. Figure adapted from Hallström et al. [53]. Licensed under CC BY 4.0.

Several studies have highlighted the high climate impact of current dietary habits in Sweden. The Swedish diet, along with diets in other Nordic countries, generates significantly higher GHGE compared to dietary patterns in most low- and middle-income countries, and even surpasses emissions from diets in several high-income nations [64]. The estimated average GHGE associated with food consumption in Sweden amount to roughly 2 tonnes of CO_2-eq per person per year, corresponding to approximately 5.5 kg per day [67]. This level is more than three times higher than the estimated per capita emissions of 1.4 kg per day (0.5 tonnes per year) considered compatible with within planetary boundaries for the food system [25]. An international assessment comparing dietary patterns across 156 countries, ranked Sweden as the 13th highest in terms of diet-related GHGE, closely following countries such as New Zealand, Australia, the United States, and Argentina [68]. In these countries, including Sweden, the primary drivers of elevated GHGE were identified as high consumption of meat and dairy products.

Agriculture has a critical potential to mitigate climate change and might be one of the most cost-effective fields to approach [69]. Shifting to less animal-based to more plant-based foods is one of the single most effective dietary changes to reduce environmental impact [25]. Despite this, global meat consumption continues to rise. Between 2000 and 2022, global meat production increased by 45%, driven by both population growth and increased per capita consumption, reaching 337 million tonnes annually [70]. In Sweden, current consumption is approximately 79 kg of meat per person per year based on national per capita food supply data. Between 1980 and 2022, this figure rose from 64 kg to a peak of 81 kg per person per year [71]. Simultaneously, per capita energy intake has increased in relation to energy expenditure, a pattern contributing to the rising prevalence of overweight and obesity observed over the past five decades. Overconsumption of food, which is sometimes called 'metabolic waste', is an important part of dietary environmental impact [72-75], and research has estimated it makes up 1.6% of total global GHGE [76].

Food waste is another major environmental concern. Despite awareness, food waste in Sweden continues to rise. On average, 34 kg of edible food is discarded per person each year without necessity [77]. Food waste patterns differ across income contexts. In low-income settings, most waste occurs during production and post-harvest stages, whereas in high-income settings, consumer-level waste is the main contributor [25]. On a global scale, as much as one third of all food produced is estimated to be lost or wasted [78, 79].

Climate change, as a result of increasing GHGE, is likely to reduce possibilities for future food production, decrease nutrient content of cultivated crops, and increase the presence of harmful substances in food production [25, 80], posing a significant threat to public health. Extreme weather events may also disrupt food transportation and storage, affecting both availability and quality. In some parts of the world, climate change is already undermining food security [81]. In a worst-case scenario, global crop yields could decline while nutrient quality, including protein and mineral content, also deteriorates [82]. It is estimated that every additional degree Celsius of global warming on average will drag down the world's ability to produce food by 120 calories per person per day, in other terms 4.4% of current daily consumption [83]. This would likely increase the number of people experiencing some level of food insecurity, an estimate that already affects 2.3 billion individuals world-wide today [6].

Food in sustainable development

Food and agriculture to some extent relate to all of the 17 Sustainable Development Goals (SDGs) and many of their 169 targets (**Figure 12**) [84]. SDG 1 (No poverty) addresses issues such as social protection, land rights, and resilience, while SDG 2 (Zero hunger) is dedicated to ending hunger, improving food security and nutrition, and promoting sustainable agriculture. SDG 3 (Good health and well-being) is closely linked to diet-related health outcomes and the prevention of non-communicable diseases. The connection between food systems and natural resources is also central to SDG 13 (Climate action), SDG 14 (Life below water), and SDG 15 (Life on land). Food is further linked to SDG 6 (Clean water and sanitation), SDG 10 (Reduced inequalities), SDG 12 (Responsible consumption and production), and SDG 16 (Peace, justice and strong institutions). While current unsustainable dietary habits hinder progress towards these goals, transforming human diets is essential for achieving them [24, 85].

Food and nutrition indicators illustrate the double burden of malnutrition, with persistent undernourishment, inadequate dietary diversity among children and adults, and rising obesity rates worldwide [86]. At the same time, unsustainable agricultural practices, including overuse of fertilizers, inefficient water use, land degradation, biodiversity loss, and high GHGE undermine both food security and environmental goals, underscoring the central role of diets and food systems in achieving the SDGs.

According to the *Sustainable Development Report 2025* [86], global progress towards the SDGs is largely off track, with none of the 17 goals currently on course to be achieved by 2030. While only 17% of the targets are advancing as planned, improvements have been made in access to basic services and infrastructure, as well as in reducing child and neonatal mortality.

The Global Nutrition Targets for 2015–2025 aimed to reduce stunting, wasting, anaemia, and low birth weight, prevent childhood overweight, increase exclusive breastfeeding, and curb diet-related non-communicable diseases. According to the *2022 Global Nutrition Report*, some progress has been made in reducing stunting and wasting, increasing breastfeeding, and limiting further increases in childhood overweight, yet anaemia still affects nearly one third of women of reproductive age and low birth weight remains common [11]. Very few countries are on track for the non-communicable diseases related targets, with obesity and diabetes continuing to rise globally.

Figure 12. The Sustainable Development Goals (SDGs) and nutrition.
Obtained from the Food and Agriculture Organization of the United Nations (FAO) [87]. Licensed under CC BY -NC-SA 3.0 IGO.

According to *The State of Food Security and Nutrition in the World 2025*, global hunger and food insecurity remain at concerning levels despite modest improvements since the Covid-19 pandemic [6]. In 2024, about 673 million people (~8% of the world's population) faced hunger, and 2.3 billion experienced moderate or severe food insecurity, which is 335 million more than in 2019. Rising food prices and inflation continue to limit access to healthy diets, especially for low-income households. While global food insecurity has declined slightly since 2021, it remains above pre-2015 levels, with increases in Africa and gradual decreases in Asia and Latin America. Nutrition indicators show mixed progress, while child stunting has declined and rates of exclusive breastfeeding have increased, levels of child wasting and overweight remain stagnant, and both adult obesity and anaemia among women of reproductive age have worsened. This report also introduced minimum dietary diversity as a new SDG indicator, showing that only one third of children (6–23 months) and two thirds of women achieve adequate dietary diversity, leaving many at risk of micronutrient deficiencies.

Sustainable dietary patterns

Sustainable Healthy Diets according to FAO and WHO

Sustainable Healthy Diets are dietary patterns that promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable. The aims of Sustainable Healthy Diets are to achieve optimal growth and development of all individuals and support functioning and physical, mental, and social wellbeing at all life stages for present and future generations; contribute to preventing all forms of malnutrition (i.e. undernutrition, micronutrient deficiency, overweight and obesity); reduce the risk of diet-related NCDs; and support the preservation of biodiversity and planetary health. Sustainable healthy diets must combine all the dimensions of sustainability to avoid unintended consequences.

Sustainable Healthy Diets: Guiding Principles 2019 [88].

Since food is so central to our largest environmental and public health challenges, shifting to sustainable diets is necessary for achieving the SDGs and maintaining our existence within the planetary boundaries [89, 90]. Diets that are energy-balanced and rich in nutritious, low-impact plant-based foods can help reduce the environmental burden of food systems and support progress towards the SDGs [91, 92].

Numerous studies have shown that self-identified dietary patterns with restricted intake of animal-based foods, such as being a flexitarian, vegetarian or vegan, have a lower environmental impact compared to average western diets [34, 93-97]. In addition to environmental gains, diets rich in nutritious plant-based foods may confer health benefits. Foods generally associated with positive outcomes for both health and the environment include legumes, wholegrain products, vegetables, tubers and sustainable choices of seafood, fruits, plant-oils and nuts. In contrast, while red meat is a good source of several essential nutrients, high consumption is linked to an increased risk of colorectal cancer and contributes substantially to dietary environmental impact. Intake of processed meat, on the other hand, is associated to adverse health outcomes but may provide environmental benefits by using low-value by-products from animal production that otherwise might not be used for human consumption. Furthermore, sugar-sweetened beverages and other discretionary foods and beverages, are linked to adverse health impacts but often have low environmental impact unit of product, although their environmental impact from total consumption may be considerable due to high intake levels **(Figure 13)** [23].

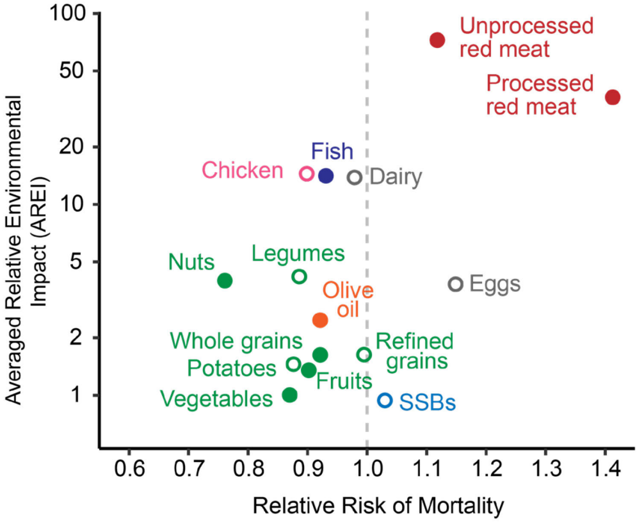


Figure 13. Associations between mortality risk and environmental impact of different food groups.
Each point represents a food group, showing the relative risk of mortality per additional daily serving (x-axis) against the averaged relative environmental impact (AREI) across five environmental indicators (greenhouse gas emissions, land use, eutrophication, acidification, and scarcity-weighted water use) (y-axis). Obtained from Clark et al. [23]. Licensed under CC BY 4.0.

On a population level, a shift towards more environmentally-friendly diets rich in plant-based foods is estimated to substantially reduce the incidence of chronic diseases and mortality, particularly in high-income countries [98, 99]. The health outcomes associated with climate-adapted diets depend, however, on their composition and quality [100]. Well-designed dietary patterns, characterized by high intakes of vegetables, fruits, legumes and wholegrains, moderate consumption of dairy, fish, and poultry, and limited amounts of discretionary foods and meat, can improve overall diet quality compared with current Western diets. Such improvements include lower intakes of energy, total and saturated fat, and sodium, alongside higher intakes of dietary fibre and wholegrains [17, 101]. At the same time, climate-friendly diets may reduce the intake and uptake of certain micronutrients primarily found in animal-based foods, such as vitamin B12, selenium, iron, zinc, calcium, and vitamin D [101-104].

A sustainable dietary pattern is therefore not defined by a single food group or nutrient, but by the overall balance of the diet, its environmental footprint, and its capacity to support both short- and long-term human health. As food systems continue to face climate, health, and equity challenges, sustainable diets offer a pathway that highlights the interconnectedness of environmental stability and human wellbeing, and they form a key component in efforts to achieve global health and sustainability targets.

The EAT-Lancet diet framework

Planetary boundaries

Nine Earth system processes are considered critical for maintaining planetary stability. In 2009, the concept of 'planetary boundaries' was introduced to define safe operating limits for these processes [105, 106]. The aim is to prevent human activities from pushing the Earth system beyond these limits, thereby maintaining a 'safe operating space' for humanity. The state of each boundary is classified into three levels: below the threshold (safe), within the zone of uncertainty (increased risk), and beyond the zone of uncertainty (high risk). While changes are typically linear within the safe zone, non-linear effects may occur once the uncertainty zones are passed, potentially triggering irreversible changes, so-called 'tipping points'. However, due to scientific uncertainties, the exact thresholds for some boundaries remain are uncertain.

The nine planetary boundaries are: climate change, biodiversity loss, land-use change, freshwater use, disruption of biogeochemical flows (nitrogen and phosphorus), ocean acidification, atmospheric aerosol loading, stratospheric ozone depletion, and novel entities (e.g. chemical pollutants). In 2025, seven of the nine planetary boundaries are considered to be exceeded [106], as illustrated in **Figure 14.** These include biosphere integrity (due to habitat loss and climate change), climate change (driven primarily by GHGE), biogeochemical flows (from excessive nitrogen and phosphorus inputs), land-system change (mainly through deforestation), freshwater change, atmospheric aerosol loading, and the introduction of novel entities such as microplastics, heavy metals, persistent organic pollutants, antibiotics and other pharmaceuticals. The planetary systems are interconnected, like dominoes, so exceeding one boundary can influence others. For example, climate change contributes to ocean acidification and biodiversity loss, while land-use change impacts water availability and ecosystems. These interactions mean that transgressing one boundary can accelerate the transgression of others.

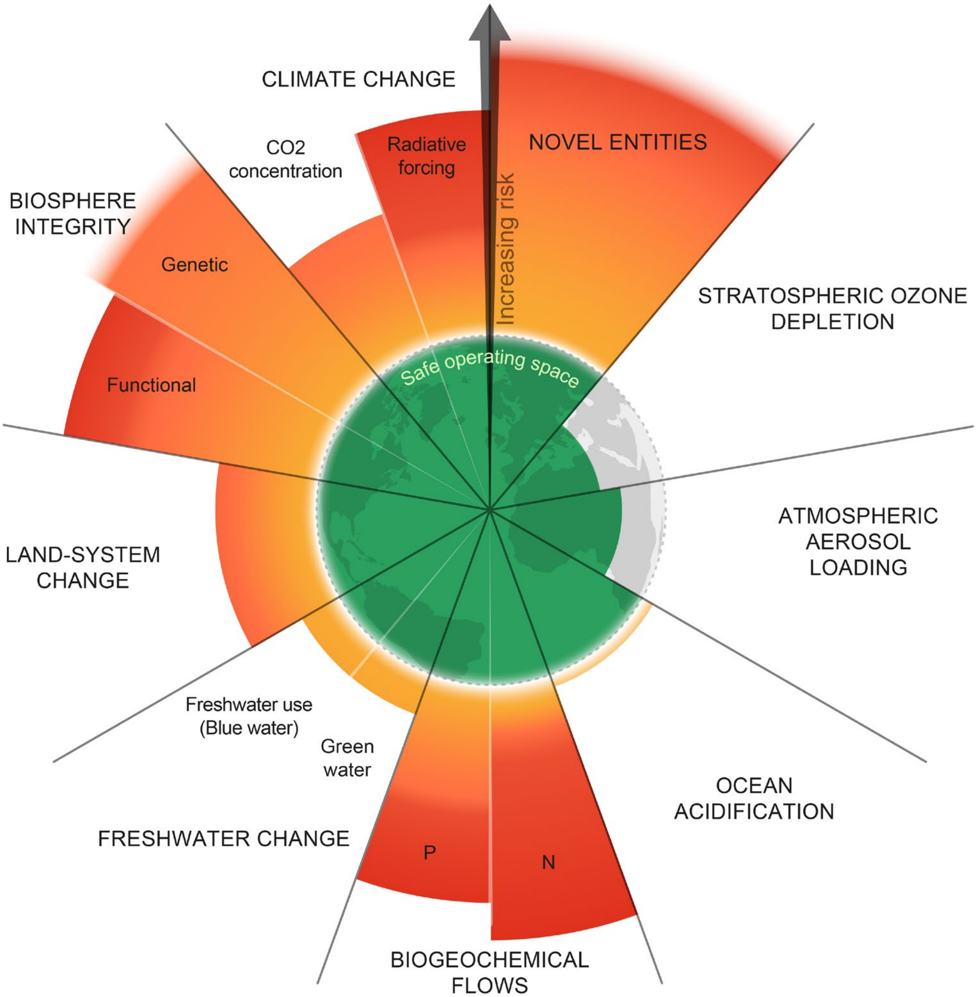


Figure 14. Planetary boundaries 2025.
The figure illustrates nine Earth system processes and their boundaries that define a safe operating space for humanity. Green indicates conditions within the safe zone, yellow indicates rising risk, and red indicates where boundaries have been exceeded. Credit: Azote for Stockholm Resilience Centre, based on analysis by Sakschewski and Caesar et al. (2025) [106]. Licensed under CC BY-NC-ND 3.0.

Food production plays a major role for the possibility to stay within planetary boundaries (**Figure 17**). Nearly half of all food is produced in ways that exceed one or more boundaries [107]. The United States and the European Union, accounts for a large share of global food-related GHGE and nutrient pollution, meaning that national overshoots in these regions have a disproportionate impact on the planetary boundaries [108]. To translate planetary boundaries into a food system context, the EAT-Lancet Commission 1.0 [24] and the updated EAT-Lancet 2.0 [25] define planetary boundaries for the global food system, setting safe limits for food-related climate impact, cropland use, freshwater use, nutrient flows and other planetary boundaries. These can be downscaled to the individual level by dividing global limits by world population [62], enabling assessments of whether national or individual diets stay within a fair share of the global safe operating space.

While Sweden as a country has a smaller global impact, it is important to acknowledge that the average diet in Sweden exceeds planetary boundaries for the food system by 1.6 to 4 times, depending on the environmental domain [39, 40, 62, 109]. Animal products, meat in particular, are the main contributors to GHGE, land use, and biogeochemical flows (nitrogen and phosphorus), while plant-based foods and discretionary foods have a relatively larger contribution to freshwater use and biodiversity loss [39, 40].

The EAT-Lancet diet 1.0

In 2019, the EAT-Lancet Commission published a landmark report that introduced the concept of a 'planetary health diet' and assessed how dietary patterns influence both human health and the environment, explicitly linking them to six of the nine planetary boundaries [24]. Widely recognized as the EAT-Lancet report, this publication got wide international attention and has since shaped discussions around sustainable food consumption and informed dietary guidelines in several countries. The report presented global projections to 2050, factoring in population growth, dietary trends, food waste, and agricultural improvements. A central premise was that the global population will reach 10 billion by 2050, an increase of 2 billion people in relation to the current population. This calls for major transformations in food systems, including dietary shifts, reduced food waste, and more sustainable production methods. Simulation-based modelling[4] highlighted that only by addressing all three domains it is possible to provide nutritional adequacy for a growing population while remaining within planetary boundaries.

[4] Simulation-based modelling refers to computational methods to estimate how hypothetical changes, such as dietary shifts, could affect health and environmental outcomes. These approaches test explicit dietary scenarios, often assuming linear relationships between adherence levels and changes in food intake or risk factors, and can simulate full adherence to a dietary pattern even when it is not observed in real-world populations.

To guide such transitions, the Commission introduced a global reference diet including a set of intake targets for major food groups. Designed for healthy adults, the EAT-Lancet diet[5] aims to align nutritional adequacy with environmental sustainability. Based on a daily energy intake of 2500 kcal, the EAT-Lancet diet includes both target values and acceptable ranges of food intake to allow for contextual flexibility (see **Table 1**). It emphasizes plant-based foods such as wholegrains, fruits, vegetables, legumes, nuts, and unsaturated oils, while allowing moderate amounts of fish, poultry, and dairy (**Figure 15**). Consumption of red meat and added sugars should be kept to a minimum. For instance, the recommended intake of whole grains is 232 grams per day, which is substantially higher than both the current Swedish dietary guideline of 90 grams per day [17, 110], and the Swedish median intake of 40 grams per day [111]. In contrast, the recommended intake of red meat is limited to 14 grams raw meat per day (approximately 98 grams per week), representing a major reduction compared with the Swedish recommendation of 350 grams cooked (corresponding to 400–500 grams raw) per week [110]. The current average consumption in Sweden is about 680 grams of red meat per week (raw weight) according to national dietary surveys of adults and consumption statistics [71].

The EAT-Lancet Commission's simulation-based modelling efforts suggest that widespread adherence to the EAT-Lancet diet, combined with improved food production and reduced food waste, could enable the global food system to stay within the planetary boundaries while nourishing 10 billion people by 2050 [24]. The modelling also shows that following the EAT-Lancet diet could prevent 11 million premature deaths per year, accounting for 19–24% of all global deaths from diet-related chronic diseases. If widely adopted, food-related GHGE could fall to 13 kg CO_2-eq per person per week, or 680 kg annually, compared to a current Swedish average of about 2 tonnes per person per year [53].

[5] Since the diet was commonly referred to as 'the EAT-Lancet diet' during the first years following its publication, and this terminology was used in our early papers, I have chosen to retain this phrasing rather than replace it with 'the Planetary Health diet' in this thesis.

Table 1. The EAT-Lancet diet from 2019.
The planetary health diet as defined by Willett et al. [24]. The diet is based on a daily intake of 2500 kcal.

Food groups	Daily intake (possible range), g/day
Wholegrains	
Rice, wheat, corn, and other †	232 (total grains 0–60% of energy)
Tubers or starchy vegetables	
Potatoes and casava	50 (0–100)
Vegetables	
All vegetables	300 (200–600)
Dark green vegetables	100
Red and orange vegetables	100
Other vegetables	100
Fruits	
All fruits	200 (100–300)
Dairy foods	
Whole milk or derivative equivalents (e.g. cheese)	250 (0–500)
Protein sources ‡	
Beef and lamb	7 (0–14)
Pork	7 (0–14)
Chicken and other poultry	29 (0–58)
Eggs	13 (0–25)
Fish	28 (0–100)
Legumes	
Dry beans, lentils, and peas	50 (0–100)
Soy foods	25 (0–50)
Peanuts	25 (0–75)
Tree nuts	25
Added fats	
Palm oil	6.8 (0–6.8)
Unsaturated oils ¶	40 (20–80)
Dairy fats (included in milk)	0
Lard or tallow ‖	5 (0–5)
Added sugars	
All sweeteners	31 (0–31)

For an individual, an optimal energy intake to maintain a healthy weight will depend on body size and level of physical activity. Processing of foods such as partial hydrogenation of oils, refining of grains, and addition of salt and preservatives can substantially affect health but is not addressed in this table. Wheat, rice, dry beans, and lentils are dry, raw. †Mix and amount of grains can vary to maintain isocaloric intake. ‡Beef and lamb are exchangeable with pork, and vice versa. Chicken and other poultry is exchangeable with eggs, fish, or plant protein sources. Legumes, peanuts, tree nuts, seeds, and soy are interchangeable. §Seafood consists of fish and shellfish (e.g. mussels and shrimps) and originate from both capture and from farming. Although seafood is a highly diverse group that contains both animals and plants, the focus of this report is solely on animals. ¶Unsaturated oils are 20% each of olive, soybean, rapeseed, sunflower, and peanut oil. ‖Some lard or tallow is optional in instances when pigs or cattle are consumed.

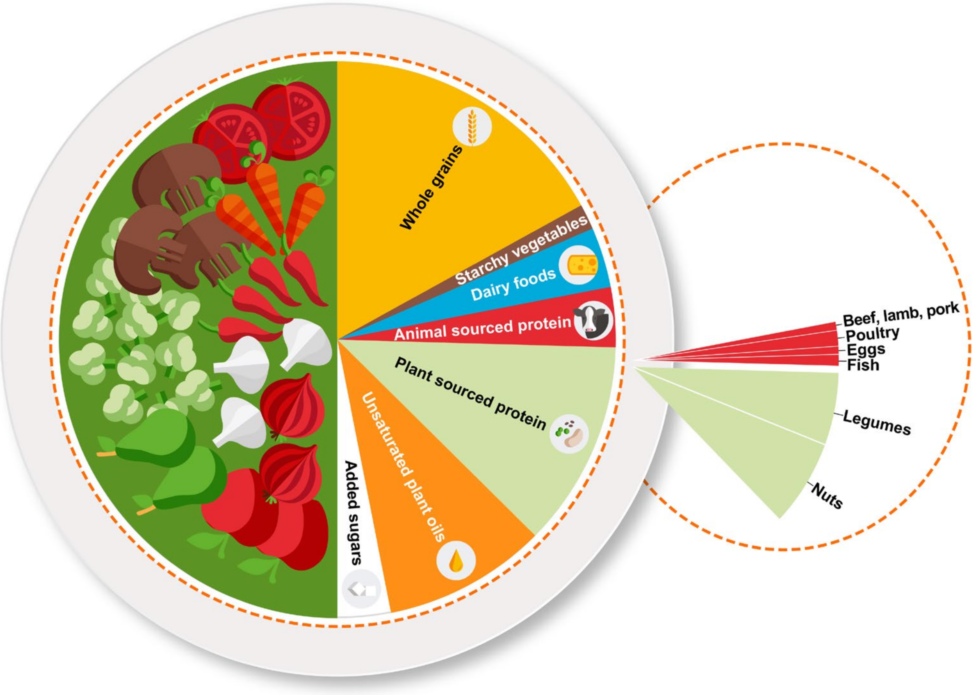


Figure 15. The proportion of food groups in the EAT-Lancet diet.
The figure illustrates the recommended daily intake targets, emphasizing a diet rich in plant-based foods with limited amounts of animal-sourced foods, added sugars, and saturated fats from Willett et al. [112].

In practice, adopting the EAT-Lancet diet would require substantial dietary changes in many countries, including Sweden (**Figure 16**). Most noteworthy, this would involve a substantial reduction in red meat intake and increased consumption of wholegrains, legumes, vegetables, and fruits [64, 113]. The EAT-Lancet diet has been partly reflected in dietary guidelines developed across the world, for example in Denmark with sustainable guidelines for both the general population and older adults, drawing directly on the EAT-Lancet framework [102]. In parallel, environmental sustainability is being incorporated into an increasing number of national dietary guidelines, a 2022 analysis reported that 37 of 83 evaluated national food-based dietary guidelines included references to sustainability [114]. This includes the Nordic Nutrition Recommendations [17] and dietary guidelines in Sweden [110].

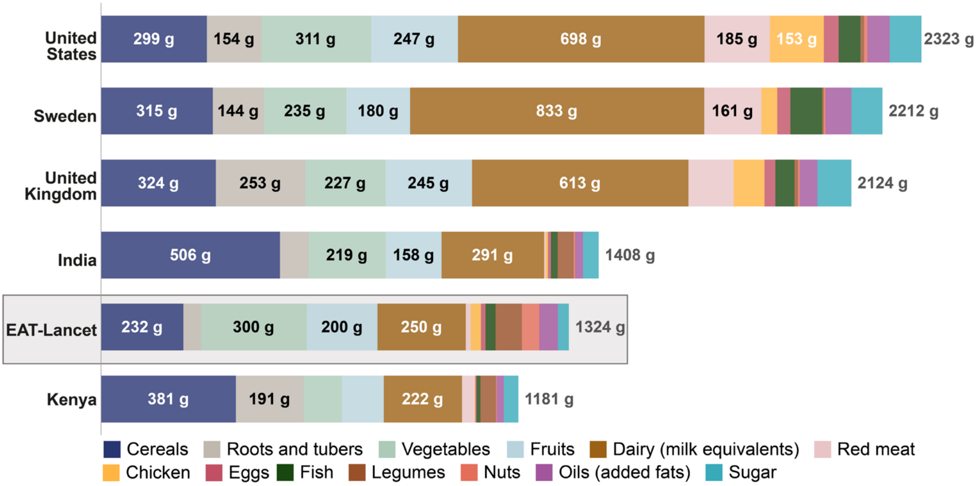


Figure 16. How actual diets compare with the EAT-Lancet diet.
Diets are shown as average daily per capita supply of different food groups, compared to the EAT-Lancet. Data from the Food and Agriculture Organization. Adapted from Our World in Data [115]. Licensed under CC BY 4.0.

Globally, the consumption of red meat, starchy vegetables such as potatoes, and eggs is higher than the levels recommended in the EAT-Lancet diet (**Figure 16**), while the intake of vegetables, fruits, legumes, wholegrains, and nuts falls below the targets. For example, in the United States, red meat consumption would need to decline substantially, whereas in countries such as India, where current intake is much lower, an increase would be possible [115].

The EAT-Lancet diet 2.0

In October 2025, the second EAT-Lancet Commission report on healthy and sustainable diets was published [25]. This updated report expands its scope beyond health and environmental sustainability to include justice. Going a step further than its predecessor, it examines global food systems through the lens of human rights, focusing on the right to food, a healthy environment, and decent work conditions. The report highlights that the diets of the world's richest 30% of the population account for more than 70% of the environmental pressures from food production, including land use and GHGE.

The report identifies the global food system as the largest driver of transgressing planetary boundaries (**Figure 17**). At the same time, it highlights the food system as a key opportunity for restoring balance within these boundaries and advancing global sustainability. Together with the planetary boundaries, the report introduces social foundations, which represent the minimum conditions necessary for people to realize their rights and to exercise individual and collective agency. When all boundaries are considered together, fewer than 1% of the global population, about 115 million people, live within both the planetary and social boundaries [25].

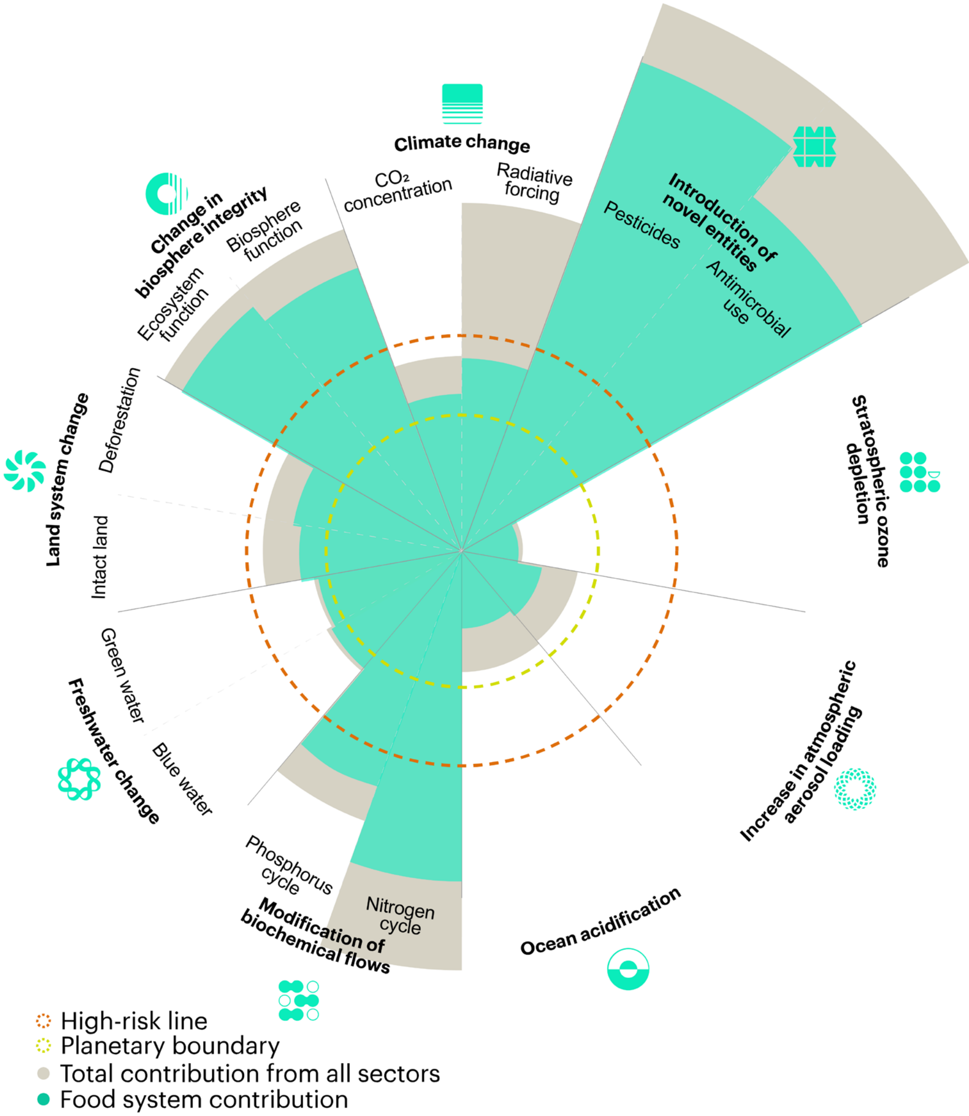


Figure 17. The contribution of the global food system to the transgression of planetary boundaries.

The figure illustrates how the global food system contributes to the exceedance of the planetary boundaries. The green area represents the food system contribution. Obtained from Rockström et al. [25]. Licensed under CC BY 4.0.

Compared with the first report, the new EAT-Lancet report is supported by more comprehensive evidence and simulation-based modelling, and it assesses the global food system in relation to nine, in contrast to previously only six, planetary boundaries. The overall dietary recommendations remain largely unchanged, with some minor adjustments and rounding of values (see **Table 2**). For example, the target for red meat is now 15 grams per person instead of 14, and for wholegrain 210 grams instead of 232 grams. The reference energy intake has been revised from 2500 to 2400 kcal. Sodium has been added as a specific dietary component. The report also emphasizes prioritizing minimally processed foods and beverages.

Table 2. The EAT-Lancet diet from 2025.
The planetary health diet as defined by Rockström et al. [25]. The diet is based on a daily intake of 2400 kcal.

Food groups	Daily intake (possible range), g/day
Plant foods*	
Wholegrains †	210 (20–50% of daily energy intake)
Tubers and starchy roots ‡	50 (0–100)
Vegetables §	300 (200–600)
Fruits	200 (100–300)
Tree nuts and peanuts	50 (0–75)
Legumes	75 (0–150)
Animal-sourced foods**	
Milk or equivalents (e.g. cheese)	250 (0–500)
Chicken and other poultry	30 (0–60)
Fish and shellfish ††	30 (0–100)
Eggs	15 (0–25)
Beef, pork, and lamb	15 (0–30)
Fat, sugar, and salt	
Unsaturated plant oils ‡‡	40 (20–80)
Palm oil and coconut oil	6 (0–8)
Lard, tallow, and butter‖	5 (0–10)
Sugar (added or free)	30 (0–30)
Sodium	<2

Most foods are assumed to be unprocessed or minimally processed. At the individual level, the optimal energy intake to maintain a healthy weight in adults and growth in children depends on body size, level of physical activity, and physiological status (e.g. pregnancy or lactation in women). The targets, ranges, and options in this flexitarian version of the planetary health diet are intended to provide flexibility within a specific energy intake, with intake of animal-sourced foods not to exceed approximately two servings per day, with one being dairy (250 g milk or milk equivalents) and one being non-dairy (e.g. 75–100 g from fish, poultry, red meat, or eggs). *Mostly whole, unprocessed, or minimally processed foods; when processed, added sugar, refined starch, saturated fat, and sodium should be minimal. †Wholegrain rice, wheat, maize, oats, millets, sorghum, and other wholegrains are all interchangeable and replace refined grains. ‡Examples include potatoes, yams, cassava, sweet potatoes, and taro. §Combinations of dark green, red and orange, and other vegetables, including aquatic plants. ¶All fruits and berries. ||A variety of legumes is desirable; for calculations, we used 50% soy and 50% other legumes (e.g. dry beans, lentils, chickpeas, and peas). **Beef, lamb, and pork are interchangeable. Red meat, chicken, and other poultry can be replaced with eggs or fish, or other sources of plant protein. Dairy food servings are interchangeable with approximately 30 g servings of poultry, fish, or pork, provided calcium intake is satisfied by other food groups. Foods should be mostly whole, unprocessed, or minimally processed. ††Includes fish and shellfish (e.g. mussels and shrimps) from capture and farming. ‡‡Unsaturated oils include olive, soybean, rapeseed (or canola), sunflower, peanut oil, and most other plant or vegetable oils. §§Energy values for butter, tallow, and lard are included with dairy and meats.

Nordic Nutrition Recommendations 2023

Since the 1980s, the Nordic Council of Ministers have supported the collaborative development of joint Nordic Nutrition Recommendations (NNR), which have been updated approximately every ten years. The work on the Nordic Nutrition Recommendations is funded by the Nordic Council of Ministers, together with relevant authorities in the Nordic countries.

The most recent and comprehensive compilation of research on diet and health is the *Nordic Nutrition Recommendations 2023* (NNR 2023) [17]. All five Nordic countries jointly contributed to this revision, as well as the Baltic countries Estonia, Latvia, and Lithuania. The process has been extensive, involving several hundred researchers and experts. These experts were selected based on their scientific qualifications and after undergoing conflict-of-interest reviews, to ensure the independence and integrity of the work. The conclusions have been presented in around 50 scientific background papers. Both the background material and the proposed new recommendations were submitted for public consultation and are publicly available online via open-access journals and websites.

NNR 2023 describes dietary patterns that promote both short- and long-term health. It also includes recommendations for daily energy and nutrient requirements. While human health remains the foundation of the recommendations, NNR 2023 is the first edition to also consider the environmental and climate impact of food consumption. The NNR serve as the scientific basis for future national dietary guidelines in Sweden and other Nordic countries. The overall conclusion is that diets that promote health are, in most cases, also favourable from an environmental perspective. The NNR recommend a predominantly plant-based diet, while still allowing for the inclusion of meat, fish, and dairy products, and a limited intake of discretionary foods and beverages.

NNR 2023 includes recommendations for 36 micronutrients, with increased recommended intake for 12 nutrients and reduced intake for two compared to the previous recommendations in 2014. Additionally, NNR 2023 provides recommendations for 15 food groups. For some of these groups, quantitative recommended intakes are provided based on their health impacts and nutritional value. In the case of red meat, the recommended maximum intake of 350 g per week was determined on health grounds; it would likely have been lower if environmental impact alone had guided the recommendation. However, the authors concluded that there was insufficient scientific evidence to set recommended amounts solely based on environmental or climate considerations.

To guide the assessment and planning of micronutrient intake, several terms are used to describe recommended levels and to evaluate adequacy or potential risk. These include the Average Requirement (AR), Recommended Intake (RI), Adequate Intake (AI), Provisional AR, and the Tolerable Upper Intake Level (UL). Their definitions and uses, as outlined in the NNR 2023, are summarized in **Table 3**.

Table 3. Nutrient Intake terminology and definitions in the Nordic Nutrition Recommendations from 2023 [17].

Average Requirement (AR)	The average daily nutrient intake level that is estimated to meet the requirements of half of the individuals in a particular life-stage group in the general population. AR is usually used to assess adequacy of nutrient intake of groups of people, and may be used in planning for groups.
Recommended Intake (RI)	The average daily dietary nutrient intake level that is sufficient to meet the nutrient requirements of nearly all (usually 97.5%) individuals in a particular life-stage group in the general population. It can be used as a guide for daily intake by individuals. Usually used to plan diets for groups and individuals.
Adequate Intake (AI)	The recommended average daily intake level based on observed or experimentally determined approximations or estimates of nutrient intake by a group of people that are assumed to be adequate. The AI has larger uncertainty than RI, and can be used when an RI cannot be determined. The AI is expected to meet or exceed the needs of most individuals in a life-stage group.
Provisional AR	The average daily nutrient intake level that is suggested to meet the requirements of half of the individuals in a particular life-stage group. The provisional AR, which is an approximation of AR, has larger uncertainty than AR. It is calculated by multiplying AI by a factor of 0.8. It can be used when an AR cannot be determined.
Tolerable Upper Intake Level (UL)	The highest average daily nutrient intake level that is likely to pose no risk of adverse health effects to almost all individuals in the general population. As intake increases above the UL, the potential risk of adverse effects may increase.

Micronutrients in the human diet

Micronutrients are vitamins and minerals required in small amounts but essential for maintaining health, growth, and normal physiological functions [116]. Although they contribute only a minor fraction of total dietary intake, they play central roles in metabolic pathways, immune defence, and tissue maintenance. Inadequate intake or poor bioavailability of micronutrients can lead to deficiencies with significant health consequences, while sufficient intake supports optimal development and disease prevention.

Vitamins

Vitamins are organic compounds required in small amounts for normal physiological functioning [116]. They are classified as essential nutrients, since the human body cannot synthesize them in sufficient quantities, and they must therefore be obtained from the diet, supplements, or sunlight. Vitamins play crucial roles in regulating metabolic processes, immune defence, growth, and tissue repair. While some act as cofactors in enzymatic reactions, others function in a hormone-like manner. To date, 13 vitamins have been identified, of which four are fat-soluble and nine water-soluble. Most vitamins are present in varying amounts in both plant- and animal-based foods, although there are exceptions: vitamin C is predominantly found in fruits and vegetables, whereas vitamin B12 and vitamin D are mainly present in animal-sourced foods.

Minerals

The human body consists primarily of four elements: carbon, hydrogen, oxygen, and nitrogen, which together account for about 96% of total body mass. The remaining 4% comprises minerals [116]. To date, 15 minerals are recognized as essential for human health. These are classified as macroelements when the daily requirement exceeds 100 mg, and as microelements (trace elements) when the requirement is lower. Minerals are indispensable for numerous physiological functions. Calcium, phosphorus, and magnesium are fundamental components of bone tissue. Magnesium, zinc, copper, selenium, and manganese are required for, or act in collaboration with, enzymes. Iron is a key component of haemoglobin and enables oxygen transport from the lungs to tissues, while zinc plays a critical role in DNA synthesis and cell division. Mineral absorption depends on both host status, the nutrient's chemical form, and the overall dietary composition. Many nutrients are absorbed more efficiently when body stores are low [117-119]. Most minerals are present in both plant- and animal-sourced foods, although their concentrations and bioavailability vary.

Iron occurs in two forms: heme iron, found only in animal-sourced foods and constituting roughly half of the total iron in meat, and non-heme iron, which is present in both animal- and plant-based foods [116]. Although heme iron usually represents a smaller proportion of total dietary iron, it is absorbed more efficiently and more independent of other dietary factors. For non-heme iron on the other hand, absorption is strongly influenced by other dietary compounds, with inhibitors such as phytates and polyphenols reducing uptake, and enhancers such as vitamin C and the 'meat factor' improving it.

Zinc is more abundant in animal-sourced foods but is also found in legumes and wholegrains. Its bioavailability is reduced by phytates found in plant-based foods, which are abundant in unrefined cereals, legumes, seeds, and nuts, and limit absorption. Consequently, the bioavailability of these minerals is generally lower in plant-based diets, including those containing meat substitutes, due to higher phytate content [120], the absence of the so-called 'meat factor' [121], and, for iron, the exclusive presence of non-heme forms. The absorption of non-heme iron can be enhanced by vitamin C or other organic acids.

The selenium content of foods depends largely on the concentration of selenium in the soil where crops are grown. Soil levels vary widely between regions, directly affecting dietary intake and introducing uncertainty in nutrient composition estimates. Soils in much of Europe have low selenium concentrations, resulting in lower levels in locally produced foods [122].

Iodine is a mineral mainly found in seafood such as fish, shellfish, and algae [116]. Because animal feed is fortified with iodine in Sweden, milk and dairy products also contribute to iodine intake. In addition, some table salts are fortified with iodine, and the use of iodised salt is recommended in Sweden [123].

Nutrient status

Vitamin D

Low vitamin D intake, combined with limited sun exposure, full-body clothing, or darker skin pigmentation, increases the risk of deficiency. At northern latitudes, cutaneous synthesis occurs only during the brighter months, making deficiency most common in late winter and early spring. Deficiency may impair calcium absorption and increase the risk of osteomalacia and osteoporosis. Vitamin D exists in two main forms with similar biological functions but different origins [116]. Vitamin D2 (ergocalciferol) is produced by plants, fungi, and yeast when exposed to ultraviolet light. It enters the human diet primarily through fortified foods and some supplements. Vitamin D3 (cholecalciferol) is produced in the skin during sunlight exposure and is also found in animal-sourced foods such as fatty fish, egg yolk, and fortified products. Vitamin D3 is generally considered more effective at raising and maintaining serum 25-hydroxyvitamin D concentrations. Vitamin D is converted in the liver to 25-hydroxyvitamin D (25OHD), which is considered the best indicator of vitamin D status [124]. The optimal serum concentration remains debated, but levels below 30 nmol/L indicate an increased risk of rickets and osteomalacia, while concentrations between 50 and 125 nmol/L are generally regarded as sufficient for bone health [125]. In Sweden, the National Food Agency recommends a minimum level of 50 nmol/L, whereas others suggest 75 nmol/L as optimal [126]. The National Institutes of Health (NIH) defines the reference value as 50 nmol/L [127].

Vitamin D status is affected by obesity, country of birth, age, and season, reflecting differences in sunlight exposure [128, 129].

Folate

Folate deficiency occurs mainly among pregnant women and individuals with celiac disease but may also result from poor dietary habits. It can cause megaloblastic anaemia, characterized by enlarged red blood cells. Elevated mean corpuscular volume (MCV) and plasma homocysteine are typical findings, although high homocysteine may also indicate vitamin B12 deficiency. Although plasma folate is influenced by recent folate intake, it is considered to be a suitable marker of folate status in large epidemiological studies [130]. Serum folate concentrations below about 6.8 nmol/L are considered low according to the NIH [127].

Zinc

Zinc deficiency is reported to be uncommon but may occur in individuals with poor dietary intake, impaired appetite, or delayed wound healing [116]. Although plasma levels do not always reflect total body stores, zinc concentration in serum or plasma is widely used as a biomarker of zinc status [131]. It has been suggested to be a better indicator under extreme dietary conditions [132, 133]. Serum zinc levels can fluctuate by up to 20% during the day and decrease after meals [134], therefore, fasting morning samples are recommended for accurate assessment. Plasma zinc concentrations below 10.6 µmol/L indicate deficiency according to the NIH [127]. Serum zinc levels vary with stress, inflammation, infection, and albumin concentration [131], and can fluctuate by up to 20% during the day depending on food intake [134].

Selenium

Dietary selenium intake in Sweden is relatively low, especially among vegetarians, due to low selenium content in European soils. Clinical symptoms of deficiency are rare, and selenium status is seldom assessed in clinical practice. Serum selenium remains one of the most used biomarkers for evaluating selenium status, despite its limitations as a marker for dietary intake [135, 136]. Serum selenium concentrations below approximately 63 ng/mL are considered below reference levels, according to NIH [127]. High BMI has been associated with lower selenium levels [137].

Iron

Iron deficiency is the most common nutritional deficiency in Sweden, particularly among children, adolescents, and women of reproductive age [18, 19, 116]. Assessment of iron status is best based on a combination of serum ferritin, transferrin, and haemoglobin (Hb) [138]. Ferritin reflects iron stores, while low concentrations indicate deficiency. Prolonged deficiency leads to anaemia, characterized by reduced haemoglobin levels, defined as below 120 g/L in women and 130 g/L in men according to the WHO [139]. Infections and inflammatory conditions can influence biomarker interpretation, as ferritin often increases while haemoglobin tends to decrease [116].

Dietary patterns and dietary indices

Dietary pattern research offers a holistic view of diet by evaluating the combined effects of foods as they are typically consumed, rather than isolating individual nutrients or foods [140]. Well-established patterns such as the Mediterranean diet, the Healthy Eating Diet and the DASH diet have been widely used to inform dietary guidelines aimed at promoting health and preventing chronic disease. These frameworks emphasize overall eating habits, making them valuable tools in nutritional epidemiology. They differ from self-identified dietary patterns like being vegetarian or vegan which are often based on a binary variable (yes/no) of a single or few food groups.

Although many dietary patterns share core features, such as encouraging the consumption of fruits, vegetables, wholegrains and legumes while limiting intake of salt, discretionary foods and red and processed meats, each emphasizes different components based on specific health or environmental priorities. For instance, the alternative Mediterranean diet (aMED) highlights olive oil, fish, and nuts; the Dietary Approaches to Stop Hypertension (DASH) targets sodium reduction to support blood pressure; the Mediterranean-DASH Intervention for Neurodegenerative Delay (MIND-diet) focuses on cognitive-protective foods like berries; and the healthful plant-based diet index (hPDI) scores healthy plant foods positively and animal-based items negatively [141].

Adherence to dietary patterns can be measured using dietary scores, and for some diets several different scores exist. Since 2019, several research groups have developed scoring systems to evaluate adherence to the EAT-Lancet diet. Although all are based on the same overall framework, they differ in their construction, scoring criteria, and interpretation as outlined on page **79** and onwards.

Dietary scores: conceptual and methodological considerations

According to Burggraf et al. [142], several key considerations must be addressed when developing, applying, or evaluating a dietary index. These include decisions related to scoring direction, threshold design, data granularity, and analytical approach. These methodological principles guided the development and evaluation of the EAT-Lancet diet indices applied in this thesis.

Aim of dietary score

Dietary scores are intended to assess the overall diet quality. They are used in research to study associations with disease risk and nutritional quality. Research by Willett and McCullough [143] highlights the value of refining dietary indices for this purpose. For example, while the original Healthy Eating Index (HEI) showed only modest associations with chronic disease, the Alternative Healthy Eating Index (aHEI), which incorporates the quality of fats, carbohydrates, and protein sources, is more strongly associated with reduced risk, particularly for cardiovascular disease [143].

However, when the goal is to measure adherence to a specific dietary pattern (such as the Mediterranean or the EAT-Lancet diet), it is important to use the score that best captures the characteristics of that pattern, rather than selecting a score solely based on which yields the strongest associations with health outcomes. A score optimized to maximise statistical associations risks drifting away from the underlying principles of the dietary pattern it is intended to represent. In such cases, the interpretation becomes problematic, as it becomes unclear whether observed associations reflect adherence to the intended dietary pattern or the consequences of methodological adjustments made to improve predictive strength. Ensuring that the score aligns with the conceptual foundations of the dietary pattern therefore helps maintain both scientific validity and transparency.

When developing or applying dietary scores, methodological decisions influence both interpretation and comparability of results. Based on Burggraf et al. [142] and research underlying this thesis, scoring systems can be discussed along several key dimensions, each of which affects how dietary adherence is defined and analysed.

Scoring direction

Each food group included in the score must have a clearly defined scoring direction, specifying whether higher intake is considered beneficial or detrimental. Based on this, appropriate cut-off values are selected to quantify adherence.

Binary vs. multilevel scoring

Binary scoring systems assign points based on whether intake exceeds a single predefined threshold, with no further differentiation among higher or lower levels of adherence. In contrast, multilevel or proportional scoring systems categorize individuals across a range of intake levels, offering a more detailed picture of dietary adherence within the population.

Fixed vs. population-based cut-offs

Dietary scores may rely on fixed, predefined thresholds that are independent of the cohort under study, or on cut-offs derived related to the actual intake distribution within a specific population. For example, a population-based approach might assign points to participants whose vegetable consumption exceeds the cohort median. While this can improve internal comparability, it may reduce generalizability across populations with different dietary habits and the possibility for the scores to measure adherence of food intake in relation dietary guidelines.

Level of dietary detail

Dietary indices also vary in the level of detail required. Some scores group foods into broad categories (e.g. 'vegetables'), while others make finer distinctions, such as separating vegetables by colour (e.g. green, orange, yellow). Some indices also score intake based on the percentage of energy contributed by a food group rather than the absolute intake. Higher granularity allows more precise evaluation but may not be feasible in all cohorts due to limitations in dietary data. On the other hand, using broad categories may obscure meaningful differences in the consumption of key food subgroups.

Analytical approach

The choice of analytical method is critical, particularly regarding energy adjustment. When dietary indices are analysed without adjusting for total energy intake, comparisons reflect both differences in dietary composition and total intake. Energy-adjusted analyses, by contrast, isolate dietary quality independent of the quantity of food consumed. This approach is widely used in epidemiological studies of health outcomes. In contrast, it is not used to the same extent in studies evaluating environmental impacts. The environmental impact of food consumption is highly dependent on the total amount of food consumed [144], which might not be captured in energy adjusted analyses. Absolute food intake levels are also important because nutritional recommendations and environmental goals are generally expressed in absolute terms. In addition, outcomes such as GHGE, land use, and resource demands are suggested to primarily be driven by the absolute quantity of food rather than its relative nutritional quality [24, 145]. Energy-adjusted environmental impact can provide other important insights and inform substitution guidelines.

Score-based approaches vs. simulation-based modelling approaches

Score-based methods are inherently limited by the specific food groups included in the scoring framework, meaning that not all consumed foods are captured. For example, none of the existing EAT-Lancet dietary indices account for alcohol intake, so differences in alcohol consumption do not affect adherence scores. A key advantage of score-based approaches is that they are grounded in observed dietary behaviours and capture the natural variation in adherence within a population. Because dietary changes across adherence levels are often non-linear, these methods can help identify which food groups contribute most to differences in diet quality. However, when full adherence is rare or absent in the study population, the scoring approach may have limited interpretability.

Simulation-based modelling approaches, in contrast, are designed to test explicit dietary scenarios, often assuming linear relationships between level of adherence and changes in food group intake or risk factors. These models rely on external data to define realistic adherence levels and can simulate full adherence to a dietary pattern, even when such adherence is not observed in real-world populations.

Rationale

The topic of this thesis was chosen based on research gaps identified in 2019 and onwards. In 2019, at the time of the publication of the EAT-Lancet reference diet, methods for measuring adherence to the diet were limited, raising the question of which scoring approach best reflected the recommendations. Furthermore, it was unclear whether adherence to the diet was associated with positive health outcomes in observational studies, and how such adherence might influence micronutrient intake and the risk of nutrient deficiencies.

Another research gap concerned the health implications of more climate-friendly diets. Studies of self-selected dietary patterns such as vegetarian or vegan diets provided insights about those groups but often grouped individuals into broad categories. This limited the ability to disentangle the role of specific dietary components and did not capture the full spectrum of dietary variation in the general population. Few investigations had assessed dietary GHGE as a continuous variable, which allows a more nuanced evaluation of dose–response relationships between environmental impact and health outcomes. This represents a more contemporary approach than comparisons restricted to a few diet groups and is crucial for identifying whether incremental reductions in GHGE, achievable through moderate dietary changes, are associated with health and nutritional benefits.

The scope of this thesis is broad, spanning several interrelated disciplines, including nutrition, epidemiology, and environmental science. It has therefore not been possible to explore every aspect in depth. Instead, the focus has been on the interconnections between these fields and on understanding how dietary patterns simultaneously influence human health and environmental sustainability.

Aims

General aim

The overall aim of this thesis was to assess the associations between environmental impacts of diets, nutritional adequacy, and health outcomes.

Specific aims

Paper I	Develop a dietary index to quantify adherence to the EAT-Lancet diet. Assess the association between the dietary index with all-cause and cause-specific mortality.
Paper II	Compare different versions of the EAT-Lancet diet scores, and estimate their associations with all-cause mortality, stroke, and GHGE in three cohorts.
Paper III	Assess nutrient adequacy of the EAT-Lancet as defined by different scores, based on micronutrient intake and status.
Paper IV	Examine the associations between dietary GHGE and the risk of all-cause and cause-specific mortality, cardiovascular disease, and diabetes.
Paper V	Examine the associations between dietary GHGE, and nutritional risks and benefits based on micronutrient intake and status.

Methods

Study populations

All papers underlying this thesis are based on data from the Malmö Diet and Cancer Study (MDC). In addition, one paper also includes data from the Diet, Cancer and Health Study (DCH, Denmark) and the Mexican Teachers' Cohort (MTC, Mexico). Together, these cohorts provide detailed information on diet, lifestyle, and health, with long follow-up through national registers, enabling analyses of long-term risks of chronic disease and mortality.

Malmö Diet and Cancer Study (MDC)

The Malmö Diet and Cancer Study (MDC) is a population-based prospective cohort established to investigate associations between diet and cancer [146]. It was conducted in Malmö, Sweden, with baseline data collection carried out between 1991 and 1996. Initially, all individuals born between 1926 and 1945 who were residents of Malmö Municipality on 1 January 1991 were invited to participate (n = 53,325) [147]. The cohort was updated quarterly to account for migration and deaths, to avoid classifying the deceased or those who moved from the city as non-responders. In 1995, the inclusion criteria were expanded to men born between 1923 and 1945 and women born between 1923 and 1950. Younger women were specifically included to enable studies of breast cancer in premenopausal women. At baseline, men were therefore aged 46–73 years and women 44–73 years. In total, the defined birth cohorts encompassed 74,138 participants.

Participants were recruited between 1 January 1991 and 25 September 1996 [148]. Personal invitations were sent to a randomized sample of the target population, followed by one or two reminders, and later supplemented with follow-up phone calls. Through this active recruitment strategy, 23,016 individuals were enrolled in the study. An additional 5505 participants were recruited through passive methods, such as public advertisements in the form of posters and pamphlets placed in primary health care centres, hospitals, libraries, pharmacies, and on buses. Recruitment also took place during a one-week city festival in Malmö and through selected organizations, while media outreach was used to further raise awareness of the study. The main message was that public contribution was needed to be able to clarify the relation between diet and cancer. There was no monetary reward, only souvenirs such as T-shirts, pens, and plastic bags. Passive responders were older and more frequently female, born in Sweden and living together with others.

Individuals with insufficient proficiency in Swedish or with cognitive impairments that prevented completion of the dietary assessment were excluded at baseline, based on staff evaluations during the initial screening. In total, 28,098 individuals completed the baseline examination and reporting dietary data, corresponding to a participation rate of 41% [147].

At the first baseline visit, anthropometric measurements, blood pressure, and blood samples were collected [146]. Participants, in groups of six to eight, were instructed on how to complete the study questionnaires, including a comprehensive self-administered questionnaire with 105 main items and multiple sub-questions covering demographic, lifestyle, socioeconomic, and health-related factors such as smoking, alcohol use, physical activity, education, and medical history. They also received instructions for completing a food diary and a food frequency questionnaire (FFQ). Participants were asked to record their usual meal pattern, which was then used to agree on which meals would be included in the menu book registration. The start date for the registration was also determined at this visit. Approximately two weeks later, participants returned for a second visit, during which a nutritionist-led structured diet interview was conducted, and the questionnaires were reviewed for completeness.

Comparisons between MDC participants and non-participants showed higher mortality rates in non-participants [147]. Additionally, a mailed health survey was sent in 1994 to a random sample of subjects from the MDC target group. In total, 1567 (75%) individuals responded to the questionnaire. The result showed that MDC participants were similar in sociodemographic and lifestyle factors but reported somewhat better subjective health [148].

The MDC has been a part of the European Prospective Investigation into Cancer and Nutrition (EPIC) since 1993. EPIC is the largest study ever made of diet and health, involving over half a million people in ten European countries: Denmark, France, Germany, Greece, Italy, the Netherlands, Norway, Spain, the United Kingdom, and Sweden. The researchers are based at 23 centres in 10 countries [149].

The papers in this thesis include different numbers of participants from the MDC, based on the aim of the specific study. **Figure 18** shows a flowchart of participants included in the studies underlying this thesis.

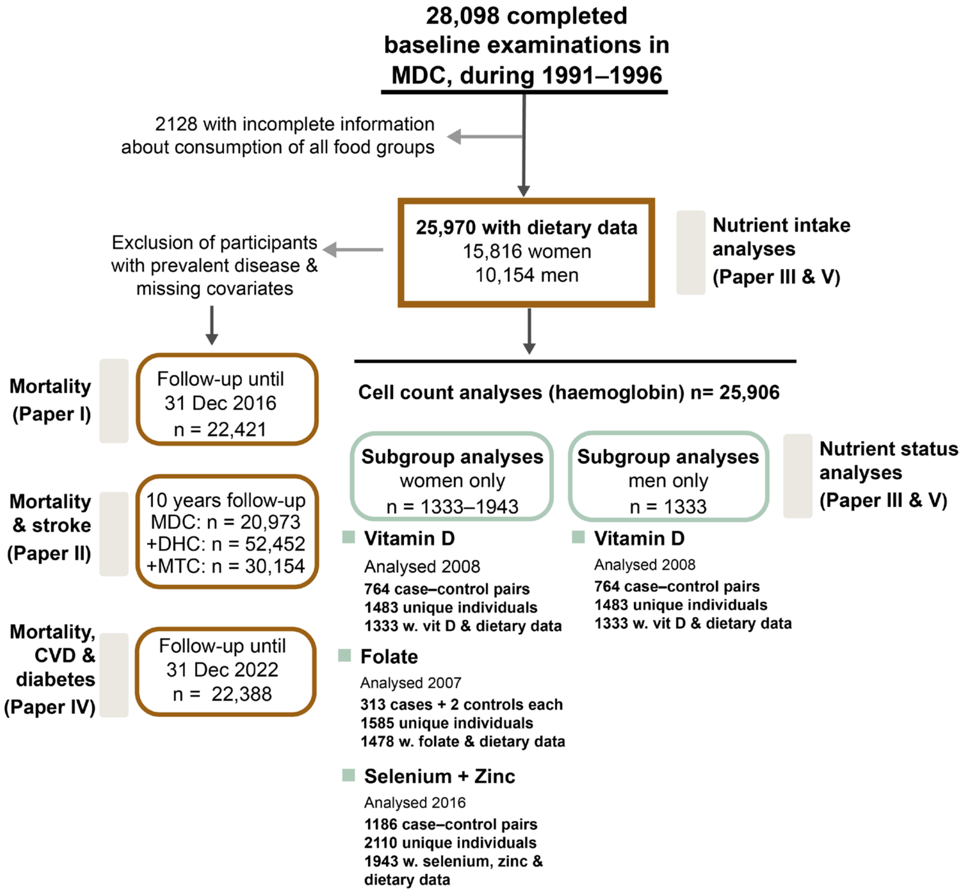


Figure 18. Participants included in different papers of this thesis.
MDC = Malmö Diet and Cancer Study; DHC = The Diet, Cancer and Health; MTC = Mexican Teachers' Cohort.

Dietary assessment in the MDC

Dietary intake at baseline was assessed using a validated, modified diet history method, developed specifically for the MDC [150].

This method consisted of three complementary components designed to capture both habitual and recent intake:

- Seven-day food diary
- 168-item FFQ
- Dietary interview lasting 60 or 45 minutes.

The seven-day food record captured cooked meals, cold beverages (milk, juice, soft drinks, water, and alcoholic drinks), and dietary supplements consumed over seven consecutive days. Lunch and dinner were selected for recording because of their variability. Portion sizes were estimated using standardized guides, and the records were reviewed during the dietary interview to avoid overlap with the food frequency questionnaire. Participants documented their intake in a structured booklet and were instructed to provide detailed information on cooking methods, specific types of foods (e.g. meat, fish, and vegetables), fat content in products such as cheese and milk, food brands, and volumes of beverages consumed.

The FFQ in the MDC was designed to capture habitual intake over the preceding year, with the specific aim of covering foods not recorded in the seven-day food diary. It focused on items consumed regularly and with little day-to-day variation, such as hot beverages, sandwiches, edible fats, breakfast cereals, yoghurt, milk, fruits, cakes, sweets, and snacks. In total, the FFQ included 168 food items, and participants reported both frequency and portion sizes. When filling out the FFQ and the food record, a booklet with a 48-item portion guide was used.

At the second visit, approximately two weeks after baseline, participants submitted both the food diary and the FFQ. A structured dietary interview was then conducted by trained nutritionists, lasting about 60 minutes (reduced to 45 minutes after September 1994 due to revised coding routines). Portion sizes from the seven-day food record were verified using photographic aids, including a more comprehensive photographic atlas than the one used at home. Typically, participants were shown a set of four photographs displaying different portion sizes of the same dish, with one set provided for each dish or food registered in the menu book. They were encouraged to describe their usual portion sizes as precisely as possible, even if they differed from the photographs. Recipes for meals could be selected from standard entries, modified when needed, or newly created if required. Based on the meal pattern filled out at the first visit, the interviewer also ensured that food items were not double counted between the diary and the FFQ. In total, 17 trained interviewers conducted these assessments during the six-year baseline period, supported by strict quality control procedures, standardized coding rules, and regular data checks.

Different dietary assessment methods come with their own advantages and limitations [151]. The combined dietary method used in the MDC was designed to integrate the strengths and minimize the weaknesses of individual methods. It aimed to capture food and nutrient intake as precisely as possible, while still being feasible to apply in a large population.

Coding, nutrient calculation, and quality control procedures

Dietary data from the questionnaire, menu book, and diet history interview were coded, entered, and converted into nutrient intake values using the interactive computer software KOSTSVAR (AIVO AB) and the Swedish National Food Agency's database PC KOST2-93 [150]. The database contained approximately 1600 basic foods and was expanded with cohort-specific recipes and food codes for the MDC. During coding of foods and mixed dishes, the software guided interviewers through a system of 'recipe identifiers' to capture preparation methods and ingredients. When necessary, new individual recipes could be created.

In 1994, coding routines were streamlined by restricting modifications of recipes and relying more on standard entries. This reduced interview time from 60 to 45 minutes without affecting nutrient estimates, or validity [150]. A variable distinguishing the original and revised versions was introduced. Although estimated energy intake was slightly reduced after this change, participant ranking was not substantially affected.

Quality control procedures in the MDC were extensive and multi-layered. To ensure standardization and data quality, interviewers received extensive in-service training, supported by detailed coding rules and continuous quality control. Weekly training sessions and biannual workshops addressed coding and data entry challenges. Quality control routines included monthly computerized checks of extreme portion sizes, and energy, nutrient, and food group intakes, which were either verified or corrected if erroneous. In addition, energy intake to basal metabolic rate (EI/BMR) ratios were calculated as described below [152].

Dietary supplement data were obtained from the Swedish Medical Products Agency for registered products, and from manufacturers or retailers for others. In the MDC dataset, nutrient contributions from both food and supplements were available.

Misreporters of energy intake

Extreme values for portion sizes, energy intake, nutrients, and major food groups were systematically verified and corrected when errors were detected. In addition, energy intake to basal metabolic rate (EI/BMR) ratios were calculated by age and sex, and reports with implausible EI/BMR values were flagged as potential misreports and re-examined for inaccuracies [152]. To further refine the evaluation, individual physical activity levels (PAL) were estimated from self-reported leisure-time, occupational, household, and sedentary activities as reported in the questionnaire. Reported energy intakes were then compared with expected energy expenditure derived from PAL, allowing participants to be classified as low-energy reporters, adequate-energy reporters, or high-energy reporters. Unlike the Goldberg cut-off method [153], which uses fixed PAL values and 95% confidence limits around EI/BMR to identify misreporting at the group level, the MDC approach applied individualized PAL estimates to classify participants at the individual level. This method thereby accounted for variation in activity patterns across participants and was designed to minimize both random and systematic errors in dietary reporting, providing a more reliable basis for analyses of diet–disease associations.

In the MDC, 22.6% of women and 20.2% of men were classified as low-energy reporters, while high-energy reporters were rare (1.4% of women and 0.7% of men) [152]. Misreporting was associated with higher BMI: 44% of obese women and 34% of obese men underreported, compared with 13% of women and 12% of men with BMI <25. It was also more common among participants with low education (28% of women and 27% of men with only primary education) compared with those with higher education (15% and 12%, respectively). Among women, dieting behaviour was linked to higher odds of underreporting. Low-energy reporters tended to describe a diet lower in total energy but with apparently higher nutrient density, suggesting selective underreporting of energy-dense foods. Misreporting was further associated with manual occupations, unemployment or disability pension, and with poorer self-rated health and chronic disease [152].

Dietary changers

At baseline in the MDC, about one quarter of participants (24% of women and 23% of men) reported having substantially changed their food habits in the past [154]. The most common reasons were health-related, particularly conditions linked to the metabolic syndrome, while non-health reasons such as retirement, economic hardship, or changes in household circumstances were also reported, more often by women. Past food habit change was strongly associated with obesity: women with BMI $\geq$ 30 had 65% higher odds of reporting dietary change compared with normal-weight women, and the corresponding figure for men was 53%. The highest mean BMI was observed among those reporting health-related changes, whereas the lowest was seen in participants who reported non-health-related changes. Individuals who had changed their diet longer ago tended to have lower BMI than those who had made more recent changes, suggesting possible weight reduction over time. Socioeconomic and lifestyle factors were also linked to past dietary change, which was more common among participants with higher education, those living alone, non-Swedish-born individuals, retirees, ex-smokers, and non-drinkers.

Validity and reproducibility in the MDC

The dietary method used in the MDC has demonstrated good ranking validity[6] and reproducibility[7]. Two methodological studies conducted in Malmö in 1984 laid the foundation for the dietary assessment strategy in the MDC. Both compared an extensive quantitative food frequency questionnaire with a modified diet history method combining a shorter FFQ and a food record.

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[6] Validity refers to whether a study or measurement accurately reflects the concept it's intended to measure.

[7] Reproducibility refers to the ability of a study or measurement to be replicated or repeated with consistent results, regardless of who performs the procedure or if it uses different equipment.

The validity study [155, 156] evaluated relative validity of the modified diet history method by comparing dietary intake data against 18 days of weighed food records collected across one year in 206 participants aged 50–69 years. At the group level, reported energy intake was approximately 18% higher than the reference method. On average, 55–59% of participants were classified into the same energy intake quartile. Absolute intakes were particularly higher for potatoes, milk products, and fats, while intakes of fish, cream, and alcohol (both sexes), meat (women), and rice, pasta, and eggs (men) were lower. For absolute intake of major food groups, correlations ranged from 0.50 (fish) to 0.82 (meat) in men, and from 0.58 (vegetables) to 0.91 (meat) in women. Energy-adjusted Pearson correlations for key nutrients ranged from 0.52 to 0.69. For selected micronutrients, correlations were 0.75 for folate in both men and women, 0.58/0.44 for zinc, and 0.46/0.44 for selenium.

The reproducibility study [157] assessed stability over time by repeating the two methods one year apart among 241 Malmö residents of the same age range. Both methods showed good reproducibility, specifically the combined method in women and for key food groups such as fruits and vegetables.

Covariate Assessment

For the purposes of this thesis, a range of baseline measures from the MDC were included to allow adjustment for potential confounders and to describe participant characteristics. These variables were selected based on their established associations with both dietary habits and health outcomes and were consistently available across all analyses. Anthropometric, sociodemographic, and lifestyle factors were assessed through standardized measurements and validated questionnaires at baseline, as described below.

Weight and height were measured at the initial visit. BMI was calculated as kg/m^2 and categorized as normal (<25), overweight (25–29), or obese (≥ 30). Baseline questionnaires assessed sociodemographic, lifestyle, and health factors. Leisure-time physical activity was quantified by multiplying reported weekly time for 17 activities by activity-specific intensity factors and summing to a total activity score, which was categorized into quintiles [158].

Alcohol was assessed from the food diary and the FFQ. In the studies included in this thesis, intake was categorized into four groups based on reported intake: abstainers, low (<15 g/day women; <20 g/day men), medium (15–30 g/day women; 20–40 g/day men), and high (>30 g/day women; >40 g/day men) [159]. Smoking status was classified as current, former, or never smoker. Educational attainment was grouped as ≤ 8 years, 9–10 years, 11–13 years, or university degree. Season was categorized as winter (December–February), spring (March–May), summer (June–August), or autumn (September–November).

To account for potential sources of bias, several adjustment variables were created. Seasonal variation in dietary intake was controlled for by including a variable categorizing the season of dietary assessment. Another variable indicated the version of the dietary assessment method, distinguishing between interviews conducted before and after September 1994, when coding routines were revised and interview length was reduced. Participants who reported major past dietary changes were identified as 'past diet changers'. In addition, under- and over-reporters of energy intake were flagged using a variable derived from the energy intake to basal metabolic rate ratio as described above.

Nutrient intake

When assessing dietary nutrient adequacy, cut-offs were based on the Average Requirement (AR) and Recommended Intake (RI) levels defined in the Nordic Nutrition Recommendations (NNR 2023) [17]. The AR represents the intake estimated to meet the needs of half the individuals in a given group, while the RI covers the needs of nearly all individuals. Dietary micronutrient intake levels were compared with gender- and age-specific (51–70 years) reference values for AR and RI as outlined in the Nordic Nutrition Recommendations from 2023.

Blood sample collection and analysis of nutrient status

Non-fasting blood samples (45 ml) were collected by trained nurses. Haemoglobin (Hb), haematocrit (HCT), mean corpuscular volume (MCV), mean corpuscular haemoglobin (MCH), and mean corpuscular haemoglobin concentration (MCHC) were measured directly from the blood cell count, and these measurements are available for the entire cohort.

Within one hour of collection, plasma and serum were separated and stored at −80°C in the MDC biobank [148]. At later stages, samples were retrieved from storage and analysed for specific research questions. Serum and plasma samples from cases and matched controls have been retrieved from the biobank at different time points for various analyses.

Plasma folate concentrations were measured in 2007 in 1478 women to investigate the association between folate status and breast cancer risk among postmenopausal women [160]. Analyses were performed using a two-step immunoassay with alkaline phosphatase labelling and magnetic separation.

In 2008, serum was analysed for vitamin D (25-hydroxyvitamin D, including $25OHD_2$ and $25OHD_3$), parathyroid hormone (PTH), calcium, phosphate, creatinine, and albumin in relation to breast cancer risk among women [161]. The study included 764 case–control pairs. In the same year, serum samples from 943 case–control pairs of men were analysed to investigate prostate cancer risk in relation to $25OHD_2$, $25OHD_3$, PTH, and calcium. [162]. Serum $25OHD_2$ and $25OHD_3$ were measured using high-performance liquid chromatography (HPLC), while PTH was assessed with the Immulite® 2000 Intact PTH immunoassay (Diagnostic Products Corporation, Los Angeles, CA). Since $25OHD_2$ primarily derives from dietary supplements and $25OHD_3$ is endogenously synthesized and found in some foods, only 90 individuals had detectable $25OHD_2$ levels. Therefore, $25OHD_3$ was used in subsequent analyses. The papers included in this thesis have included the analyses of vitamin D but none of the other biomarkers from the same occasion.

In 2015, serum selenium and zinc were measured in 1186 case–control pairs of women to investigate breast cancer risk [163]. Analyses were performed by ALS Scandinavia AB, Sweden, using inductively coupled plasma-sector field mass spectrometry (ICP-SFMS; Thermo Element 2) with single-element standards traceable to NIST. For each sample, 0.15 ml of serum was diluted to 10 ml in an alkaline solution containing 0.1% NH_3 and 0.005% EDTA/Triton-X. To ensure accuracy, the reference material Seronorm (Lot 0608414; Sero AS, Norway) was analysed alongside the samples.

An overview of the different biomarker analyses is outlined in **Figure 18**. Nutrient status was assessed in **Paper III** and **Paper V**.

Reference values for haemoglobin were based on the World Health Organization (WHO) [139], and those for serum and plasma biomarkers were based on the National Institutes of Health (NIH) [127].

Outcome assessment – mortality and chronic disease in the MDC

Participants were followed from study entry until the date of disease diagnosis, death, emigration, or the end of follow-up, whichever occurred first. The follow-up period extended until 31 December 2016 in **Paper I**, and until 31 December 2022 in **Paper IV**. In **Paper II**, 10 years of follow-up time was chosen to align the observation time across the three cohorts.

In **Paper I**, **Paper II,** and **Paper IV**, we excluded individuals with a pre-baseline diagnosis of cancer, diabetes, or cardiovascular disease, and individuals with missing information on dietary intakes or relevant covariates. In **Paper II**, we further excluded individuals who reported implausible energy intakes (for women: <500 or >3500 kcal/day; for men <800 or >4200 kcal/day).

Information on vital status and emigration was obtained from the Swedish National Tax Agency, Statistics Sweden, and the National Board of Health and Welfare. Diagnoses and causes of death were identified through linkage of personal identification numbers to national health registers, using the International Classification of Diseases, Ninth Revision (ICD-9) and corresponding codes in later revisions. Cause of death data were retrieved from the Swedish Cause of Death Register. Cardiovascular mortality was defined by ICD-9 codes 390–459, and cancer mortality by codes 140–239. In **Paper I**, the mean follow-up time was 20 years, during which 7030 participants died. In **Paper IV**, the mean follow-up was 28.5 years, and 11,213 deaths occurred. In **Paper II**, the follow-up time was 10 years, and 1420 deaths were identified during the time.

Incident cardiovascular disease, included both coronary events and stroke, identified through the Swedish Hospital Discharge Register and the Cause of Death Register. Coronary events comprised fatal and non-fatal myocardial infarction and deaths from ischemic heart disease (ICD-9 codes 410–414). Stroke was defined as the first hospital discharge diagnosis of stroke (ICD-9 codes 430, 431, 434, or 436), with additional cases before 2010 identified through the local STROMA register [164]. In total, 5322 incident cardiovascular disease cases were recorded during the follow-up period in **Paper IV**. In **Paper II,** incident stroke was analysed, and 694 cases occurred.

The diabetes cases reported in **Paper IV** were identified through linkage with eight national and regional health registers, complemented by seven re-examination screenings and sub-cohort studies [165]. The registers included the Swedish National Diabetes Register [166], the Swedish Cause of Death Register, the Swedish Inpatient and Outpatient Registers, the Swedish Prescribed Drug Register (ATC code A10), the regional Diabetes 2000 Register, the Malmö HbA1c Register, and the ANDIS (All New Diabetics in Scania) study [167]. In the national patient and cause of death registers, diabetes was defined using ICD-10 codes E10–E14 and O24.4–O24.9. By the end of follow-up on 31 December 2022, a total of 4324 incident diabetes cases had been identified. Among participants with information on diabetes type, 2150 were classified as type 2 diabetes, and 179 as type 1 diabetes, latent autoimmune diabetes in adults (LADA), secondary, or other types. For 1995 participants, the diabetes type was unknown. Since classification data were incomplete, all identified diabetes cases were included in the analyses regardless of type. Given that the cohort consisted of individuals aged 45 years and older, the vast majority of cases were expected to represent type 2 diabetes.

The Diet, Cancer and Health Study (DCH)

To assess the generalisability of results from **Paper I,** and enable possible replication of findings from the MDC in another Nordic population, the Danish Diet, Cancer and Health Study (DCH) was included in **Paper II**. The cohort provides comparable dietary and lifestyle data, collected using similar instruments and during the same time period as in the MDC. Its inclusion allows cross-validation of results within a population with broadly similar food culture and environmental conditions, thereby strengthening the robustness of the overall findings.

This prospective cohort was established in Denmark between December 1993 and May 1997 to investigate associations between lifestyle factors and chronic disease risk [168]. A total of 160,725 individuals aged 50–64 years, residing in the greater

Copenhagen and Aarhus regions and free from a prior cancer diagnosis, were invited to participate, of whom 57,053 enrolled.

At baseline, participants completed a lifestyle questionnaire, a 192-item semiquantitative FFQ covering habitual intake during the previous year, and a standardized health examination at one of two study centres. Dietary data from the FFQ were converted into daily intakes of foods and nutrients using FoodCalc software in conjunction with the Danish National Food Tables. The FFQ was validated against two independent seven-day food records, showing acceptable validity for nutrient intakes.

For the present analyses, individuals with a pre-baseline diagnosis of cancer, stroke, myocardial infarction, or diabetes were excluded. Participants were followed through linkage with the Danish Civil Registration System, the National Patient Register, the Cause of Death Register, and the Danish Cancer Registry. During 10 years of follow-up, 3238 deaths and 1359 incident stroke cases were identified.

The Mexican Teachers' Cohort (MTC)

To examine the consistency of observed associations in a setting with markedly different dietary patterns, environmental conditions, and sociodemographic characteristics, the Mexican Teachers' Cohort (MTC) was also included in **Paper II**. This large, well-characterised cohort of women provides detailed dietary and health data and offers the opportunity to test whether associations between adherence to the EAT-Lancet diet and mortality are comparable outside a European context. The inclusion of the MTC thus broadens the global relevance of the findings and highlights potential regional differences in sustainable diet–health associations.

This prospective cohort was initiated between June 2006 and November 2010, enrolling public-school teachers aged 25 years and older from 12 Mexican states [169]. In total, 180,167 teachers were invited to participate, and 115,314 completed the baseline questionnaire, forming the cohort population. Compared with the MDC and DCH cohorts, participants in the MTC were younger and exclusively women. Recruitment began in 2006 with the enrolment of 27,979 teachers from two states, followed in 2008 by an additional 87,328 participants from ten further states.

At baseline, participants completed structured questionnaires covering reproductive health, lifestyle behaviours (including diet), and medical history. Dietary intake was assessed using a 140-item semiquantitative FFQ tailored to the cohort, which asked about habitual intake during the preceding year. This instrument was adapted from a validated 116-item FFQ, expanded with 24 additional items to reflect regional food habits, emerging dietary trends, and greater detail within food groups (e.g. lean vs. fatty fish). Reported frequencies were converted into servings per day and then into grams per day using predefined portion sizes. Energy and nutrient intakes were calculated using a food composition database developed by the National Institute of Medical Sciences and Nutrition in Mexico, supplemented with data from the USDA database.

Participants were followed through national registries and active follow-up for vital status. During the follow-up of 10 years, 567 deaths were identified in the cohort.

Measuring adherence to the EAT-Lancet diet

To evaluate whether environmentally sustainable eating was linked to health outcomes such as mortality, we developed a dietary index to assess adherence to the EAT-Lancet diet. The aim of **Paper I** was to develop this index and examine its association with mortality. At that time, only one study from the UK had created an EAT-Lancet adherence score, but it was published as a short communication, offered limited methodological detail, and relied on a binary scoring approach that, in our view, did not capture the multidimensional character of the diet. We therefore constructed a new and more comprehensive adherence score.

Development of the EAT-Lancet diet index

To assess adherence to the EAT-Lancet diet, we developed a dietary index based on the diet's specified target intakes and reference ranges [24]. Food groups were classified as either emphasized foods or limited foods based on our interpretation of the EAT-Lancet diet descriptions. It was futher guided by the EAT-Lancet reference values provided in the supplemental materials of the EAT-Lancet report [Supplemental table S2, p. 24]. If we were hesitant about the scoring direction, we reached out to representatives of the EAT-Lancet Commission. The rules for scoring are described in **Table 4**. The index includes 14 food components, each scored from 0 to 3 points: a score of 0 reflects low adherence, while a score of 3 reflects high adherence. Seven components were assigned to the emphasized category and seven to the limited category. The total score can range from 0 (no adherence) to 42 (full adherence, i.e. 14 components × 3 points).

Table 4. The EAT-Lancet diet index.
The score developed for **Paper I** [170] based on the targets and recommended ranges of the diet as described by Willett et al. [24].

	Food components in EAT-Lancet diet index[1]	Target intake (reference interval)[2]	3 pts	2 pts	1 pt	0 pts	Criteria for score distribution
EMPHASIZED INTAKE	Vegetables	300 (200–600)	>300	200–300	100–200	<100	Positive score 3 pts = intake above target intake 2 pts = lower limit of reference interval up to target intake 1 pt = 50–100% of lower limit of reference interval 0 pts = < 50% of lower limit of reference interval
	Fruits	200 (100–300)	>200	100–200	50–100	<50	
	Unsaturated oils	40 (20–80)	>40	20–40	10–20	<10	
	Legumes	75 (0–150)	>75	37.5–75	18.75–37.5	<18.75	Positive score, adjusted[3] 3 pts: intake above target intake 2 pts: 50–100% of target intake 1 pt: 25–50% target intake 0 pts: 0–25% of target intake
	Nuts	50 (0–100)	>50	25–50	12.5–25	<12.5	
	Wholegrains	232	>232	116–232	58–116	<58	
	Fish	28 (0–100)	>28	14–28	7–14	<7	
LIMITED INTAKE	Beef and lamb	7 (0–14)	<7	7–14	14–28	>28	Inverse score 3 pts: intake below target intake 2 pts: target intake to upper limit of reference interval 1 pt: 100–200% of upper limit of reference interval 0 pts: > 200% of upper limit of reference interval
	Pork	7 (0–14)	<7	7–14	14–28	>28	
	Poultry	29 (0–58)	<29	29–58	58–116	>116	
	Eggs	13 (0–25)	<13	13–25	25–50	>50	
	Dairy	250 (0–500)	<250	250–500	500–1000	>1000	
	Potatoes	50 (0–100)	<50	50–100	100–200	>200	
	Added sugar[4]	31 (0–31)	<31	31–62	62–124	>124	

[1]Food components in the index are based on the EAT-Lancet diet as grams per day, with some modifications. Vegetables are described as a single group, since no information about subgroups (i.e. green or red vegetables) was available in the MDC. Fat intake and quality are reflected as unsaturated oils and plant margarines, since no information about palm oil or lard was available. [2]Target and reference values from the EAT-Lancet diet, based on an energy intake of 2500 kcal, expressed in grams [24]. [3]Initial criteria for the positive score were not applicable, as the lower limit of the reference interval was set to 0 for those foods. [4]Since the upper limits of the reference interval and target were identical, we used an upper reference interval of target intake ×2 (=62 g). An upper limit of the reference interval of 62 g for added sugar is in line with the WHO recommendation of ≤ 10 E% [171].

Food groups in the EAT-Lancet diet

Intake of food was based on reported intakes in grams per day expressed in uncooked weight. Since the dietary data in the MDC did not fully match the EAT-Lancet food group definitions, several adaptations were required to harmonize the data with the reference diet (**Table 5**).

Table 5. Food groups in the MDC.
The food groups were used to classify intake into the EAT-Lancet diet categories in **Paper I** [170].

Components in the EAT-Lancet diet index	
Wholegrains	Fibre-rich breakfast cereals (≥ 10% fibre), rolled oats, fibre-rich soft bread (>4.5% fibre), fibre-rich crispbread (≥ 10% fibre), fibre-rich rusks (>10% fibre). We evaluate intake of wholegrain foods except corn, rice, and pasta, because corn was grouped together with vegetables, and wholegrain alternatives of rice and pasta were grouped together with refined products. In order to adjust for not including corn, rice, and pasta and still relate the intake levels in the MDC to the suggested EAT-Lancet reference values, intake of wholegrains was divided by 0.75 based on the observation that corn, rice, and pasta contribute to 25% of total cereal intake in an ongoing study in Malmö [172].
Potatoes	Boiled potatoes, fried potatoes, deep-fried potatoes, potatoes included in dishes such as potato salad and moussaka.
Vegetables	All vegetables except legumes.
Fruits	Fruits and berries.
Dairy	Whole milk or derivative equivalents. Regular milk, low-fat milk, yoghurt and other fermented milk products, hard cheese, soft cheese, cream, butter, butter-based spreads. In the EAT-Lancet diet, all dairy foods are expressed as milk equivalents. The milk equivalents we used are based on the approach used by the Woods et al., based on 'total solids', and intakes of different dairy products were consequently multiplied with the following factors: whole milk 1.0, cheese 5.0, cream 2.7, and butter 6.5 [64].
Beef and lamb	Beef, lamb, minced meat of pork and lamb, processed meats with beef and lamb including sausages.
Pork	Pork, minced meat of pork, processed meats with pork including ham, bacon, and sausages.
Chicken	Chicken, turkey, duck, goose, and other poultry.
Eggs	Boiled eggs, fried eggs, and eggs in dishes such as omelet and pie.
Fish	Fatty fish, lean fish, fish products, shellfish.
Legumes	Dry beans, lentils, peas, soy. Targets and index refer to raw weight. Peas, lentils, beans, tofu, soy-containing meat replacement products.
Nuts	Peanuts or tree nuts. All nuts and seeds including peanuts, nut mixes such as almond paste.
Unsaturated oils	All plant oils and plant margarines.
Added sugar	Sucrose and monosaccharides except sugars in fruits and vegetables [173].

Because no direct data on wholegrain consumption were available in the MDC, cereal intake was recalculated to approximate wholegrain intake. Wholegrain consumption was estimated from fibre-rich cereal products, excluding corn, rice, and pasta, as these were either grouped with vegetables or could not be separated from refined grains. To allow comparability with the EAT-Lancet reference values, estimated wholegrain intake was divided by 0.75. This adjustment was based on data from the MDC indicating that the excluded foods contribute approximately 25% of total cereal intake [172].

Dairy intake was recalculated as milk equivalents, using the same factors applied by Wood et al. [64]. This approach is based on the 'total solids' content of different dairy products, with conversion factors as follows: whole milk = 1.0, cheese = 5.0, cream = 2.7, and butter = 6.5. Added sugar intake was calculated as the sum of sucrose and monosaccharides, excluding naturally occurring sugars in fruits, vegetables, and juices, as described by Ramne et al. [173].

Comparisons between different EAT-Lancet dietary indices

Since 2019, several scoring systems have been developed by different research groups to assess adherence to the EAT-Lancet diet. In **Paper II**, seven scores that had been published up to 2023 were compared, of which all could be applied on the DHC. Six scores could be applied to the MDC and MTC cohorts. The score by Cacau et al. [174] could not be used because it required data on the energy contribution of different food groups, which was not available in those cohorts.

The scores were first compared using a qualitative approach, guided by the criteria from Burggraf et al. [142]. Since I was the author of one score, I did not participate in its grading. We also examined how the scores categorized food groups into foods to promote, foods to balance, and foods to limit. Finally, we assessed the associations of the scores with mortality in all cohorts, with stroke in the MDC and DCH, and with GHGE in the MDC.

Dietary climate impact

In this work, adherence to the EAT-Lancet diet was considered an indicator of reduced environmental impact, as defined using the six planetary boundaries considered in the first version of the EAT-Lancet report. To specifically evaluate GHGE of participants' diets, climate impact of reported food intake was estimated using life cycle assessment (LCA) data in **Paper II**, **Paper IV**, and **Paper V**. The LCA approach allows for the quantification of GHGE associated with food production and distribution, providing a comprehensive measure of the climate impact of foods.

The dietary climate impact was calculated by multiplying GHGE per kg of food by the daily food intake levels from the MDC.

Life cycle assessment (LCA) sources and assumptions

The climate data used in the papers underlying this thesis were primarily sourced from Hallström et al. [53]. These data were based on life cycle assessments (LCA) calculated to be representative for Swedish consumption. The climate impact values of specific foods are calculated as weighted averages of climate impact data representative for production systems feeding the Swedish population, either from national production or via food import. The share of self-sufficiency and production origin of imported food was based on national statistics [53]. The system boundaries account for GHGE from cradle to consumer and included emissions from food waste along the system studied (**Figure 19**), whereas emissions from land-use change and changes in soil carbon were not captured. The climate data were mainly based on calculations using 100-year global warming potential factors[8]. As food intake in the MDC was mainly reported as raw weights, emissions from home cooking were not included in the GHGE estimates applied. Dietary GHGE were expressed as kilograms of CO_2-equivalents (kg CO_2-eq) per person and year. See example of GHGE values in **Table 6**.

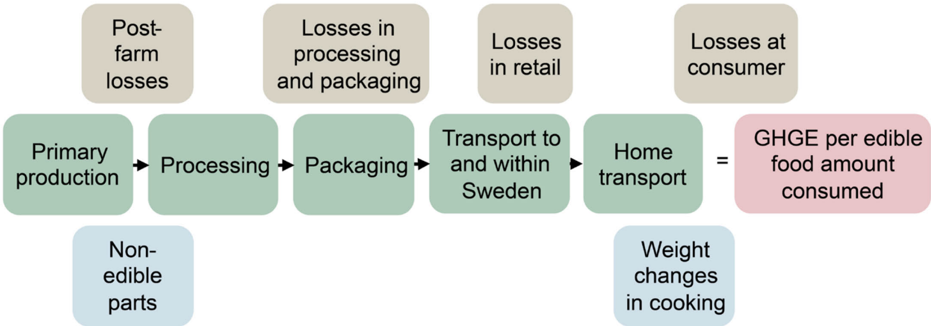

Figure 19. System boundaries in life cycle assessments (LCAs) on which included papers are based.
Illustration of the system boundaries of climate data used in this thesis. Figure adapted Hallström et al. [53]. Licensed under CC BY 4.0.

[8] For animal-based foods and rice, GWP factors from IPCC AR5 (2014) were used, accounting for climate–carbon feedback (Methane (CH_4) = 34; Nitrous oxide (N_2O) = 298). Due to data limitations, older factors from IPCC AR4 (2007) (Methane = 25), were applied for other plant-based foods.

Dietary GHGE were linked to individual food intake data in the MDC. Unique emission factors were assigned to all 117 food groups within the dietary dataset, and total daily GHGE for each participant were calculated by summing emissions from all reported food items. Intake reported in raw weight was matched with climate data per unit of uncooked weight, and cooked food intake was matched with data per unit of cooked weight. Accounting for cooking-related weight changes may influence GHGE estimates by up to 30% [55], and was therefore considered an important step in the analysis.

Table 6. Examples of dietary GHGE (kg CO_2-eq per kg edible weight) for different food groups. The foods are grouped into low, medium, and high impact based on values from Hallström et al. [53].

Low climate impact (< 2 kg CO_2-eq/kg)	**Medium** (2–5 kg CO_2-eq/kg)	**High** (> 5 kg CO_2-eq/kg)
Root vegetables	Garden vegetables	Beef
Potatoes	Chicken	Lamb
Cabbage	Fish	Pork
Legumes	Eggs	Cheese
Grains	Cream	Butter
Bread	Rice	Shellfish
Fruit	Vegetable oils	
Berries	Nuts and seeds	
Milk, yoghurt	Sweets, candy	
	Snacks	
	Wine and liquor	

For food items not covered by Hallström et al. [53], such as lard, coconut fat, industrial soups, nutritional powders, and powdered sauces, data from the RISE Climate Database [175] were used. For mutton, updated values were obtained from Moberg et al. [62]. These databases were chosen for their compatibility with the system boundaries and functional units used in Hallström et al. (i.e. emissions per kg raw or cooked food at the retail stage). To harmonize data from RISE, adjustments were made for emissions related to packaging, home transport, cooking, and food losses at retail and consumer stages, using the conversion factors described by Hallström et al. [53]. All external data were harmonized to align with the system boundaries used in this study. Reported dietary intakes were adjusted for non-edible components and weight changes during preparation to ensure accurate matching with GHGE values. All values were manually reviewed to confirm consistency in assumptions and units.

For some foods, such as certain vegetables, fruits, berries, lean fish (<5% fat), and fatty fish (>5% fat), intake data were available only for broad categories. To increase the quality of the climate impact assessments these food categories were broken down to more specific food groups for which climate data were available. Intake levels of plant foods were estimated based on Swedish category averages calculated from national consumption data [176]. For fish, weighted average consumption of the most commonly consumed species in Sweden (cod, Alaska pollock, and saithe for lean fish; salmon and herring for fatty fish) were applied using national consumption statistics published by RISE [177].

Other food groups with considerable uncertainty included sweets and snacks, where a single LCA value was used to represent the entire category (for example, potato chips for 'snacks, chips, etc.'). In reality, both climate impact and consumption vary across items within these groups. For a few categories where multiple items were grouped together, such as rice and pasta or fresh fruits, assumptions about consumption proportions were informed by intake patterns from a national dietary survey conducted in 1997–1998 [176].

Climate impact from spices, broth, and vinegar was excluded due to limitations in both LCA data and intake information. These items were reported within broad food groups that combined liquids and dried products, making precise estimation difficult. Moreover, their total intake was very low, and their contribution to overall climate impact was therefore considered negligible. Fortification and supplementation were also excluded from the climate estimates, as these involve minimal quantities and lack consistent LCA data, and their contribution to total dietary GHGE is assumed to be negligible for the same reasons.

Modelling dietary GHGE[9]

When preparing **Paper IV** and **Paper V**, it became evident that estimates of dietary GHGE in previous studies were difficult to compare. Different LCA databases had been used, often with varying system boundaries and assumptions, which influenced the results. Furthermore, dietary GHGE had been modelled in different ways: expressed per day, per kcal, or per kg of food. Another approach applied was to standardize food intake per energy unit and then apply the environmental impact data. Energy adjustment procedures also varied across studies. To illustrate these methodological differences in studies of mortality and disease, **Table 7** summarizes key characteristics of selected cohort studies that have investigated dietary GHGE in relation to health outcomes.

[9] The background and rationale for the modelling approaches to dietary GHGE are presented here in the Methods section, even though some of this information could also be seen as results and reported in the Results section.

Table 7. Comparisons of different modelling approaches for dietary GHGE, mortality and disease in previous studies.
From **Paper IV**[178].

	kg GHGE/day	kg GHGE/kcal	kg GHGE/kg food	
Study	Biesbroek et al. [179]	González et al. [180]	Laine et al. [181]	Watanabe et al. [182]
GHGE	kg/day	Food groups standardized by 2000 kcal. GHGE applied to the standardized food groups.	kg/kg food	kg/kg food
LCA-data from	Blonk Consultants	Clune et al. [183]	SHARP	Production-based Japanese input-output table (IOT)
Mean GHGE	3.9 kg	3.0 kg	6.0 kg	2.8 kg
Mean GHGE in lowest/highest group	Q1/Q4 2.9/5.1	T1/T3 2.1/4.0	Q1/Q5 3.6/8.4	Q1/Q5 1.6/2.6
Characteristics of highest GHGE group	Younger, higher energy intake, higher BMI, male	*Not reported*	*Not reported*	Younger, female
Covariates [Stratified by]	Sex, with and without energy [age]	Sex [recruitment centre, age]	Age, marital status, education, physical activity, smoking, BMI	Age, sex, BMI, smoking, alcohol, marital status, occupation, sleep, energy, physical activity, history of diabetes or hypertension
Study results	No significant association with mortality	Higher risk of mortality, CVD and type 2 diabetes	Higher risk of all-cause mortality, CHD-mortality, CVD-mortality, and cancer mortality	U-shaped relation with all-cause mortality

With the aim of better understanding how different approaches influence basic estimates, I applied several methods in the MDC (**Table 8**), some of which were used in the papers included in this thesis. In the first approach, dietary GHGE were summarized per day, showing a mean of 5.9 kg CO_2-eq for Swedish adults (5.4 kg for women and 6.7 kg for men). Higher GHGE was associated with being younger, having a higher energy intake, and being male. In the second approach, GHGE were related to energy intake. The mean energy intake was 2279 kcal per day, corresponding to 2.6 kg CO_2-eq per 1000 kcal. Among women, the mean energy intake was 2031 kcal and 2.6 kg CO_2-eq per 1000 kcal, and among men, 2635 kcal and 2.7 kg

CO_2-eq per 1000 kcal. Participants in the highest GHGE per 1000 kcal quintile were younger, had a higher BMI, a lower total energy intake, and were more often female.

Table 8. Mean values and characteristics of participants in the highest GHGE groups in MDC, using different explorative approaches.
Values are based on assessments from the MDC, with the aim of comparing different approaches of analysing dietary GHGE.

	1. kg CO2 eq/day	2. *kcal/day	3. *kg food & drink/day	4. *kg bodyweight
Mean in MDC (min–max)	5.9 (1.2–24)	2279 (516–8396)	3.5 (1.0–9.9)	73 (31–170)
GHGE (CO2-eq)/*	-	2.6 (0.69–8.74)/1000 kcal	1.7 (0.34–5.64)	0.08 (0.02–0.35)
Characteristics of highest GHGE group	Younger, higher energy intake, male	Younger, higher BMI, lower energy intake, female	Younger, lower BMI, higher energy intake, male	Younger, lower BMI, higher energy intake, female

The third approach considered the total mass of foods and drinks consumed, averaging 3.5 kg per person and day. This corresponded to 1.7 kg CO_2eq per kg of food and drinks. High GHGE values were associated with being younger, having a lower BMI, higher energy intake, and being male. Lastly, a fourth approach was explored, in which GHGE was expressed in relation to body weight. The mean was 82 grams of GHGE per kg body weight. Here, high GHGE values were associated with being younger, having a lower BMI, higher energy intake, and being female. An additional possible approach, not conducted here, would be to standardize food group intakes to a fixed energy level (for example, 2500 kcal).

To explore the relationships between different expressions of dietary GHGE, energy intake, and BMI, pairwise correlation coefficients were calculated and visualized in a correlogram (**Figure 20**). Strong correlations were observed between GHGE per day and GHGE per kg body weight, as well as between GHGE per day and total energy intake. Emissions per 1000 kcal were moderately correlated with GHGE per day and with GHGE per kg food but negatively correlated with energy intake. GHGE per kg of food were moderately correlated with GHGE per day. These patterns suggest that different methods of expressing dietary GHGE emphasize distinct aspects of the data, for example whether variation is mainly driven by total energy intake, body size, or the overall mass of foods consumed.

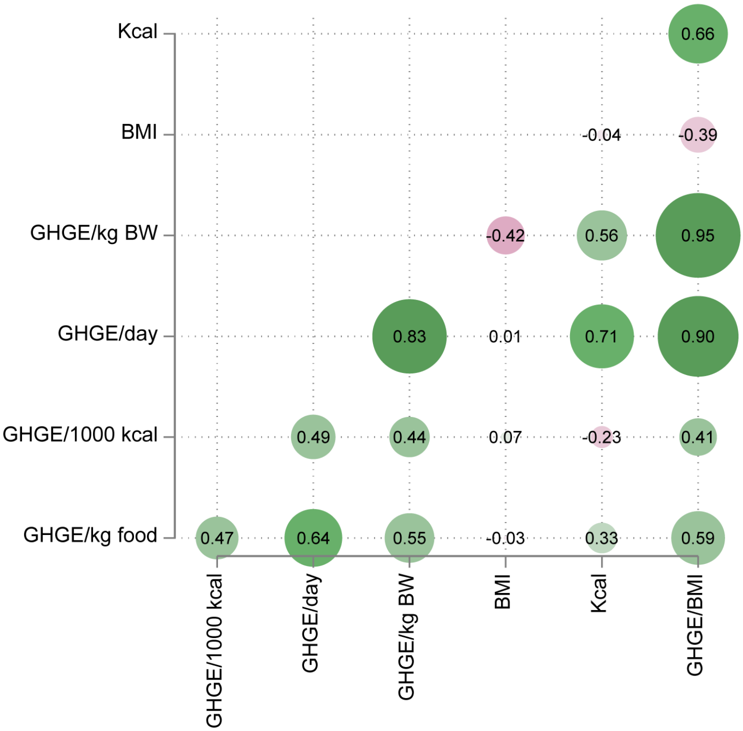

Figure 20. Correlogram of different GHGE metrics, BMI, energy intake (kcal), and body weight (BW).
The figure illustrates Pearson correlation coefficients between the variables. Greenhouse gas emissions reported in kg of CO_2-eq.

For **Paper IV**, we chose dietary GHGE per day as the exposure, adjusted for energy intake in the main analyses. This decision was based on the rationale that mortality and disease risk often are influenced by total energy intake, and our primary interest was the association with GHGE independent of energy. We also modelled dietary GHGE per day without energy adjustment, adjusted for energy using the residual method, and expressed as GHGE per kg of food in supplementary analyses.

For **Paper V**, which focused on micronutrient intake and status, the main model was based on dietary GHGE per day as the exposure, without energy adjustment. The rationale for that was that micronutrient intake is strongly dependent on total energy intake [145], and dietary nutrient recommendations and climate goals are provided as absolute values per day or year. Adjusting for energy would therefore risk removing the associations of primary interest.

In **Paper II** GHGE per day was the outcome in the analyses of adherence to the EAT-Lancet diet, and we adjusted for total energy intake to ensure consistency with the models used for mortality and stroke.

An overview of the GHGE modelling approaches applied in the papers included in this thesis is presented in **Table 9**.

A comprehensive assessment of how different modelling strategies for GHGE influence estimates of micronutrient intake has been conducted in another paper [145], which is not included in this thesis.

Table 9. Overview of different modelling approaches of dietary GHGE, for papers included in this thesis.

	Exposure		Outcome
	Paper IV	**Paper V**	**Paper II**
GHGE/day	X	Main analysis	
GHGE/kg food	X		
GHGE/1000 or 2000 kcal	X	X	
GHGE/day adjusted for energy (standard method)	Main analysis		X
GHGE/day adjusted for energy (residual method)	X		

Statistical analyses

The statistical analyses in this thesis were designed to address the overarching aim of exploring how environmentally sustainable diets relate to nutritional adequacy and long-term health outcomes. The intention was to apply appropriate analytical methods while keeping the approach as straightforward and transparent as possible, and to maintain parsimony by avoiding unnecessary analytical complexity. Each paper used methods suited to its specific research question and type of data. The analytical process began with careful planning and evaluation of potential causal structures, followed by descriptive and inferential analyses examining associations between dietary exposures and health outcomes. Life-course and lifestyle factors were considered as potential confounders, and models were progressively adjusted to evaluate their influence on observed associations.

Analytical preparation

The analytical processes begun with planning and idea generation. In some projects, a Directed Acyclic Graph (DAG) has been constructed. A DAG is a diagram that visually represents hypothesized causal relationships between variables and helps identify potential biases and confounding factors [184]. By outlining assumed connections, DAGs support the design and analytical steps required to correctly estimate causal effects.

For **Paper I**, **Paper II**, and **Paper III**, where the EAT-Lancet diet was the exposure, such causal assessments were relevant. In contrast, for **Paper IV** and **Paper V** focusing on dietary GHGE, the analyses were not based on assumed causal relationships but rather on associations. In this context, causality originates from the food groups consumed, while GHGE functions as a composite measure. Confounders were defined as variables related to both exposure and outcome but not acting as mediators on the causal pathway.

The different studies included in this thesis applied statistical methods suited to their specific research aims. An overview is provided in **Table 10**.

Table 10. Overview of statistical methods used in papers included in this thesis.

	Paper				
	I	II	III	IV	V
Descriptive statistics	X	X	X	X	X
Systematic review		X			
Qualitative assessment		X			
Correlation	X		X		X
Linear regression/General linear model	X	X	X		X
Logistic regression			X		X
Kaplan–Meier curves	X				
Cox regression	X	X		X	
Cubic splines	X	X		X	

Systematic review

A literature review was conducted for all papers, and for **Paper II** a systematic review was performed. The review was registered in PROSPERO (CRD-42021286597) and reported according to PRISMA guidelines. We searched PubMed, Embase, Scopus, and Web of Science for prospective cohort studies assessing adherence to the EAT-Lancet reference diet in relation to health outcomes.

Qualitative assessment

In **Paper II** we conducted a qualitative comparison of published diet scores representing the EAT-Lancet reference diet. For each identified score we extracted key features, including the number and types of dietary components, the scoring system (binary, ordinal, or proportional), and the possible score range. Each score was then compared with the original EAT-Lancet reference diet. To assess the quality of score construction, we applied criteria adapted from Burggraf and colleagues, covering aspects such as index dimensions, components, scaling procedure, cut-off values, and valuation function [142].

Descriptive statistics and modelling approaches

In all studies included in this thesis, descriptive statistics were used to summarize the basic characteristics of participants and their exposures. Such tables condense large datasets into simplified summaries, assisting readers in evaluating the generalizability of study findings. We initially avoided significance testing in these tables, in line with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines [185, 186] and other guidance [187]. This decision was based on concerns that significance tests may encourage misinterpretation and inappropriate comparisons, shifting the focus away from the primary research objectives. In some papers, however, significance tests were later added during the peer-review process at the request of reviewers.

Beyond summarising participant characteristics, the way baseline data are presented can also influence how results are interpreted. I believe that the description of baseline characteristics is not a neutral exercise, as it depends on how the exposure is defined. For instance, when studying dietary GHGE, describing quintiles based on GHGE per 1000 kcal provides a different picture of the population than quintiles based on GHGE per day later adjusted for total energy intake. Similarly, the choice between overall quintiles, sex-specific quintiles, increments of 10%, or predefined categories influences how the baseline population is portrayed.

We used different approaches to categorize the participants in the different papers. In **Paper I** participants were categorized into five groups based on their EAT-Lancet diet adherence scores, with group boundaries set manually to achieve approximately equal group sizes. In **Paper II** and **Paper III** we assessed adherence based on 10% increment scores to make comparison between EAT-Lancet scores possible. In **Paper IV** and **Paper V** we categorized participants into sex-specific quintiles of dietary GHGE per day.

Correlation analysis

Correlation analysis is a statistical method used to measure the strength and direction of the relationship between two variables [188]. A positive correlation indicates that both variables increase together, whereas a negative correlation indicates that one decreases as the other increases. Correlation does not imply causation but can highlight important patterns in the data.

In **Paper I** we examined correlations between different food groups to highlight potential co-consumption patterns. In **Paper III** we assessed the relationships between several EAT-Lancet diet scores, visualized in a correlogram. In **Paper V** we studied the correlations between dietary micronutrient intake and corresponding micronutrient status in blood or plasma. Across all papers, correlation analyses were descriptive, providing an overview of the strength and direction of associations.

Regression analysis

To move beyond simple correlations and explore potential causal relationships, we used regression analyses that allow adjustment for confounding factors [189]. In regression, a line or curve is fitted by minimizing the difference between observed and predicted values, typically using the least squares method. Linear regression estimates average outcomes: by inserting a given exposure value (x), one can calculate the predicted average outcome (y). These predictions, also called estimated marginal means or margins, are reliable within the observed range of data (interpolation) but uncertain beyond it (extrapolation) [189].

In our analyses, we applied both continuous variables (e.g. the EAT-Lancet index, dietary GHGE) and categorical variables (e.g. tertiles, quartiles, quintiles). Modelling continuous variables retains all values and fits the regression line closely to the data. Grouping reduces values to group means, which limits the influence of outliers but also lowers statistical power, making significant associations harder to detect.

In **Paper I** we used the general linear model (GLM), which is an extension of linear regression [190]. Whereas linear regression often models the relationship between a continuous outcome and a single predictor, the GLM framework accommodates multiple predictors and both continuous and categorical independent variables within the same model.

When the outcome was binary, such as nutrient intake above average requirement or recommended intake, we applied logistic regression. This approach provides results as odds ratios or probabilities of the outcome.

We used regression models in all papers included in this thesis except **Paper V**.

Survival analyses

Survival analysis, or time-to-event analysis, is well suited for longitudinal studies where participants are followed until a defined outcome occurs [188]. Despite the term 'survival', outcomes are not limited to mortality but may also include disease incidence or recurrence.

To visualize time-to-event data in **Paper I**, Kaplan–Meier curves were used. These curves estimate the probability of remaining event-free (in this case, alive) over time and allow intuitive comparison across groups [188]. The stepwise declines indicate when events occur, and differences between curves reflect variation in risk across exposure categories.

Cox regression

A common analytical approach in survival analyses is the Cox proportional hazards model, which enables adjustment for confounders. We applied this model to study associations between the EAT-Lancet diet and risk of mortality (**Paper I** and **Paper II**), and stroke (**Paper II**) and between dietary GHGE and risk of mortality, cardiovascular disease, and diabetes (**Paper IV**). Hazard ratios express relative risk, comparing the hazard of an event in one group to that of a reference group. In **Paper I**, we also assessed absolute risks to complement relative measures. A central assumption of Cox regression is proportional hazards, meaning that hazard ratios remain constant over time. To assess the proportional hazards assumption in **Paper I**, interactions between time and covariates were tested for all-cause and cause-specific mortality. In **Paper IV**, the assumption was evaluated using Schoenfeld residuals and log-rank tests. Although the methods differ slightly, both aimed to assess the same underlying assumption. In both papers, the assumption was not fully met for some variables. Stratified analyses were therefore performed but did not materially change the results. Because the violated covariates differed across outcomes and models in **Paper IV**, this would have required stratifying for different variables in each analysis. Fully stratifying all models, even for variables that met the assumption, would have added unnecessary complexity. As the estimates were essentially unchanged, unstratified models were retained in the main analyses.

Restricted cubic splines

In **Paper I**, **Paper II**, and **Paper IV**, adjusted Cox proportional hazards regression models were further explored using restricted cubic splines to visualize potential non-linear relationships. The EAT-Lancet diet score and dietary GHGE were divided into segments at predetermined knots, following Harrell's recommended percentiles [191]. This approach allowed for flexible modelling of potential non-linear associations without imposing a strictly linear assumption.

Covariates and adjustments

We fitted models with increasing levels of adjustment, from crude to fully adjusted. Covariate selection was guided by hypothesized causal structures using DAGs. Common covariates across papers included age, sex, smoking, alcohol consumption, physical activity, and education. BMI was added in a separate model to explore its potential role as a mediator. Total energy intake was included when appropriate, for example in analyses of disease and mortality. For analyses of micronutrient status markers, storage time of blood samples was additionally adjusted for. All analyses were based on complete cases, with individuals missing covariate data excluded.

Sensitivity analyses varied by paper. Examples include exclusion of participants with events occurring within the first two years of follow-up, potential energy misreporters, and those reporting previous dietary change. In some analyses, participants with baseline cancer, diabetes, or cardiovascular disease were also excluded, either individually or in combination.

Energy adjustment

Across the papers, total energy intake was either adjusted for directly, considered in sensitivity analyses, or discussed in relation to the research question. The choice of approach depended on whether energy intake was viewed as a confounder, mediator, or part of the exposure. A separate paper is dedicated to the implications of different methods for energy adjustment in relation to micronutrient intake [145], which is not included in this thesis.

Statistical software

Different statistical software programs were used across the papers. Analyses were primarily conducted in SPSS, Stata, and R, with specific versions applied in each study. In some cases, complementary functions such as restricted cubic splines or absolute risk estimates were performed in additional software. An overview of the program versions used is provided in **Table 11**.

Table 11. Overview of statistical software used in the papers included in this thesis.

	Program version used in papers				
	I	II	III	IV	V
SPSS	27.0				27.0
Stata	15.0	17.0	18.0	19.0	18.0
R	4.0.2			4.4.0	

Ethical considerations

When conducting research, it is essential to ensure that the benefits outweigh the risks involved [192]. Risks may relate to both physical harm and the integrity of participants. Several ethical considerations were therefore central in this doctoral thesis, particularly concerning confidentiality and personal integrity when handling sensitive data. All data from the MDC were processed according to the 'Personal Data Act', and researchers only had access to coded data, thereby reducing the risk of privacy violations. Participants in the MDC provided written informed consent at baseline, including consent for linkage of their data to relevant registries. This consent was documented in medical records or a separate registry, and a copy was given to each participant. The risks posed to participants in the MDC in relation to my work were minimal, as analyses relied exclusively on previously collected data, such as dietary information and blood samples. Participants were not expected to receive personal benefits beyond the general value of contributing to research. The main ethical approval was granted by the Ethics Committee at Lund University (original approval DNR LU 51-90), with complementary approvals for the micronutrient analyses.

For the Danish Diet, Cancer and Health Cohort (DCH), all participants provided written informed consent at baseline. Ethical approval was obtained from regional scientific ethics committees in Denmark, and linkage to health registries was carried out under national data protection regulations. For the Mexican Teachers' Cohort (MTC), written informed consent was also obtained, and ethical approval was granted by the Institutional Review Board at the National Institute of Public Health in Mexico. When including data from the DCH and MTC in the present work, only the local researchers responsible for these cohorts had direct access to identifiable data and conducted all analyses on site. The collaborative analyses shared within this doctoral thesis were therefore based exclusively on harmonized, coded data, ensuring participant confidentiality.

All studies included in this thesis comply with the Declaration of Helsinki and its subsequent revisions [193].

Results and discussion

Results from the five studies underlying this thesis provide insights into how more environmentally sustainable diets influence both short- and long-term health. The first part presents result on adherence to the EAT-Lancet diet in the MDC and its association with mortality, followed by a comparison of alternative scoring systems across three cohorts. Next, micronutrient adequacy is assessed using both intake data and biomarkers. Further, the thesis addresses climate impact of diets in relation to major health outcomes, and the relationship between dietary GHGE and nutritional adequacy. Methodological aspects such as score construction, energy adjustment, and exposure definition are discussed to explain variations across studies and guide interpretation.

Adherence to the EAT-Lancet diet and associations with health and climate impact

Measuring adherence to the EAT-Lancet diet

In **Paper I**, we developed a new dietary index to evaluate adherence to the EAT-Lancet diet and examined its association with mortality. The index was applied to 22,421 participants in the MDC. Out of a maximum of 42 points, the mean adherence score was 17.9, with men scoring 16.8 and women 18.5 (**Figure 21**). Adherence was highest for the recommendations on poultry, fish, and fruits, and lowest for legumes, nuts and seeds, wholegrains, beef/lamb, and pork (**Figure 22**). It is important to note that the group with the highest adherence to the EAT-Lancet diet does not reflect full adherence, as intakes of several food groups still deviate considerably from the target levels.

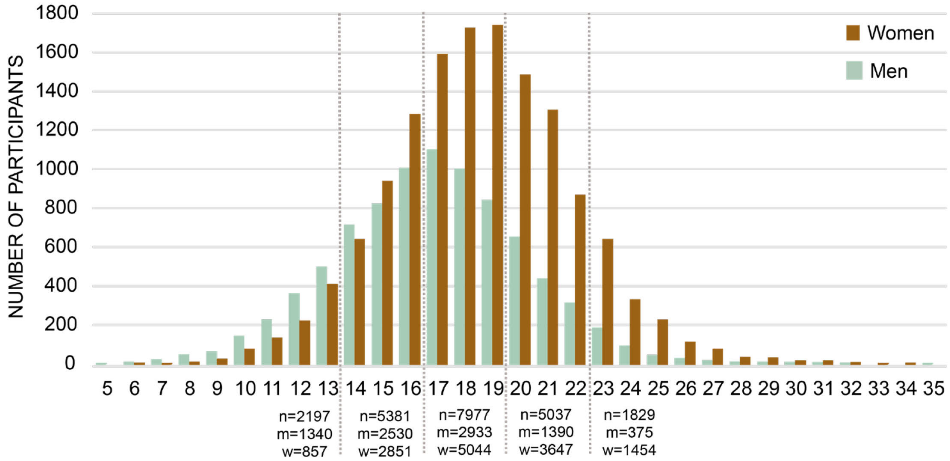

Figure 21. Distribution of adherence scores to the EAT-Lancet diet.
Distribution among 22,421 participants in the MDC. Scores could range from 0 to 42 points. Women showed slightly higher mean score (18.5) compared with men (16.8). Dotted lines marks cut-offs between the five groups used in the analyses. Adapted from from **Paper I** [170]. Licensed under CC BY 4.0.

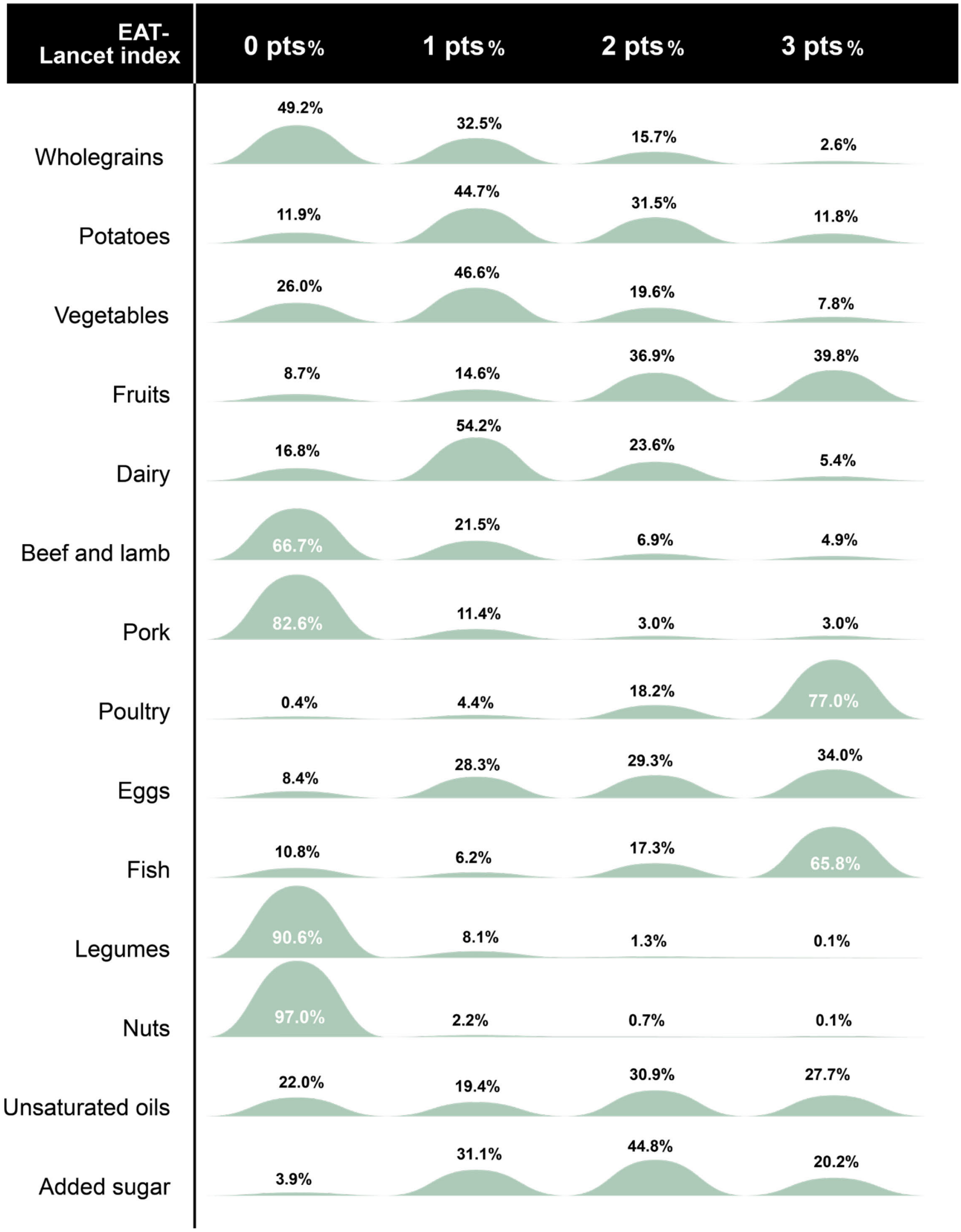

Figure 22. Distribution of the EAT-Lancet score points for the 14 food groups in the MDC. Distribution among 22,421 participants in the MDC. Adapted from from **Paper I** [170]. Licensed under CC BY 4.0.

Mortality in relation to the EAT-Lancet diet

During a mean follow-up of 20 years, 7030 deaths occurred, including 2655 from cancer and 2192 from cardiovascular disease. Participants with the highest adherence to the EAT-Lancet diet (≥ 23 points) had a significantly lower risk of mortality compared with those with the lowest adherence (≤ 13 points) (**Figure 23**). High adherence was associated with a 25% lower risk of all-cause mortality, a 24% lower risk of cancer mortality, and a 32% lower risk of cardiovascular mortality, in the fully adjusted model.

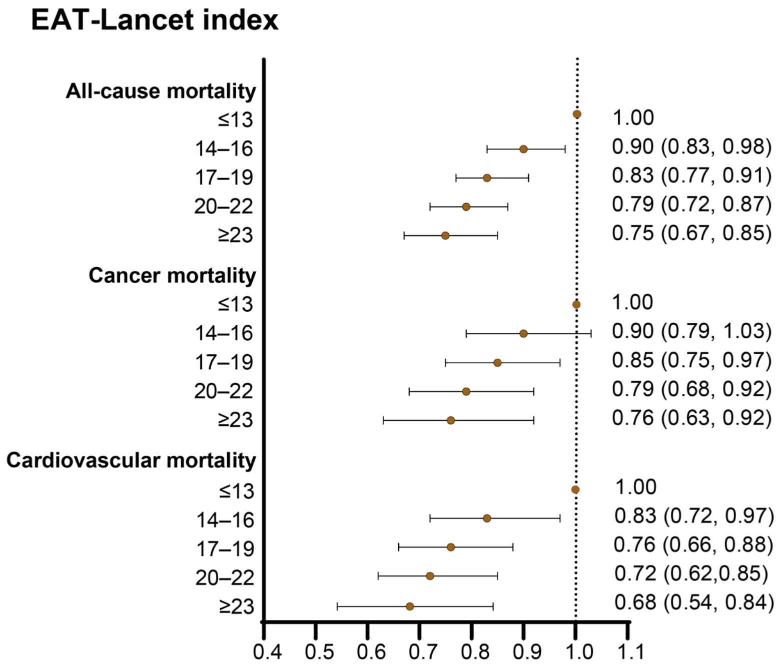

Figure 23. Hazard ratios (95% CI) for all-cause-, cancer-, and cardiovascular mortality across groups of the EAT-Lancet diet index in the MDC.
Estimated using Cox regression. Results are based on the fully adjusted model from **Paper I** [170]. Licensed under CC BY 4.0.

Using restricted cubic splines, we visualized that there was a consistent decline in mortality with higher EAT-Lancet scores **(Figure 24)**. At the food group level, higher intakes of wholegrains, vegetables, and fruits were positively associated with lower all-cause mortality, whereas higher egg consumption was linked to increased mortality risk, as illustrated in **Figure 24**. The low intake of legumes and nuts in this population limited the ability to assess their associations with mortality.

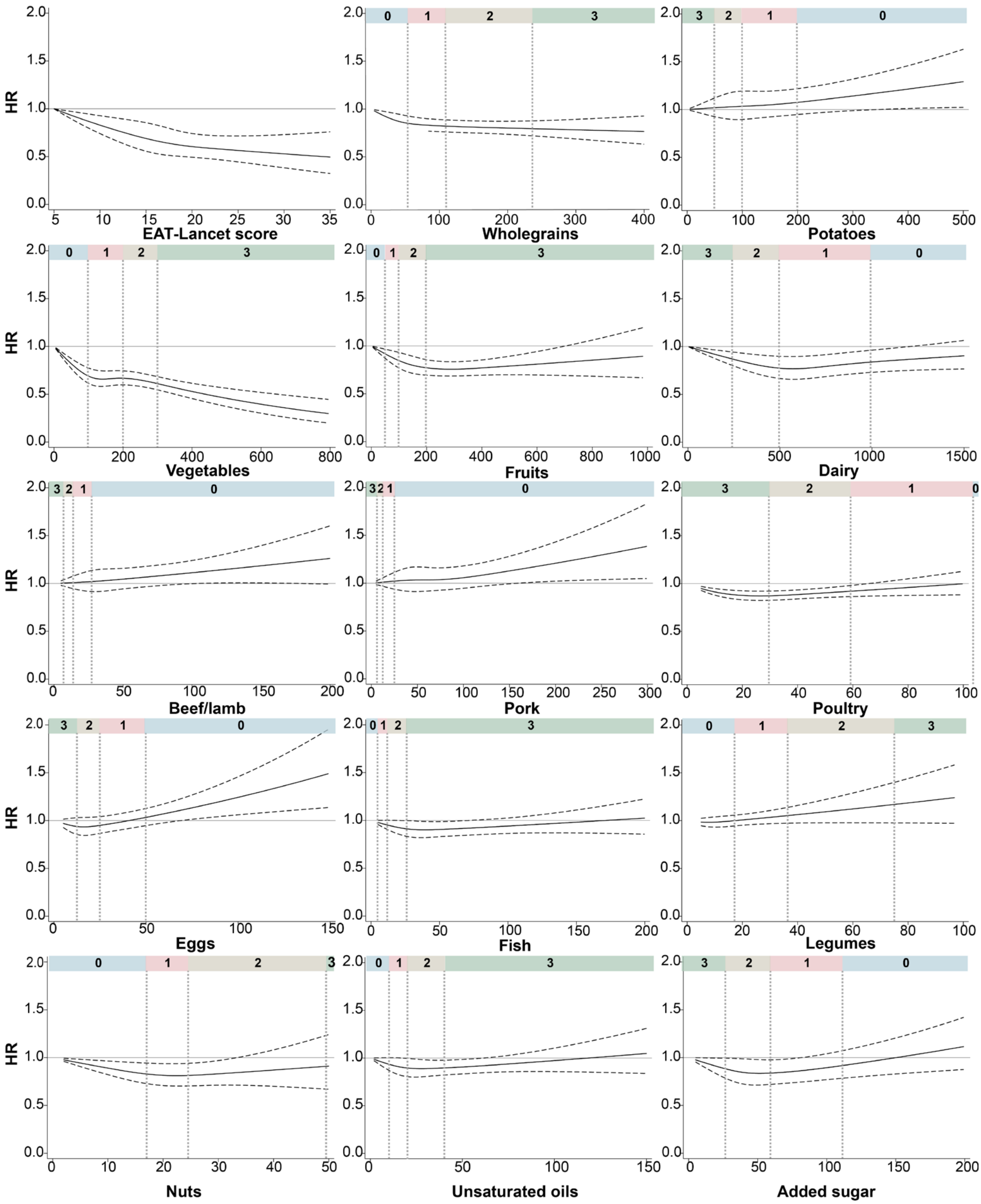

Figure 24. Restricted cubic splines for the total EAT-Lancet index and individual food components in relation to all-cause mortality in the MDC.

Analyses were conducted using fully adjusted Cox regression. Solid lines show hazard ratios and dotted lines show 95% confidence intervals. Food items are analysed as grams per day. Adapted from **Paper I** [170].

Paper I contributes to the overall thesis narrative by examining and providing results showing that higher adherence to the EAT-Lancet diet is associated with lower mortality, thereby supporting the idea that diets aligned with environmental sustainability can also promote long-term health. By now, numerous studies have assessed long-term health outcomes associated with adherence to the EAT-Lancet diet showing positive associations. However, only a few studies have examined the EAT-Lancet diet in populations from low- or middle-income countries [194-197].

Comparing scores and assessing mortality and stroke

In **Paper II,** we included participants from three cohorts: the Malmö Diet and Cancer Study (MDC, n = 20,973), the Danish Diet, Cancer and Health Cohort (DCH, n = 52,452), and the Mexican Teachers' Cohort (MTC, n = 30,151). We compared seven different scoring systems designed to capture adherence to the EAT-Lancet diet. Interpretations of the EAT-Lancet diet varied widely across these approaches, resulting in differences in how foods were grouped into three broad categories: foods to promote, foods to balance, and foods to limit. Vegetables, fruits, and nuts were consistently classified as foods to promote or balance, and wholegrains were promoted in most scores. In contrast, added sugars, saturated fats, red meat, poultry, dairy products, tubers and starchy vegetables, and eggs were more often categorized as foods to balance or to limit. **Paper II** provided an overview of these approaches, which has since been complemented by an EAT-Lancet score developed at Harvard [198] as illustrated in **Figure 25**.

Figure 25. Summary of how each food group in the EAT-Lancet reference diet is incorporated into some of the most common EAT-Lancet diet indices [199].
Adapted from **Paper II**, updatedin a mini-review about the EAT-Lancet diet [199]. Licensed under CC BY 4.0.

The construction of the scores also differed. Some were population-based, classifying intakes relative to the distribution within the study population (e.g. above or below the median), whereas others relied on fixed criteria, either as absolute thresholds expressed in grams per day or as relative thresholds based on the contribution of food groups to total energy intake. The scoring structures varied as well: some were binary, while others were ordinal or proportional. In addition, some scores incorporated energy adjustment, whereas others did not. An overview of the qualitative assessment of the different scores from **Paper II** is provided in **Table 12**.

Table 12. Description of EAT-Lancet diet scores.
Scores as identified through the systematic review conducted for **Paper II** [168], with addition for the score from Bui et al. for this thesis [198].

First author, year (ref)	Name of score	n components (positive, balanced, negative)[a]	Type of score[b]	Score description	Possible score range
Knuppel, 2019 [200]	EAT-Lancet diet score	14 (3, 1, 10)	Binary score, fixed criteria (g/day)	1 point if intake is above or below set intake threshold, 0 if not. Intakes are based on g/day. The total score is the sum of points for each component.	0–14
Hanley-Cook, 2021 [201]	EAT-Lancet diet score with minimum intake values	14 (0, 13, 1)	Binary score, fixed criteria (g/day)	1 point if intake is within the recommended range, intake 0 if not. Intakes are based on g/day. The total score is the sum of points for each component.	0–14
Cacau, 2021 [174]	The Planetary Heath Diet Index, (PHDI)	16 (5, 7, 4)	Proportional score, fixed criteria (/kcal)	0 points if no intake in emphasized foods or too-high intake in de-emphasized foods. Proportional score up to 10 points for optimal intake and, for balance foods, proportional score down to limit. Includes ratios of types of vegetables included, each up to 5 points. Intakes are based on caloric density from that food.	0–150
Trijsburg, 2021 [195]	World Index for sustainability and Health	13 (4, 9, 0)	Proportional score, fixed criteria (g/day)	0 points if below lower limit for emphasized foods or above limit for balance and de-emphasized foods. Proportional score between up to or down to optimal intake. Score of 10 within range for de-emphasized and balance foods or above threshold for emphasized foods. Intakes are based on g/day.	0–130
Kesse-Guyot, 2021[202]	EAT-Lancet diet index	14 (3, 0, 11)	Proportional score, population based (g/day)	Used a formula to derive the score: 100 x ((sum of all components ((a_i x cut-off$_i$ – (consumption$_{ij}$ x 2500 / energy intake$_j$)) / (cut-off$_i$))) / 14). a_i is 1 for limit components and -1 for components to promote. Each food has a specific cut-off. Intakes are based on g/day.	No set range
Stubbendorff, 2022 [170]	EAT-Lancet index	14 (7, 0, 7)	Ordinal score, fixed criteria (g/day)	Between 0 to 3 points according to level of adherence to the component. The total score is the sum of points for each component.	0–42
Colizzi, 2023 [203]	Healthy Reference Diet	14 (5, 7, 2)	Proportional score, fixed criteria (g/day)	0 point if no intake in emphasized foods or too-high intake in de-emphasized foods. Proportional score up to 10 points up to optimal. 10 points within optimal range. For foods to balance, proportional score to limit. Intakes are based on g/day.	0–140
Bui, 2024 [198]	Planetary Health Diet Index (PHDI)	15 (8, 1, 6)	Proportional score, fixed criteria (g/day)	0 point if no intake in emphasized foods or too-high intake in de-emphasized foods. Proportional score up to 10 points up to optimal (with exception of wholegrains). 10 points within optimal range. For foods to balance, proportional score to 2*limit. Intakes are based on g/day. All food groups are weighted as 1, except from non-soy legumes and soybeans/soy foods that are weighted 0.5 each.	0–140

We observed differences in associations with health outcomes both between the scores and across the cohorts (**Figure 26**). Among the evaluated indices, the scores developed by Stubbendorff and Colizzi were most accurate in classifying individuals according to the EAT-Lancet dietary targets. Higher adherence according to these two scores was consistently associated with lower risk of all-cause mortality in the MDC (HR per 10% increase: 0.88 for Stubbendorff, 0.89 for Colizzi) and the DCH (0.83 for both scores). In the Mexican Teachers' Cohort (MTC), associations were in the same direction but less precise due to fewer mortality events. In addition, higher adherence based on the Stubbendorff and Colizzi scores was associated with a reduced risk of stroke in both the MDC and DCH, with slightly stronger and more consistent associations in the DCH.

We concluded that although none of the seven EAT-Lancet scores could be clearly identified as superior across all evaluated aspects, the Stubbendorff and Colizzi scores emerged as the most suitable options, showing good consistency across cohorts and relevant associations with both health and environmental outcomes. We recommend using multiple scores in future studies to evaluate and strengthen the robustness of findings, given the importance of dietary recommendations for public health policy and environmental sustainability. While proportional scores provide a more nuanced distribution of participants, only a small proportion of individuals in the three cohorts fell within the intermediate ranges. Consequently, some of the proportional scores functioned more like binary scores in practice. Consistent with our conclusion that the choice of scoring approach should align with the study's purpose and context, a study from 2025 similarly emphasized that indices must be selected based on their applicability, underlying assumptions, and intended use [204]. The authors argued that binary scores offer a simplified yet valuable tool for surveys, observational studies, and public health applications, whereas proportional scoring allows a broader and more detailed understanding of dietary patterns in relation to health and sustainability. They further suggested that proportional approaches are particularly advantageous in precision-oriented research, such as clinical or epidemiological studies. Another study comparing different scores found that the EAT-Lancet index from our group produced higher adherence values overall, whereas a newly developed score (WISH 2.0) better reflected actual food consumption patterns and regional dietary differences [205].

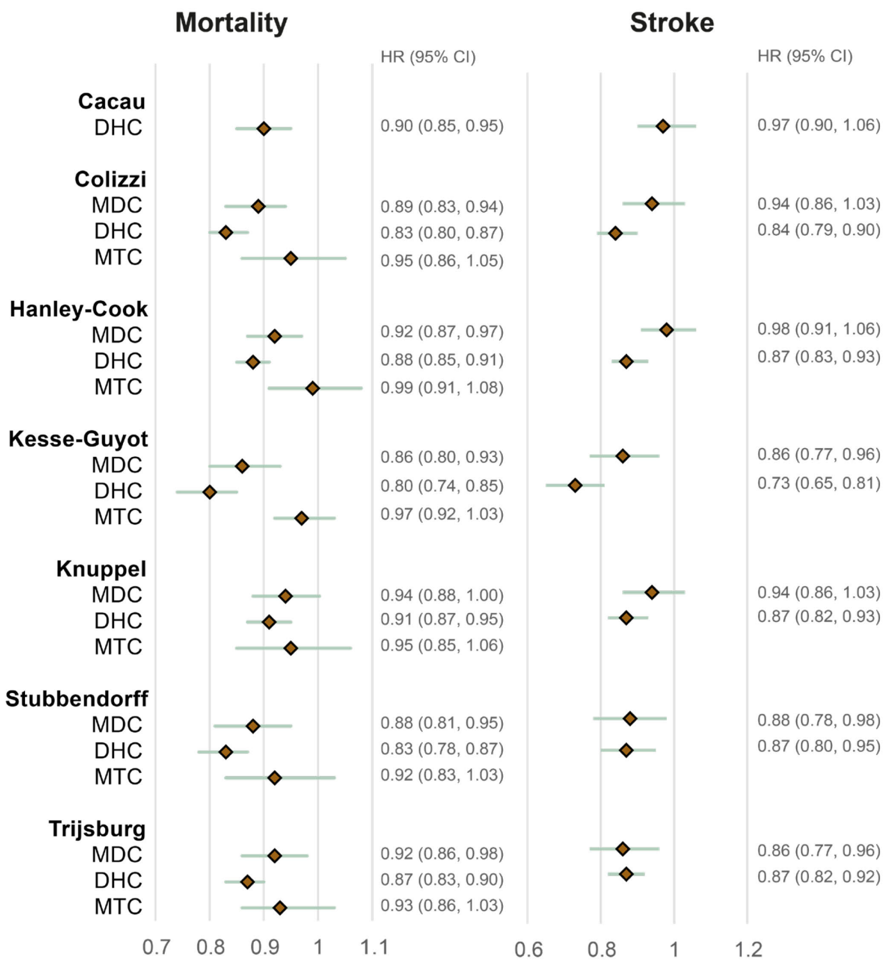

Figure 26. Hazard ratios (95% CI) for all-cause mortality and stroke incidence across different EAT-Lancet diet indices in three cohorts.
The cohorts are: the Malmö Diet and Cancer Study (MDC), the Danish Diet, Cancer and Health Cohort (DCH), and the Mexican Teachers' Cohort (MTC). Results are based on Cox regression models fully adjusted for potential confounders, from **Paper II** [168].

Paper II contributes to the thesis narrative by demonstrating how methodological choices in score construction influence interpretations of adherence to the EAT-Lancet diet and its associations with health. Overall, these findings underscore the health benefits of adherence to the EAT-Lancet diet and support its potential to reduce mortality, providing evidence to inform both dietary guidelines and sustainable public health strategies.

Further work in which I have participated has examined the associations between adherence to the EAT-Lancet diet and multiple health outcomes. We have seen that higher adherence to the diet is associated with lower risk of diabetes [206, 207], coronary events [208], heart failure [209], and atrial fibrillation [210]. The diet has also been associated with reduced dementia risk and improved risk factors [211, 212]. In a mini-review summarizing existing evidence on mortality, cardiovascular disease risk, and type 2 diabetes, we concluded that higher adherence to the EAT-Lancet diet does not show any increased health risks and in most cases reduced them, as illustrated in **Figure 27** [199]. While we investigated cancer mortality, we have not investigated cancer incidence in the MDC. However, in other studies it has been shown that higher adherence to the EAT-Lancet diet is significantly associated with reduced cancer incidence and mortality [213, 214].

Alongside my work, many other publications have been published since 2019 examining the association between adherence to the EAT-Lancet diet and various health outcomes. Taken together, these findings indicate that the higher adherence to the diet promotes long-term health, strengthening the case for integrating health and environmental aspects into future dietary guidelines and sustainable public health strategies.

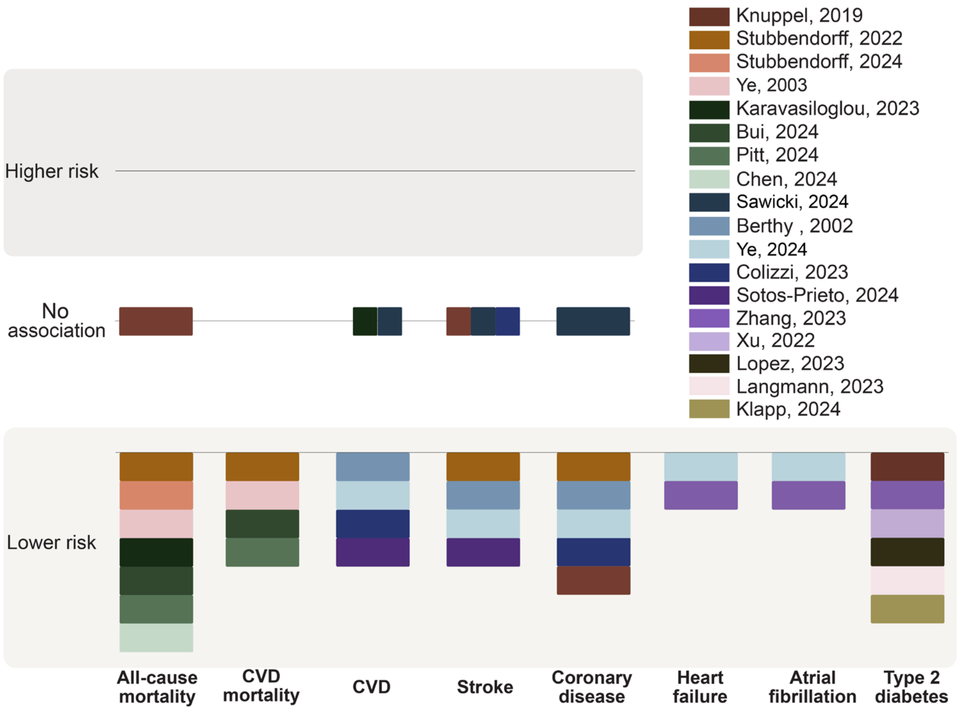

Figure 27. Overview of the results reported from prospective cohort studies investigating the associations between adherence to the EAT-Lancet diet and mortality, cardiovascular disease risk, and type 2 diabetes.
Obtained from Stubbendorff et al. [199]. Licensed under CC BY 4.0.

Micronutrient adequacy in the EAT-Lancet diet

When working on assessing long-term health outcomes associated with the EAT-Lancet diet, the question about whether the diet might come with shortfalls for micronutrient intake has remained. Its nutritional adequacy has been a topic of ongoing scientific debate. A key concern is whether the dietary pattern provides sufficient amounts of essential micronutrients such as vitamin B12, calcium, iron, and zinc [215, 216]. Although several simulation-based modelling studies have suggested that the EAT-Lancet diet is capable of meeting micronutrient requirements [25, 102, 217, 218], empirical evidence remains limited. Few studies have evaluated the diet's nutritional adequacy using self-reported dietary data [202, 204, 219-224], and even fewer had linked adherence to objective biomarkers of micronutrient status [221].

In **Paper III** we therefore studied the association between adherence to the EAT-Lancet diet, nutrient intake, and nutrient status in an observation study. As background, we first compared our findings with those from previous observational studies at that time (**Figure 28**).

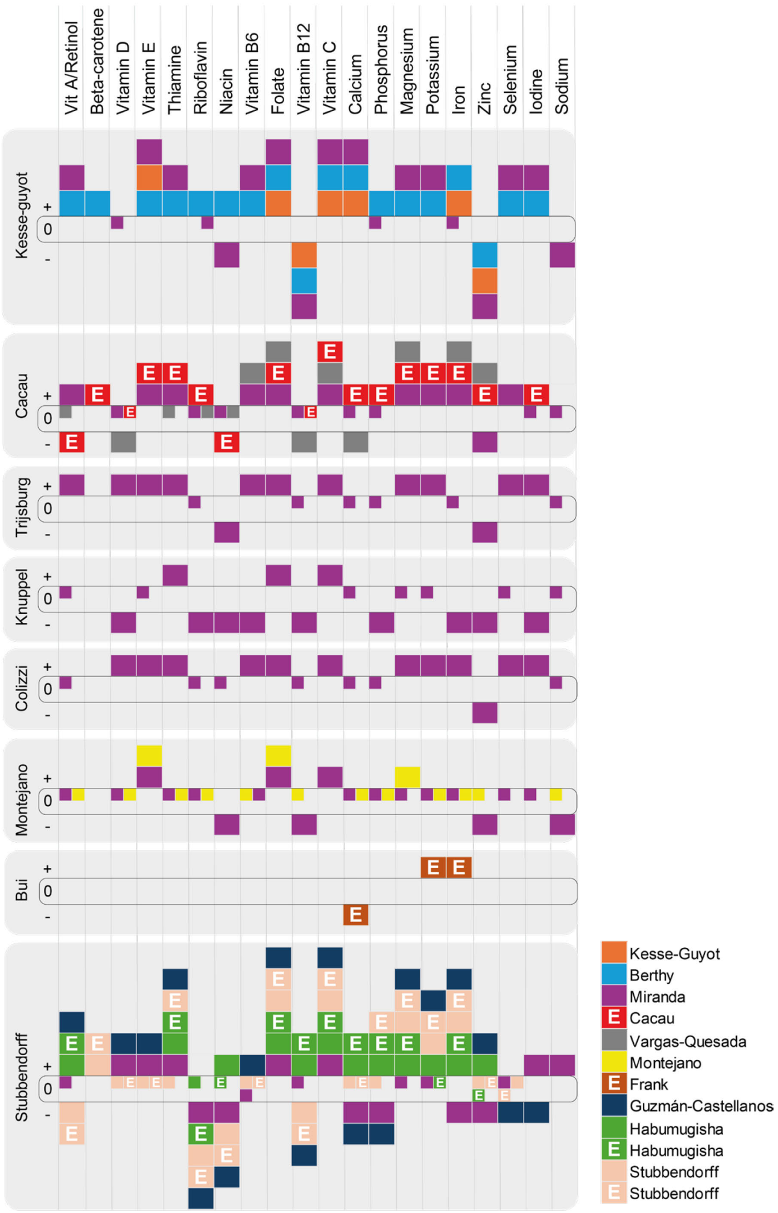

Figure 28. Micronutrient intake in relation to adherence to the EAT-Lancet diet.
Each row represents one EAT-Lancet diet score, and each coloured symbol corresponds to a specific study. Nutrients are listed along the x-axis. The direction of the association is indicated by the symbol position on the y-axis: positive (+), negative (−), or no association (0). The letter "E" denotes energy-adjusted analyses. Included studies are Miranda et al. [204] Kesse-Guyot et al. [202], Berthy et al. [219], Cacau et al. [221] (adolescent population), Vargas-Quesada et al. [223], Montejano et al. [220], Frank et al. [222], Guzmán-Castellanos et al. [224], Habumugisha et al. [225], and Stubbendorff et al. [226]. The study by Guzmán-Castellanos did not indicate which correlations that were statistically significant. From **Paper III** [227].

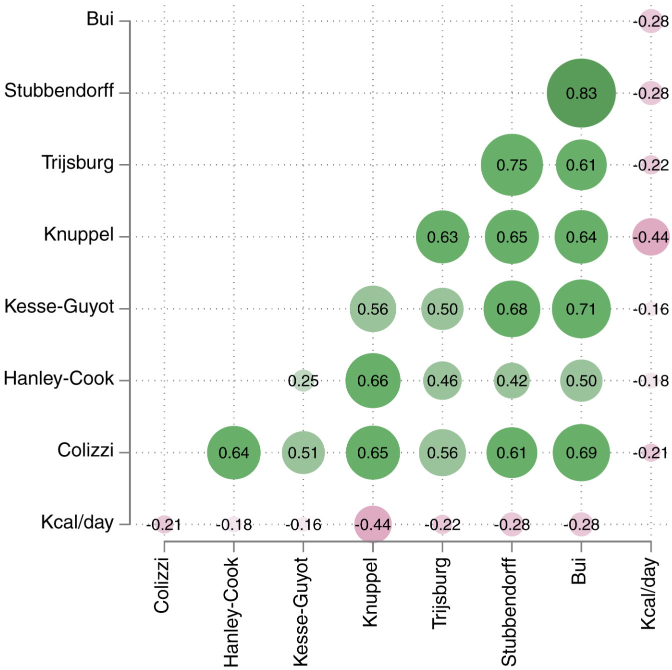

Figure 29. Correlogram between different EAT-Lancet diet scores and energy intake.
Overview of correlations from **Paper III** [227].

We evaluated the nutritional adequacy associated with varying levels of adherence to the EAT-Lancet diet using data from 25,970 participants in the MDC. Seven different EAT-Lancet diet scores were applied. All adherence scores were negatively correlated with energy intake, although the strength of the correlation varied (**Figure 29**). The strongest correlation between the scores was observed between the Bui and the Stubbendorff scores. All scores also positively correlated with dietary fibre, fruits, and vegetables, while being negatively associated with intakes of fats, sugars, and animal-sourced foods (**Figure 30**).

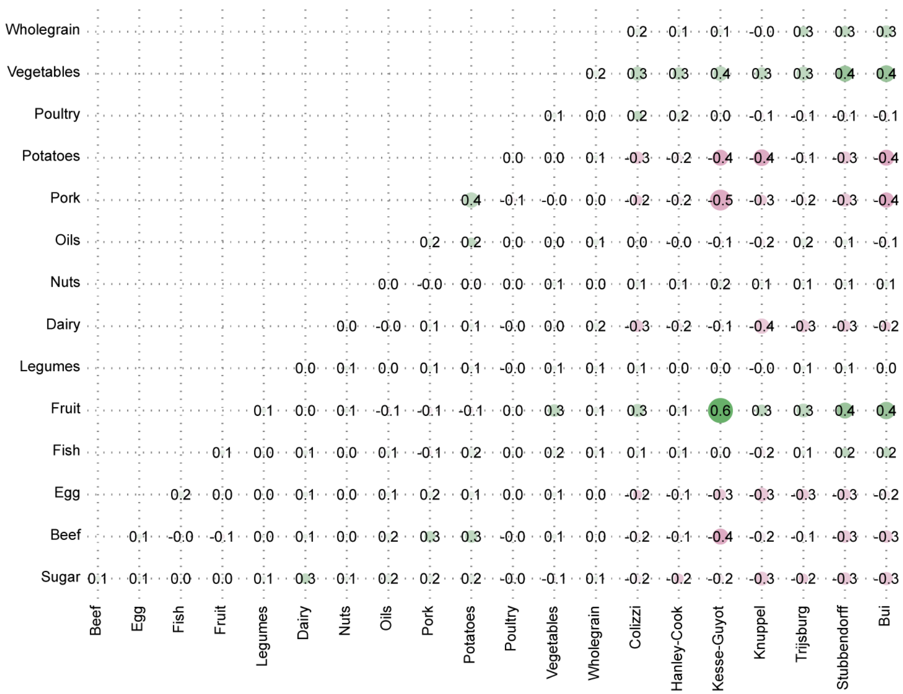

Figure 30. Correlogram between food groups in the EAT-Lancet diet and different scores. Overview of correlations from **Paper III** [227].

We assessed the intake of 17 micronutrients. In unadjusted analyses, higher adherence to the EAT-Lancet diet was generally negatively associated with daily micronutrient intake, with the exception of vitamin C, which consistently showed a positive association. Negative associations were particularly pronounced for vitamin D, thiamine, riboflavin, niacin, vitamin B12, phosphorus, and zinc.

When intake was expressed per 1000 kcal or adjusted for total energy intake, these associations shifted towards neutral or positive, indicating similar or greater nutrient density in diets with higher adherence. This raises an important methodological consideration: when the score is constructed from intake in grams of food groups, what does it mean to adjust for energy intake? Careful reflection is therefore needed when interpreting such results and when communicating results to a broader audience.

Other studies have shown varying results. A study conducted in eight South American countries using the score developed by Cacau et al. showed that higher adherence to the EAT-Lancet diet was associated with greater intake of vitamin B6, folate, vitamin C, magnesium, and zinc, and with lower intake of vitamin B12, vitamin D, and calcium [223]. A study from Spain concluded that participants with higher adherence to the EAT-Lancet diet had greater overall nutrient adequacy, although this varied across nutrients [224]. A French study found that different adherence scores correlated differently with micronutrient intake, where indices using proportional scoring showed stronger and more consistent positive associations with overall nutrient adequacy, while binary indices showed weaker and less reliable correlations [204]. Across scores, lower adequacy was generally observed for zinc, niacin, and vitamin B12.

Further work to which I have contributed, conducted in other cohorts and not included in this thesis, examined micronutrient intake in relation to the EAT-Lancet diet and found that higher adherence was predominantly associated with greater micronutrient intake [225, 226]. Other studies, using simulation-based modelling, show that the reference intake levels in EAT-lancet diet can meet most nutritional requirements, with the exception of vitamin D and iodine, which may therefore require supplementation [102]. In the EAT-Lancet 2.0, nutrient adequacy of the diet has also been confirmed in their simulation-based modelling analyses [25]. However, it is important to note that these studies do not take bioavailability into account.

Taken together with previous studies, it is evident that both the choice of scoring system and the methodological approach strongly influence the findings about micronutrient adequacy of the EAT-Lancet diet.

To go beyond nutrient intake, nutritional adequacy was assessed in **Paper III** using biomarkers for folate, vitamin D, selenium, zinc, and haemoglobin. Biomarker analyses indicated that greater adherence to the EAT-Lancet diet was associated with reduced risk of folate deficiency but slightly increased the risk of anaemia in women (**Figure 31**). Selenium, zinc, and vitamin D deficiencies showed no consistent relationship with adherence scores, except for a higher risk of vitamin D deficiency in men with greater adherence according to one score (Kesse-Guyot).

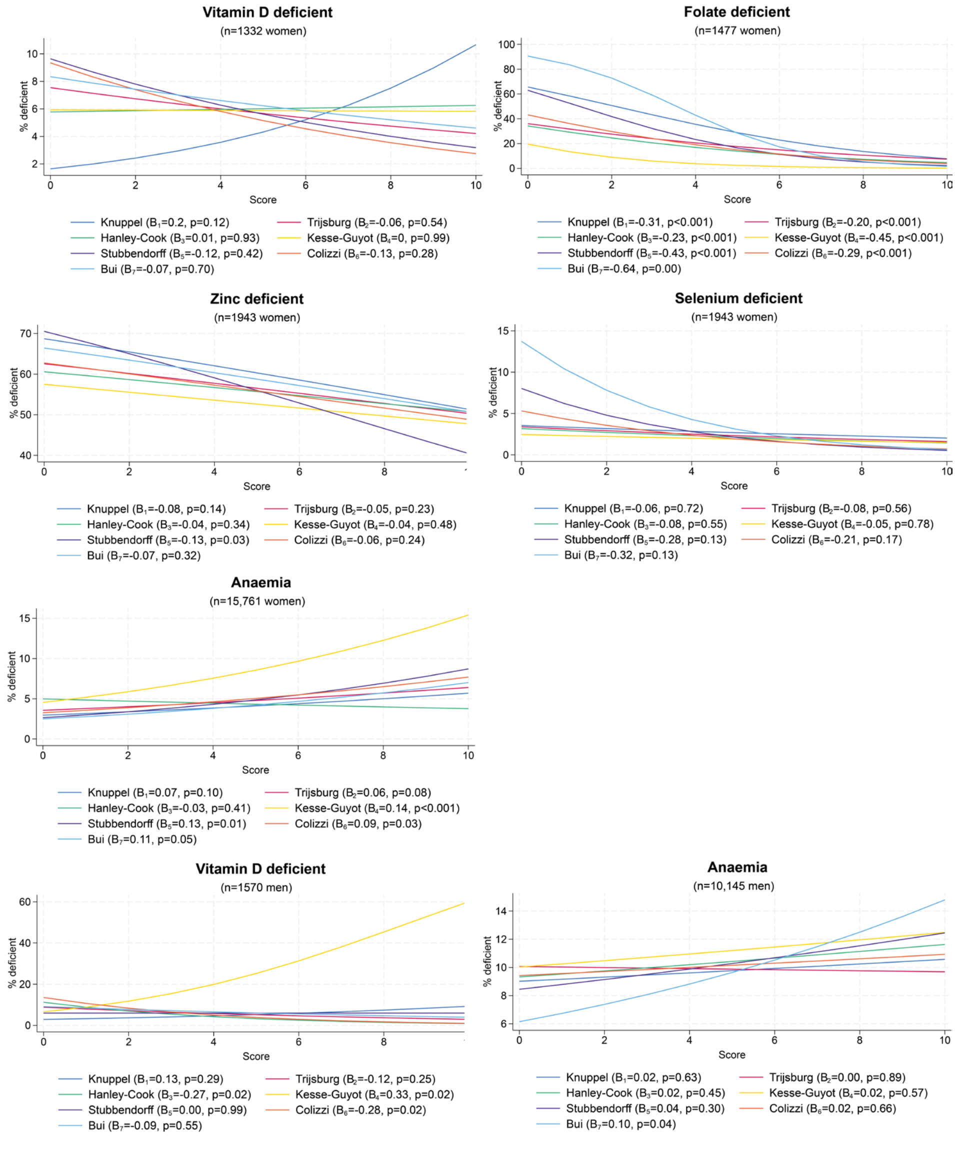

Figure 31. Probability of deficiency of different biomarkers and their association with different EAT-Lancet diet scores.
From **Paper III** [227].

Paper III contributes to this thesis by evaluating the micronutrient adequacy of adherence to the EAT-Lancet diet using both dietary intake and biomarker data in the MDC cohort. It strengthens the evidence that higher adherence to environmentally sustainable dietary patterns can be compatible with adequate micronutrient intake, while highlighting nutrients and methodological aspects that require particular attention. While no participant in the cohort fully adhered to the EAT-Lancet diet, the paper cannot resolve the debate about whether following the EAT-Lancet diet results in inadequate intake of important micronutrients. However, the paper evaluates the direction and consistency of the observed associations, and overall, these results suggest that higher adherence to the EAT-Lancet diet generally supports adequate micronutrient intake and does not increase the risk of most micronutrient deficiencies. Nevertheless, the exact nature and strength of these associations depend strongly on the dietary scoring method and energy adjustment used, highlighting the need for standardized approaches in assessing diet sustainability and nutritional adequacy. It is also important to examine how dietary shifts affect vulnerable groups such as pregnant women, adolescents, children, and older adults. For example, studies indicate that adolescents with lower dietary climate impact [18] or those adhering to vegetarian or vegan diets [19] have a higher risk of iron deficiency. Understanding such subgroup differences is essential to ensure that transitions toward more sustainable eating patterns support adequate nutrition across all population groups.

Climate impact and adherence to the EAT-Lancet diet

In addition to evaluating health outcomes, we also assessed the climate impact of adhering to the EAT-Lancet diet in the MDC in **Paper II**.

Three scores demonstrated that higher adherence was associated with lower GHGE, two showed a positive association, and one indicated no difference (**Figure 32**). These findings once again illustrate that the observed associations depend strongly on the choice of scoring method, underlining the importance of methodological consistency when evaluating both health and environmental outcomes.

Our results show that higher adherence to an EAT-Lancet-aligned diet reduces dietary GHGE, which is in line with some previous research [198]. Yet, GHGE represent only one dimension of environmental impact. In Germany, scenario analyses suggest that shifting towards such diets could cut emissions and land use but may raise water-use pressures depending on food sourcing [228]. A global analysis further shows that about half of the world's population lives in countries unable to source the diet from domestic land alone, although combining dietary shifts, improved efficiency, and waste reduction could enable up to 95% of the population to do so [229].

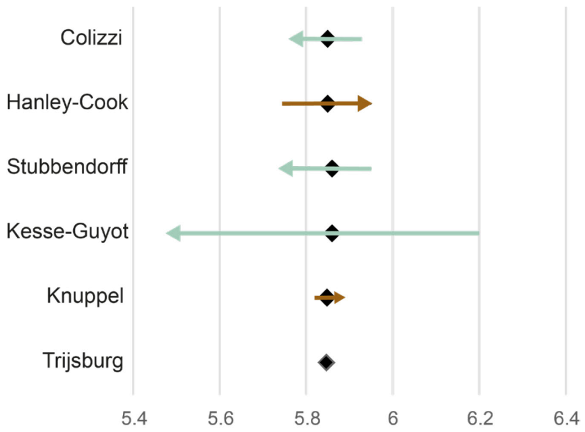

Figure 32. Dietary GHGE as assessed by different scores in the MDC.
Values repressent the 10th, 50th, and 90th percentiles. Based on data from **Paper II** [168]

In the EAT-Lancet report 2.0 from 2025 it has been demonstrated, via rigorous simulation-based modelling approaches, that adherence to the EAT-Lancet diet is associated with lower climate impact as well as other environmental impact [25].

Climate-friendly diets and associations with health

Defining and modelling climate impact of diets

The climate impact of diets can be defined in many ways. Different modelling approaches answer different questions, which makes comparisons between studies challenging. Our results show that varying methodological choices can lead to different conclusions, and that the selected approach may, intentionally or unintentionally, influence the outcomes. This has been demonstrated in **Paper I** and **Paper V** as well as in another paper by our group, not included in this study [145]. It is also important to note that the group[10] with the lowest climate impact in a given population does not necessarily represent a climate-friendly diet, as their average emissions may still exceed climate targets.

[10] The term 'climate-friendly diets' in this section refers to the group with the lowest dietary climate impact within the studied population.

Mortality and chronic disease in climate-friendly diets

In **Paper IV**, we investigated associations between dietary GHGE and all-cause mortality, cancer mortality, cardiovascular mortality, cardiovascular disease incidence, and diabetes. The study included 22,388 participants from the MDC who were followed for an average of 28.5 years. During follow-up, 11,213 participants died, including 3609 from cancer and 3451 from cardiovascular disease. In addition, 5322 incident cardiovascular disease cases and 4324 incident diabetes cases were identified.

Participants in the highest quintile of dietary GHGE had a 38% higher risk of developing diabetes compared with those in the lowest emission quintile, after adjustment for sociodemographic and lifestyle factors. This association was attenuated to 13% after further adjustment for BMI. For cancer mortality, participants in the highest emission quintile had an 18% higher risk, although the linear trend was significant only in the least adjusted model. For all-cause and cardiovascular mortality, associations were weaker and became non-significant after BMI adjustment, while no clear associations were observed for cardiovascular disease incidence. Analyses using restricted cubic splines showed that associations with all-cause and cardiovascular mortality were non-linear, with significantly higher risks only among participants with very high GHGE, above approximately 8.5 kg CO_2-eq per day for all-cause mortality and 7.2 kg CO_2-eq/day for cardiovascular mortality (**Figure 33**). For cancer mortality, no evidence of non-linearity was observed, whereas for diabetes incidence the associations were linear across the different GHGE metrics and sensitivity analyses.

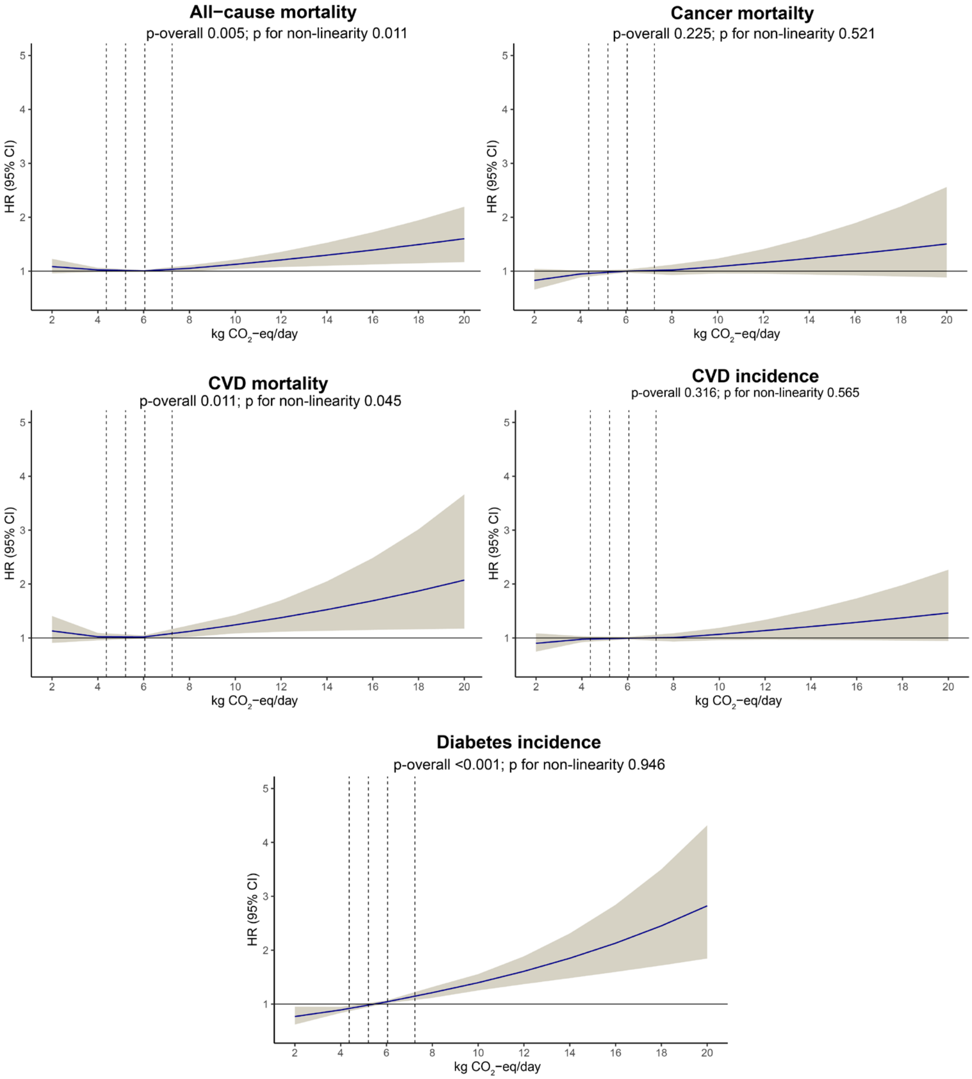

Figure 33. Restricted cubic splines of association between dietary GHGE per day and risk of mortality, cardiovascular disease, and diabetes in 22,388 individuals.
Dashed line represents cut-offs for quintiles of GHGE. Adapted from **Paper IV** [178].

Sensitivity analyses showed that excluding participants with events during the first two years or potential energy misreporters did not materially alter results. However, excluding participants who reported substantial dietary changes before baseline revealed significant linear associations with cancer mortality and cardiovascular disease incidence. Alternative modelling approaches highlighted the importance of methodological decisions; using the residual method for energy adjustment produced more linear associations for mortality outcomes, while modelling GHGE per kg food yielded weak or inconsistent associations.

In summary, diets with higher climate impact were most consistently associated with increased diabetes risk, while associations with mortality outcomes were weaker, partly non-linear, and mainly confined to individuals with very high GHGE. These findings support that climate-friendly diets do not increase the risk of mortality, cardiovascular disease, and does decrease the risk of diabetes. There might be potential co-benefits of climate-friendly diets for both public health and environmental sustainability. The results also illustrate how results depend on modelling approaches and covariate adjustments.

Our findings are in line with several large European cohorts, such as EPIC-Spain and EPIC-Europe, which reported positive associations between higher GHGE and lower mortality, cardiovascular disease, and diabetes when GHGE was expressed per unit of energy [180]. The Japan Collaborative Cohort, which examined GHGE per kg of food, observed a U-shaped relationship, where participants with the lowest and highest emissions had the greatest risk, while those in the middle had the lowest risk [182]. Results from EPIC-Europe also showed higher risks of all-cause, coronary heart disease, cardiovascular disease, and cancer mortality in relation to higher GHGE [181]. In contrast, the EPIC–Netherlands cohort, which used the same approach as in our study (GHGE per day), reported no association [179]. These discrepancies likely reflect both population differences and variation in how dietary GHGE is modelled. Another recent study found that diets with lower environmental pressures, assessed through greenhouse gas emissions, land use, water use, and other indicators, were linked to health benefits, including reduced risks of cardiovascular disease, diabetes, and cancer [230].

In the context of communicating results to the public, the methodological choices behind modelling approaches and energy adjustment are of great importance, as they may lead to different interpretations and dietary advice. For example, a study from 2025 [231] demonstrated that in unadjusted analyses, higher consumption of foods classified as ultra-processed foods was associated with higher pre-farmgate GHGE. However, when adjusted for total energy intake, the direction of association reversed, indicating lower emissions with higher proportional intake. This illustrates how analytical approaches can substantially alter conclusions and, if not clearly communicated, may cause confusion about which dietary changes truly support health and environmental sustainability [231].

Overall, **Paper IV** adds to the thesis narrative by showing that more climate-friendly diets in the population studied were not associated with higher health risks, and might instead promote health, reinforcing the harmony between environmental goals and chronic disease prevention.

Micronutrient adequacy in climate-friendly diets

In **Paper V**, we examined the relationship between dietary climate impact, measured as GHGE (kg CO_2-eq) per day, and micronutrient intake and status. Nutrient intake of 17 micronutrients was analysed in 25,970 participants, and biomarker status of 5 nutrients was assessed in smaller subgroups (**Figure 18**). The average dietary GHGE was 5.9 kg CO_2-eq per day, and higher in men (6.6 kg per day) than in women (5.4 kg per day). Red meat and dairy products contributed most to dietary GHGE (**Figure 34**).

In MDC, participants with lower dietary GHGE per day consumed fewer animal-based foods, less total energy, and had lower absolute intakes of all micronutrients. As a result, a higher proportion of participants in the higher GHGE quintiles met recommendations for nutrient intake from the Nordic Nutrition Recommendations (**Figure 35**) [17]. However, when micronutrient intake was expressed per 1000 kcal, diets with lower GHGE were generally more nutrient-dense; that is, the lowest quintile had a higher nutrient intake per 1000 kcal (**Figure 36**). These results are consistent with other studies [232], but the strength and direction of associations depend on how GHGE is expressed (**Figure 37**). Generally, higher dietary GHGE is often linked to higher micronutrient intake when expressed per day, while standardising GHGE for energy reduces or alters these associations. Energy adjustment produces a more mixed pattern, indicating that the modelling approach strongly influences the observed relationships. The impact of different GHGE metrics on micronutrient intake has been further examined in a separate paper not included in this thesis [145].

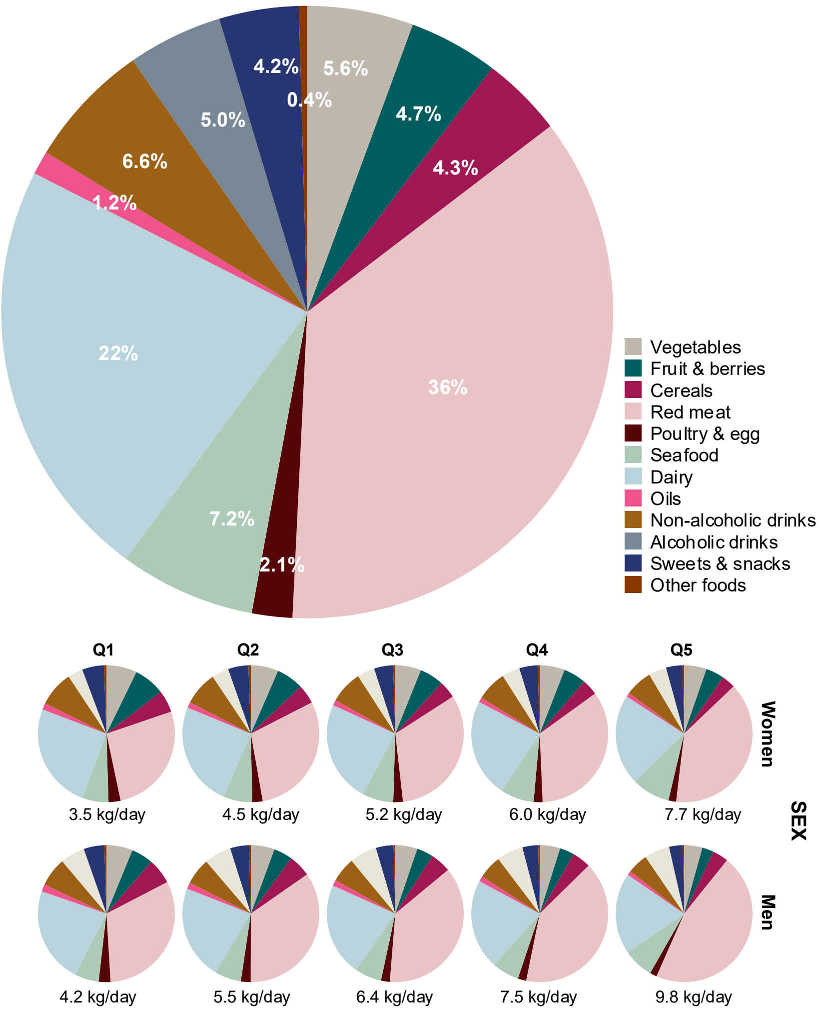

Figure 34. Contribution to dietary GHGE (kg CO2-eq per day) from different food groups in 25,970 participants from the MDC.
Adapted from **Paper V** [233]. Licensed under CC BY 4.0.

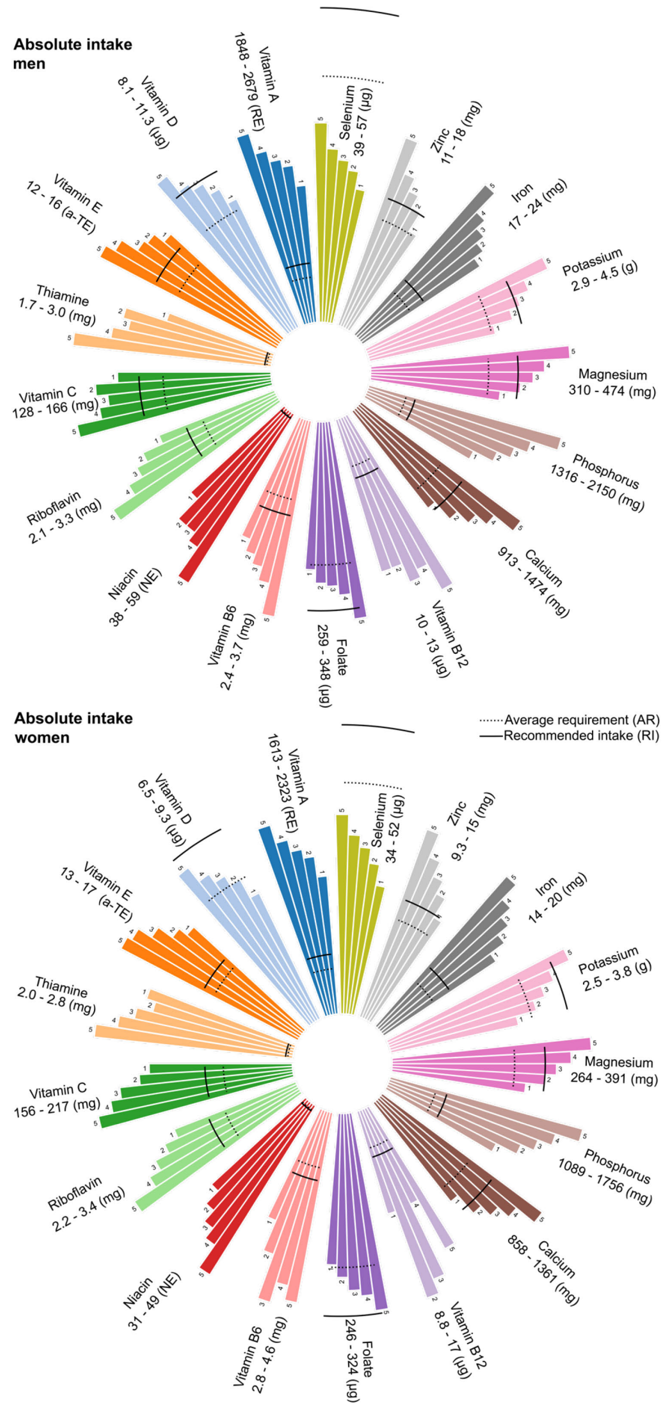

Figure 35. Micronutrent intake per day across quintiles of GHGE/day.
Adapted from Stubbendorff et al. [145]. Licensed under CC BY 4.0.

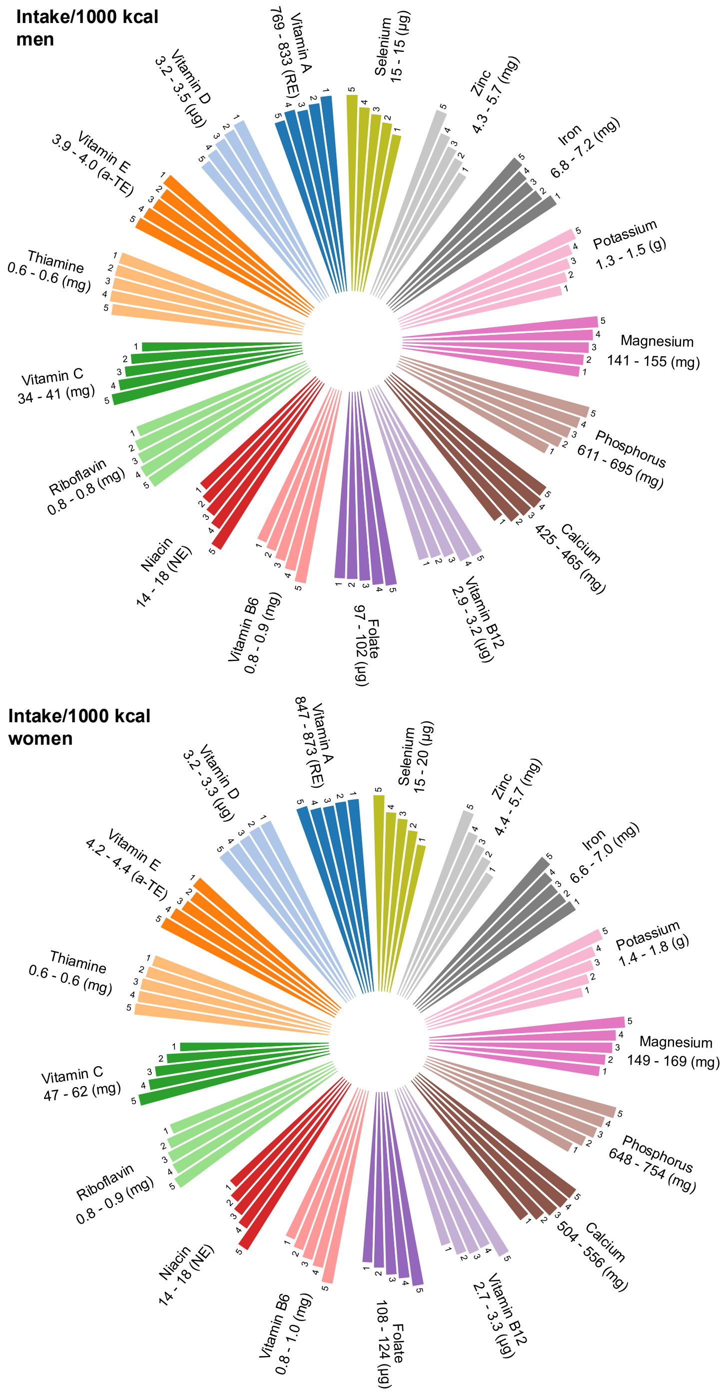

Figure 36. Micronutrient intake per 1000 kcal, across quintiles of GHGE/1000 kcal.
Adapted from Stubbendorff et al. [145]. Licensed under CC BY 4.0.

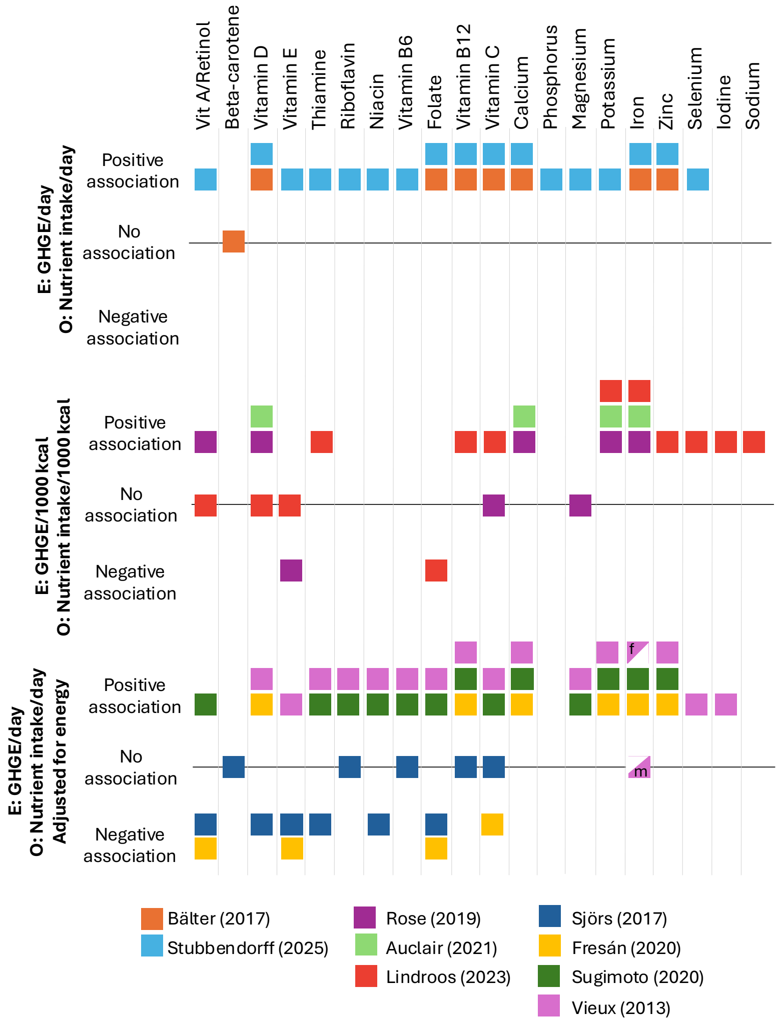

Figure 37. Dietary GHGE and its association with micronutrient intake in different observational studies.

Included studies are Bälter et al. [232], Stubbendorff et al. [233], Rose et al. [97], Auclair et al. [234], Lindroos et al. [235], Sjörs et al. [236], Fresán et al. [237], Sugimoto et al. [238], and Vieux et al. [239]. Adapted from Stubbendorff et al. [145]. Adapted from from Stubbendorff et al. [145].

Nutritional adequacy was assessed using the same biomarkers as in **Paper III:** folate, vitamin D, selenium, zinc, and haemoglobin. Correlations between micronutrient intake and status were generally weak, with somewhat stronger associations for selenium and folate (**Table 13**). Accordingly, differences in intake did not translate into major differences in biomarker concentrations.

Table 13. Pearson's correlation coefficients between nutrient intake and biomarkers.
Total intake includes dietary and supplement intake, while dietary intake does not take supplements into account. Nutrient densitiy is measured per 1000 kcal. The correlations are based on participants with serum/plasma values of different nutrients, from the MDC Study as reported in **Figure 18**. Data from **Paper V** [233].

	Serum values						
	Females					Males	
Intake	Vitamin D n=1333	Selenium n= 1943	Zinc n= 1943	Folate n= 1478	Hb n= 15,761	Vitamin D n=1570	Hb n= 10,145
Vit D, total	0.071**					0.068**	
Dietary vit D	0.132**					0.073**	
Dietary vit D/1000 kcal	0.141**					0.109**	
Selenium, total		0.306**					
Dietary selenium		0.111**					
Dietary selenium/1000 kcal		0.130**					
Zinc, total			0.018				
Dietary zinc			-0.016				
Dietary zinc/1000 kcal			0.002				
Folate, total				0.456**			
Dietary folate				0.148**			
Dietary folate/1000 kcal				0.166**			
Iron, total					-0.099**		-0.073**
Dietary iron					-0.050**		-0.043**
Dietary iron/1000 kcal					-0.018*		-0.048**

* Correlations significant at the 0.05 level
** Correlations significant at the 0.01 level

There was no association between dietary GHGE and biomarker status of vitamin D, selenium, zinc, or folate, and the proportion of participants below reference levels did not differ across GHGE quintiles **(Table 14)**. Haemoglobin concentrations were higher with higher dietary GHGE, but the prevalence of anaemia differed significantly only among women (4.6% in the lowest quintile and 3.3% in the highest).

Table 14. Associations between quintiles of GHGE per day and nutrient status.
Data from **Paper V** [233].

	Quintiles of CO_2eq/day[2]						
	1	**2**	**3**	**4**	**5**	β	**P[3]**
Females, n	257	256	267	253	300		
Vitamin D (25OHD$_3$ nmol/L)	88.1 (27.6)	89.6 (27.5)	88.2 (27.5)	91.4 (27.5)	85.9 (27.8)	-0.31	0.560
Below reference (50 nmol/L)	5.3%	6.2%	5.8%	4.4%	7.7%	0.06	0.441
n	356	377	371	405	434		
Serum selenium (ng/ml)	92.4 (16.7)	91 (16.6)	92.1 (16.6)	90.7 (16.6)	92.5 (16.7)	0.01	0.956
Below reference (63 ng/ml)	1.0%	3.7%	1.4%	3.2%	2.9%	0.14	0.178
n	356	377	371	405	434		
Serum zinc (µg/L)	10.6 (1.8)	10.3 (1.8)	10.2 (1.8)	10.4 (1.8)	10.3 (1.8)	-0.05	0.078
Below reference (10.6 µg/L)	53.1%	57.6%	59.0%	58.4%	58.9%	0.05	0.135
n	295	270	296	296	321		
Plasma folate (nmol/L)	12.7 (8.3)	12.1 (8.3)	13.1 (8.3)	12.4 (8.3)	12.1 (8.4)	-0.10	0.521
Below reference (6.8 nmol/L)	22.6%	24.7%	16.9%	14.2%	23.3%	-0.05	0.267
n	3155	3152	3155	3152	3147		
Hemoglobin (g/liter)	135.8 (9.7)	136.1 (9.6)	136.1 (9.6)	136.1 (9.6)	136.6 (9.7)	0.15	0.007
Hemoglobin below ref. (120) %	4.6%	3.6%	3.6%	3.6%	3.3%	-0.07	0.017
Males, n	354	340	315	304	257		
Vitamin D (25OHD$_3$ nmol/L)	85.2 (26)	89.2 (25.7)	86.5 (25.6)	83.8 (25.7)	88.2 (26.4)	0.02	0.966
Below reference (50 nmol/L)	7.9%	5.6%	4.9%	5.5%	5.6%	-0.09	0.289
n	2027	2031	2029	2030	2028		
Hemoglobin (g/liter)	149.6 (10.3)	150.1 (10.2)	150.1 (10.2)	150.4 (10.2)	150.3 (10.3)	0.16	0.027
Hemoglobin below ref. (130)	2.7%	2.0%	1.9%	2.0%	2.0%	-0.08	0.131

Model is adjusted for season, age, and storage time for vitamin D, selenium, zinc and folate. Hb and other values from cell count are adjusted for season and age. Serum status reference intervals are from Institutes of Health (NIH) and WHO (for hemoglobin). [1.] Values are adjusted estimated marginal means (SD). [2.] Quintiles of dietary greenhouse gas emissions per day for females/males 1: 1: <4.1/<5.0, 2: 4.1-4.8/5.0-5.9, 3: 4.8-5.6/5.9-6.9, 4: 5.7-6.5/6.9-8.2, 5: >6.5/>8.2 kg CO_2eq. [3.]P-trend for general linear model. [4.] Hematocrit, true relative percentage volume of erythrocytes (%), [5.] Mean corpuscular volume (fl, 50 liters, 10^-15 liter), [6.] Mean corpuscular hemoglobin (pg, pico gram, 10^-12 gram), [7.] Mean corpuscular hemoglobin concentration (g/liter).

Other observational studies on how the climate impact of diets is associated with micronutrient intake show conflicting results, which might partly be due to the method used, as illustrated in **Figure 37**. Only few intervention studies have been conducted on this topic. A study conducted in Ireland found that the absolute micronutrient intake was lower in the group that got dietary advice based on sustainability and health [104]. However, the lower intake was partly due to lower energy intake. Importantly, there was no difference in biomarkers between the intervention and the control group at the end of the study period. In Sweden, an observational study from 2025 found that adolescent girls with lower dietary climate impact had a higher risk of iron deficiency [18], and similar findings were observed in studies comparing self-identified vegetarians and vegans with other dietary groups [19].

Overall, **Paper V** shows that more climate-friendly diets were linked to lower absolute micronutrient intakes, but did generally not increase the risk of deficiencies. There was a slightly higher risk of anaemia in women, but not in men. These findings demonstrate that more climate friendly eating patterns can be nutritionally adequate and support public health goals. **Paper V** also underscores the importance of considering both micronutrient intake and nutrient status when evaluating adequacy, and reminds us that higher intakes are not automatically better, as excess may also entail health and environmental risks [116, 240].

Strengths and limitations of the thesis

A major strength of this thesis is the use of data from the large MDC study, a population-based prospective cohort with detailed information on diet, lifestyle, and health outcomes, and with long follow-up through national registers. The extensive follow-up of up to 30 years made it possible to study long-term associations between dietary patterns, environmental impact, and major chronic diseases, including cardiovascular disease, diabetes, and mortality. The large sample size and high-quality, register-based outcome data further strengthen the reliability of the findings, and the inclusion of two additional cohorts enhances their generalisability. The comprehensive dietary assessment method used in the MDC Study represents another important strength. By combining a 7-day food diary, a 168-item food frequency questionnaire, and a structured interview, the modified diet history method provides a high level of detail and improved validity compared with most large-scale dietary studies. This design enabled more accurate estimation of both dietary GHGE and nutrient intakes. The inclusion of objective nutritional biomarkers added another layer of strength by allowing for validation of self-reported intake and for a more robust assessment of nutritional adequacy. The combination of dietary and biomarker data therefore made it possible to evaluate whether environmentally sustainable diets also meet nutritional requirements.

A further strength lies in the integration of health and environmental perspectives, which allowed both nutritional quality, health outcomes and climate impact to be examined within the same population. This dual perspective provides an important contribution to the growing field of research connecting sustainability and health. The combination of short-term outcomes, such as risk of micronutrient deficiencies, and long-term outcomes, such as disease incidence and mortality, gives a more complete understanding of the potential synergies and trade-offs between health and environmental goals.

The climate data used in this study were based a large number of LCA data for specific food items or groups which allowed for more specific analyses. In addition, the LCA data included are representative for Swedish consumption, thus capturing differences in climate impact between different production systems from different origins.

Methodologically, several strategies were applied to increase robustness. Different approaches to modelling dietary GHGE were performed and compared, including per day, per 1000 kcal, and energy-adjusted values, to test how analytical choices influence associations and interpretations. The outcome, nutrient intake, was also modelled in different ways, as intake per day and as intake per 1000 kcal (nutrient density). When assessing adherence to the EAT-Lancet diet, different scores were compared qualitatively and quantitatively. The work underlying this thesis highlights the importance of methodological transparency and demonstrates how results can differ depending on modelling strategy. The thesis also contributes to methodological development by discussing conceptual and analytical challenges in defining sustainable diets and showing that different methodological choices can lead to different conclusions. It highlights synergies between the environmental and health perspectives, as well as pointing out potential conflicts.

Although there are several strengths, this thesis faces the challenges inherent in observational research. Dietary data were self-reported and collected at baseline only, which introduces potential measurement error and limits the ability to capture changes in diet over time. Both dietary intake data, and GHGE calculation based on these are subject to uncertainty. To explore the impact of potential misreporting in the dietary assessment, we conducted several sensitivity analyses. Uncertainty in GHGE estimates exists partly due to differences in the quality of the underlying LCA data. This is influenced by the varying availability of data for different food products, differences in methods and assumptions applied, and regional variations in production conditions. Furthermore, residual confounding and selection bias can never be fully excluded, even in large, well-characterised cohorts. The dietary data also reflect food consumption patterns from the early 1990s, which may differ from present-day diets. It might also be a limitation that consumption data and LCA data reflects different time periods. Finally, the analyses primarily reflect relative rather than absolute climate sustainability, as even the lowest-impact diets within the cohort exceeded global climate targets.

In summary, this thesis combines robust cohort data, validated dietary assessment, and long-term follow-up with elaborative analyses linking environmental sustainability, nutrient adequacy, chronic disease risk, and mortality. While limitations related to measurement, modelling, and temporality must be acknowledged, the overall design provides a strong foundation for understanding how health and environmental perspectives can be aligned. The findings highlight the need to identify synergies and bridge conflicts between these perspectives, rather than treating them as competing objectives.

Conclusion and future perspectives

Conclusion

In summary, the work presented in this thesis demonstrates that environmentally sustainable diets, assessed both through dietary GHGE and adherence to the EAT-Lancet diet, are associated with long-term health benefits, including lower mortality and reduced risk of chronic disease. Importantly, no evidence was found to suggest that such diets increase overall health risks. Regarding micronutrient adequacy, sustainable dietary patterns were generally not associated with insufficient intakes, although estimates varied by method. They did not appear to increase the risk of deficiencies and were even linked to a lower risk of folate deficiency, though a slightly higher risk of anaemia was observed. Taken together, these findings highlight important co-benefits: dietary patterns that reduce environmental impact can also promote nutritional adequacy and public health, strengthening the case for their inclusion in future dietary guidelines and sustainability strategies.

Future perspectives

Methodological considerations

Developing the field of sustainable nutrition

Research at the intersection of health, nutrition, and sustainability is still relatively young. At the same time, it is an area that has grown considerably in recent years and urgently needs to be more developed, both in terms of scope and methodological rigour. To strengthen the credibility of this research field, it is essential to reflect on methodological choices and promote transparency. At present, definitions and analytical approaches can substantially differ between studies and influence conclusions about associations between diets and their health and environmental outcomes. This creates a situation where results may be shaped, whether intentionally or unintentionally, to support a preferred narrative. Greater transparency in reporting and a commitment to methodological consistency is therefore crucial for building a reliable evidence base.

Challenges in integrating dietary GHGE

Another central challenge within the field concerns the measurement of dietary GHGE. Whether or not energy intake is accounted for in the metric or in statistical adjustments can heavily influence study outcomes [145]. This distinction is difficult to explain to the general public. If we want to promote behavioural change, it is important how study results and recommendations are communicated. This illustrates the importance of clearly stating and justifying the role of energy in analyses, as different approaches can lead to entirely different interpretations.

Transparent and consistent use of dietary indices

It is important to emphasize the need for transparent and consistent use of a priori score when assessing adherence to the EAT-Lancet diet or other diets in observational studies. In some studies, modified scores appear to have been constructed to obtain stronger estimates, instead of accurately reflecting the diet it is supposed to. This is a practice that undermines comparability and weakens construct validity. The primary aim should be to evaluate the health associations with the diet itself, which requires the scoring method to be clearly defined in advance and reflect the dietary framework. Such ‘score-surfing’, or post-hoc score modification, risks misrepresenting the diet and may compromise the credibility of the evidence base. At present, no universal or standardized scoring method exists for measuring adherence to the EAT-Lancet diet [168, 204]. Consequently, studies investigating associations between adherence and health outcomes may yield heterogeneous findings, depending on the scoring methodology applied. Future research should therefore prioritize methodological rigour and consistency to ensure that findings reliably inform policy and practice.

It is also important to consider which food groups are included in different dietary scores and how they contribute to ranking participants, as this influences both interpretation and comparability between studies. Moreover, such scores may capture only a fraction of the diet instead of reflecting the overall dietary patterns, which affects how results should be interpreted. For example, the EAT-Lancet diet score does not include commonly consumed items such as coffee, tea, alcohol, or sugar-sweetened beverages.

Beyond dietary labels and single foods: capturing real-world diets

In addition, I believe that research at the intersection of environmental impact and health should increasingly move beyond categorical definitions of dietary patterns, such as being omnivorous, vegetarian, or vegan. The variability within these groups can be considerable, and individuals who identify similarly may have very different food intakes and nutrient profiles. In practice, such categories are often used interchangeably or even merged in research, which may obscure important differences. As future dietary transitions will likely involve a gradual reduction in animal-sourced foods across the population, capturing nuances in actual intake will be essential for accurately predicting health outcomes. The ongoing protein transition toward more plant-based protein sources illustrates this continuum. Recent European data show that higher proportions of plant protein are linked to improved nutrient quality and lower environmental impact [241]. Simulation-based modelling suggests that replacing meat with plant-based alternatives can maintain adequate protein intake for most adults, though attention to amino acid quality remains important [242]. At the same time, dietary transitions involve more than substituting one protein source for another. Rather than emphasising only the reduction of certain foods, it may be more constructive to highlight what needs to increase, such as wholegrains and legumes.

From a nutritional perspective, research has gradually shifted from a focus on individual nutrients to single foods, to whole dietary patterns [243]. Future work should continue to move flexibly between these levels, as this is key for disentangling what drives associations with health outcomes. Such knowledge can guide refinements of dietary pattern scores and strengthen mechanistic understanding. I believe that there is a need for observational studies that assess the real dietary impact rather than relying solely on self-identification or simulation-based modelling, although all perspectives may be valuable in different contexts.

Lastly, nutritional adequacy has often been evaluated based solely on dietary intake estimates, which are sensitive to dietary assessment methods and nutrient databases. Future work should place stronger emphasis on biomarkers and nutrient status indicators, as these provide a more robust assessment of whether sustainable diets meet human nutritional needs.

Responsible data use and analytical integrity

The use of public datasets, often in conjunction with automated analyses or AI-based tools, has expanded rapidly [244]. While open data have considerable potential to accelerate scientific discovery, concerns have been raised about insufficient transparency and oversight in the reuse of such datasets. Recent discussions in leading journals highlight the risk that results generated without adequate understanding of study design or population context may lead to misleading conclusions and erode trust in the scientific process. Ensuring transparency in analytical decisions and maintaining comprehensive documentation of data use are therefore essential to uphold research integrity. In conjunction with selective reporting of significant findings and post-hoc modifications of analytical methods, such practices further compromise the credibility and reproducibility of scientific evidence.

Expanding the environmental scope

So far, the majority of research on environmental impacts of diets has focused narrowly on dietary GHGE or on a selection of environmental indicators. Although these studies are important, they capture only one or a few dimensions of environmental pressures. Future research should broaden the scope to include other outcomes such as land use, biodiversity loss, water use, and nutrient cycles, and ideally align with the planetary boundaries framework for benchmarking impact against environmental goals and earth limits. Quantifying adherence to the EAT-Lancet diet might offer a broader view but might come with other constraints. An evolving focus is the biodiversity impact of the diets, and the benefits of a biodiverse nature for human and environmental health [245-247]. Emphasis on integrating biodiversity into dietary assessment not only captures dimensions of resilience and sustainability but may also open new perspectives on how diverse food sources contribute to nutrient adequacy, metabolic health, and ecosystem preservation. Water scarcity is another escalating global concern that underscores the need for comprehensive, multi-dimensional evaluations of dietary environmental impact [25]. It is also important to address potential goal conflicts, as several studies have reported trade-offs between dietary climate impact and other environmental dimensions such as water use [23, 39, 43].

Expanding the sustainability scope

Sustainable diets includes more than health and environmental aspects [248]. A broader sustainability perspective also contains social, cultural, and economic dimensions that determine whether diets are accessible, affordable, equitable, and acceptable. According to the FAO, sustainable healthy diets should promote wellbeing across all life stages, have low environmental impact, and prevent all forms of malnutrition while supporting cultural values [88]. The EAT-Lancet 2.0 Commission further emphasizes the importance of integrated food system transformations that safeguard human health, equity, and planetary boundaries [25]. Future research and policy should therefore adopt a more holistic approach, ensuring that strategies for sustainable eating address nutritional adequacy alongside social justice, affordability, and cultural relevance. In addition, climate change itself may influence the nutrient quality of food. Recent evidence shows that elevated CO_2 levels and changing climatic conditions can reduce concentrations of key micronutrients such as iron, zinc, and protein in staple crops, highlighting the interconnectedness between environmental change and human nutrition [82, 249]. Recent simulation-based modelling efforts, including the 2025 EAT–Lancet Commission and related analyses, show that bundled strategies combining dietary change, productivity improvements, food loss and waste reduction, and mitigation policies provide the greatest synergistic benefits for both health and the environment, while underscoring the importance of integrating justice, affordability, and behavioural dimensions to ensure equitable and feasible food system transformations [25, 250]. Complementary simulation-based modelling demonstrates that enhancing circularity within the food system through recycling of biomass, reuse of waste streams, and reduced reliance on finite resources, can further decrease land use, GHGE, and nutrient losses, helping bring food production within planetary boundaries [251].

Communicating evidence and countering polarization

The nutritional field has become increasingly polarized, with public debate often shaped by misinformation and oversimplified narratives. This can obscure scientific nuance and erode trust in dietary and environmental research. Researchers therefore have a responsibility to communicate findings clearly, while still acknowledging uncertainties and avoiding contributions to dichotomous portrayals of foods or dietary patterns. Strengthening dialogue between scientists, food system actors, policymakers, and the public will be key to ensuring that evidence on sustainable nutrition is accurately interpreted and effectively translated into action.

In sum, advancing research in sustainable nutrition requires methodological transparency, standardized approaches, and a broader scope of both environmental and health outcomes. Without this, findings risk being fragmented and less useful for informing the urgently needed transformation of food systems.

Populations and equity in the transition to sustainable diets

Socioeconomic and regional differences

When discussing future transitions to sustainable diets, it is important to consider which population groups should be prioritized. For example, adherence to sustainable dietary patterns, such as the EAT-Lancet diet, is not evenly distributed across populations [25]. In the United States, adherence has been found to be higher among individuals with greater socioeconomic status and educational attainment [252]. In contrast, data from South America showed that adolescents from lower socioeconomic backgrounds adhered more closely to the diet than those from higher socioeconomic groups [253]. These findings suggest that socioeconomic position interacts with cultural and regional dietary practices, underscoring the need for context-specific approaches when promoting dietary change.

Broadening the scope of health outcomes and study populations

There is also a need to broaden the range of health outcomes studied within the field of environmentally sustainable diets. Current evidence mainly covers mortality, cardiovascular disease, and diabetes, but diets with lower environmental impact may also influence other aspects of health such as bone health, cognitive function, and mental health [254]. Vulnerable groups are less studied, and individuals with higher nutrient needs, limited dietary flexibility, or existing health conditions may face different risks, and their specific nutritional requirements remain insufficiently understood. Moreover, study populations have been concentrated in high-income countries. Expanding research to include low- and middle-income countries, as well as specific groups such as children, pregnant women, and older adults, is crucial for understanding global implications.

Age-specific considerations and tailored dietary strategies

Children and adolescents are often highlighted in discussions on sustainable diets because they represent future generations, and lifelong dietary habits are established early. Although their total environmental footprint is smaller than that of adults due to lower food intake, their collective impact can still be considerable given the size of this population group and the long-term effects of early dietary choices [109]. In countries such as Sweden, where meals in kindergartens and schools are provided free of charge, considerations of both health and environmental sustainability are integrated into meal planning. To achieve meaningful reductions in environmental impact in the near term, efforts need to focus on both adults and the growing elderly population and the younger populations. For older adults, adherence to sustainable dietary patterns such as the EAT-Lancet diet has been associated with health benefits even in non-healthy states [255]. Additionally, studies suggest positive associations with cognitive function, lower risk of dementia [211, 212, 256], and adequate micronutrient intake and status [225, 226] in these groups. At the same time, sustainable diets will need to be adapted to local circumstances. Nutritional requirements differ across age groups, and the environmental and cultural context varies widely between regions. Tailoring sustainable dietary guidelines to different geographic and demographic groups is therefore essential for ensuring both feasibility and equity in the transition.

The role of fortification and supplementation

As dietary patterns shift toward lower consumption of animal-sourced foods, attention to micronutrient adequacy becomes increasingly important. While sustainable diets can provide sufficient nutrients when well planned, certain micronutrients such as vitamin B12, iron, iodine, calcium, and vitamin D may require particular consideration, especially for vulnerable groups. Fortification and supplementation therefore represent complementary strategies to ensure nutritional adequacy during the transition. Several countries in the EU already have established fortification programs, for example for iodine in salt and vitamin D in selected foods, which have contributed to improved population health [257]. This has also been an important public health strategy in many countries [258]. As dietary transitions accelerate, discussions about whether additional or targeted fortification measures are needed should form part of the broader sustainability agenda [259]. Simulation-based modelling studies show that adding key micronutrients to commonly eaten and plant-based foods can enable both nutritional adequacy and lower GHGE. In Sweden, meeting vitamin D recommendations within climate limits relies heavily on fortified milk and yoghurt, underscoring the need to assess whether broader fortification strategies are necessary [260]. Integrating fortification and supplementation strategies within national nutrition and food policies could support equitable access to essential nutrients while maintaining progress toward environmental goals. This might need to be viewed as an opportunity rather than a threat to public health.

The cost of healthy and sustainable diets

Affordability remains a key barrier to adopting healthy and sustainable diets. Globally, an estimated 2.6 billion people cannot afford a healthy diet [6]. While the EAT-Lancet diet has been shown to be affordable in many high-income settings, it might exceed household per capita income for at least 1.6 billion people worldwide [261]. At the same time, some studies indicate that adherence to the EAT-Lancet diet can reduce dietary costs, as observed in in Iran [262], and in Mexico, particularly among lower socioeconomic groups [263].

Simulation-based modelling studies show that the cost and climate impact of healthy diets vary considerably between countries. Diets optimized to meet nutritional requirements with the lowest possible GHGE tend to be more expensive than those based on the cheapest available foods, although they are substantially better for the climate [264]. Global analyses of the 2025 EAT-Lancet diet suggest that food prices could decline and nutrient availability for folate, iron, and zinc improve. Yet, affordability challenges would persist in low-income regions, where the share of income spent on food remains high [265]. Other simulation-based modelling has shown that the transition toward healthy and sustainable diets, including the EAT-Lancet diet, can initially increase food costs and water use, particularly in emerging and developing economies [266]. This highlights the importance of long-term planning, financial support, and equitable policy measures to ensure that such transitions remain both feasible and affordable across regions. Moreover, the type of policy intervention used to promote sustainable eating strongly influences both equity and affordability. Policy bundles combining taxes on high-emission foods with subsidies for encouraged foods can lower emissions while improving access to sustainable diets, particularly for low-income populations [267].

From evidence to action: enabling the transition

While the evidence base for the health and sustainability benefits of diets is relatively strong, important gaps remain on how to achieve a broad transition towards more sustainable eating patterns. Future research should therefore not only clarify what constitutes a sustainable diet but also focus on how to support its adoption in practice. This includes identifying effective strategies for communication with the public, health professionals, policymakers, and other stakeholders; and evaluate the impact of interventions to provide guidelines for effective policies and actions that are impactful and cost-efficient. Research findings must be adaptable and translatable into simple, actionable guidance.

A key step is to better understand food choice and the multiple factors that shape it, including habits, preferences, cultural norms, and the physical and economic food environment [268]. As incomes rise and local food environments expand, consumers face a wider array of options at competitive prices, making it increasingly important to understand the underlying drivers of food choice, including values and preferences [269]. Policy instruments can play an important role in supporting this transition [270]. Regulations could include, for example, restrictions on marketing directed at children, bans on the import of animal products produced with high antibiotic use or low animal welfare standards, and prohibitions on the sale of red-listed fish species. Economic measures, such as taxes on selected animal-based foods or foods with higher climate impact, or subsidies for plant-based or low impact foods, may be effective but often face political and public resistance [271]. Product development that enhances taste, nutritional quality, and overall appeal of sustainable foods is also an important factor. Improving sensory characteristics, ensuring adequate nutrient content, and increasing bioavailability can promote consumer acceptance and support the transition towards more sustainable dietary patterns. Guidance-based measures, including information campaigns, labelling, and education, as well as nudging strategies such as default plant-based options or strategic product placement, are easier to implement but typically have smaller effects at the individual level. A simulation-based modelling study from the UK shows that mandatory front-of-pack nutrient warning labels could reduce obesity prevalence by about 4 percentage points and prevent or postpone more than 100,000 obesity-related deaths over 20 years [272]. Evidence from Sweden suggests that combining approaches, for example labelling that comes together with economic incentives, may increase both effectiveness and acceptance [271]. Recent studies highlight the complexity of implementation. Research from the Global Alliance for Improved Nutrition (GAIN) shows that while consumers in low- and middle-income countries are increasingly aware of environmental issues, cost and convenience remain dominant drivers of food choice, underscoring the need to frame sustainability messages in ways that resonate with consumer values [273]. Similarly, a study from the Potsdam Institute for Climate Impact Research found that food served in hospitals and nursing homes often undermines both patient and planetary health, pointing to the need for clear nutrition and sustainability standards in institutional settings [274]. Economic incentives targeting production are also central, as current agricultural subsidies remain heavily skewed towards livestock production, with more than 80% of EU subsidies directly or indirectly supporting this sector [275].

Beyond communication and policy, there is a need for research on the economic and behavioural dimensions of dietary change. Analyses of health economics and potential societal gains could provide compelling evidence to convince decision-makers and strengthen the case for investing in sustainable nutrition. At the same time, behavioural studies are essential to understand how people actually make food choices, and which interventions are most effective in different contexts.

Towards an integrated agenda for implementation

Taken together, these insights point to the need for a broader research and policy agenda on implementation, one that integrates health economics, communication strategies, behavioural science, and institutional reforms to bridge the gap between evidence and practice.

Final notes

I believe this thesis addresses a topic of critical importance in the context of the Sustainable Development Goals. When diets are both environmentally sustainable and supportive of health, the potential for co-benefits is immense. Rather than choosing between human and planetary health, we can pursue both at the same time. The harmony between these perspectives is not just possible; it is a powerful lever for change.

While challenges in the transition to sustainable diets must be acknowledged, focusing only on conflicts risks slowing progress. Instead, the emphasis should be on solutions and on the many areas where health and sustainability already align. By drawing attention to these synergies, we can strengthen the case for dietary change and build momentum for transformation meanwhile identifying how to avoid existing goal conflicts.

The future of food is not predetermined. It will be shaped by the choices of individuals, policymakers, and societies. The evidence presented in this thesis shows that sustainable diets can protect both people and the planet. This dual benefit offers a rare opportunity in public health and environmental policy: one action that addresses two of the greatest challenges of our time. The task ahead is to seize this opportunity and translate knowledge into action.

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