Towards sustainable Dutch diets

From research to policy

Reina E. Vellinga

Propositions

1. Reducing meat consumption requires financial policy measures.
   (this thesis)

2. Environmentally sustainable diets are more affordable than the healthiest diets.
   (this thesis)

3. Conflicting interest of governments, citizens and industries is a barrier to societal development.

4. Improved communication skills of researchers enhance the translation of research into policy.

5. Lack of diversity leads to bias.

6. The rejuvenation of the public sector is essential for our society.

7. Education is indispensable to counteract misinformation on social media.

Propositions belonging to the thesis, entitled

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Contents

Chapter 1

General introduction

General introduction

A large body of evidence shows that current food systems contribute to environmental degradation and increases the burden of obesity and diet related non-communicable diseases (NCDs) [1, 2]. There is an urgent need for action, as evidenced by the agendas set at the national as well as the international level. Diets, nutrition, and the environment are intricately intertwined within the 2030 UN Sustainable Development Goals (SDGs) including zero hunger (SDG2), good health and well-being (SDG3), clean water and sanitation (SDG6), responsible consumption and production (SGD12), climate action (SDG13), life below water (SDG14), and life on land (SDG15), as they interact with production, consumption, security, and equity [3]. The 2015 Paris Agreement serves as the initial commitment to limit global temperature rise to under 2°C, preferably 1.5°C, to reduce climate change [4]. The Green Deal aims for EU climate neutrality by 2050, and includes the Farm to Fork strategy for sustainable food systems [5]. In the Netherlands, the National Prevention Agreement [6], since 2018, targets lifestyle-related diseases, including those associated with poor dietary choices, while the national Climate Agreement aims to reduce greenhouse gas (GHG) emissions with 55% by 2030 compared to 1990 [7]. These agreements, however, have experienced limited practical implementation.

Necessity for action – planetary health

Current food systems significantly contribute to global environmental change, and are under pressure to provide healthy and sustainable dietary patterns for about 10 billion individuals by 2050, while a rising number of environmental systems and processes are being pushed beyond safe boundaries [8, 9]. Food production and consumption practices are responsible for up to 30% of global GHG emissions [10]. Food production is the world's largest water-consuming sector, as 84% of cropped land uses freshwater from rain, and the remaining 16% uses irrigation water [11]. Of all global water withdrawals 70% are used for irrigation [12]. Moreover, about 60% of world fish stocks are fully fished to capacity, more than 30% overfished, and although fishing efforts have increased, catch by global marine fisheries has been declining since 1996 [13, 14]. Agriculture occupies about 40% of global land [15], and is a major driver for deforestation due to the conversion of natural ecosystems to croplands and pastures [16], agricultural expansion [17], and is related to the threat of species extinction [16]. Mis- and overuse of nitrogen and phosphorus causes eutrophication and dead zones in lakes and coastal zones [18], however the application of fertilizers are considered essential to maximize crop yields to feed the growing global population [19].

In the Netherlands, the large and intensive scale of agriculture substantially contributes to the cumulative emissions and adverse effects on ecosystems. The Dutch agriculture accounts for 76% of methane emissions, 67% of nitrous oxide emissions [20], and for respectively 61% and 67% of nitrogen and phosphorus pollution to surface water in the Netherlands [21]. Furthermore, agriculture is the largest land user [22], and is the primary source of nitrogen deposition accounting for 50% [23]. Along with major contributions of the Dutch agriculture to the national economy and to international trade, over the past 120 years, 85% of all native plant and animal species have been lost [24], while global climate change has contributed to an approximately 24 cm rise of the sea level at the Dutch coast [25].

Necessity for action – human health

While the global population is aging at an unprecedented rate [26], life-expectancy has increased [27], and child and maternal mortality have declined [28], wide-scale undernutrition still exists and the burden has shifted to non-communicable diseases. More than 820 million people remain undernourished [29], 151 million children are stunted, 51 million children are wasted [30], and more than 2 billion people are micronutrient deficient [31]. Simultaneously, another 2,1 billion adults are overweight or obese [32], and the global prevalence of diabetes almost doubled in the past 30 years [33]. Unhealthy dietary patterns are the leading risk factors for overweight and NCDs, the 3rd leading cause of death, and the 5th leading cause of disability-adjusted life years (DALYs) burden [34-36].

In the Netherlands, the prevalence of unhealthy diets—marked by excessive caloric intake, elevated levels of salt, fat, and sugar, too high consumption of red and processed meats, and insufficient intake of whole grains, vegetables, legumes, fruits, and nuts—is estimated to contribute to 8.1% of the overall disease burden, 12,900 annual deaths, and healthcare costs amounting to €6 billion [37, 38]. It is the second leading cause of death and disease after tobacco use, primarily due to its association with an increased risk of cardiovascular diseases (CVD), type 2 diabetes, and several types of cancer [39]. Moreover, an unhealthy diet, including excessive caloric intake, is a significant risk factor for overweight and obesity, with the prevalence of overweight among adults in the Netherlands reaching 50% in 2020, and projected to rise to 62% by 2040 in the absence of additional effective interventions [37, 38]. Overweight and obesity are responsible for more than 10% of new cases of chronic heart failure, 15% of cardiovascular disease, and 40% of type II diabetes mellitus [37].

Needs for diet shift

Considering the current state of the environment and public health, a shift towards more sustainable diets is urgently needed. For most Western countries such as the Netherlands, a sustainable diet would typically include less animal-based foods and more plant-based foods. Such a diet is of interest to provide simultaneous benefits for both the environment and public health [40-43].

Research consistently shows higher environmental impacts for animal-based foods compared to plant-based foods [44, 45]. Clune et al., found ruminant meat to have the highest greenhouse gas (GHG) emissions, while grains, fruits, and vegetables had the lowest emissions per kg [46]. Furthermore, numerous studies support reduced environmental impacts with lower consumption of animal-based foods, particularly ruminant meat, in Western countries [42, 45, 47-49]. For instance, Perignon et al., demonstrated the potential of dietary change to reduce GHG emission and land-use demand by up to 50%, with the extent of reductions primarily contingent on the type and quantity of meat [50]. Reducing meat consumption also benefits human health, as meat overconsumption substantially contributes to the foodborne burden of disease [51]. Studies reported associations between excessive red and processed meat consumption (≥ 100–120g and 50g per day, respectively) and a 10–20% higher likelihood of colorectal cancer, type 2 diabetes, stroke, coronary heart disease, and heart failure [52, 53].

On the other hand, the consumption of fruits, vegetables, legumes, unsalted nuts, and whole grains is associated with positive health outcomes such as lowered blood pressure, reduced risks of CVD, type 2 diabetes, and cancers [54-60]. Comparisons between high vs low plant-based diets show significant health benefits associated with adopting more plant-based diets. For example, individuals following vegan, vegetarian, pescatarian, or semi-vegetarian diets had 12% lower overall mortality risk than omnivores [61], along with lower rates of overweight and obesity [62, 63]. Moreover, studies found inverse and linear associations between risk of type 2 diabetes and coronary heart diseases in diets high vs low in plant-based foods [64, 65]. This suggests that shifting towards a dietary pattern that emphasizes whole grains, fruits, vegetables, nuts, and legumes, without eliminating animal-foods, can be beneficial.

Moving beyond the consideration of food groups and the balance between plant and animal-based foods, there is a growing interest in exploring the relationship between a healthier diet and GHG emissions [66]. Whether a healthier diet is associated with lower GHG emissions compared to current diets depends on several factors, including but not limited to the definition of a healthy diet (i.e., higher adherence to national dietary guidelines, nutritionally adequate, full adoption of food-based dietary guidelines (FBDG)) [66]. In general, healthier diets tend to be associated with less GHG emissions [42]. However, when diets are modelled to optimize nutrient intake or adequacy, GHG emissions may rise compared to current diets [67]. Previous work has mostly concentrated on one environmental sustainability indicator, namely GHG emissions [66]. Therefore, additional indicators for the assessment of environmental sustainability are essential to prevent that the current emphasis on reducing GHG emissions results in a concomitant overshoot of other planetary boundaries such as water use.

Towards sustainable food systems and diets

This shift towards a sustainable diet cannot be achieved by deliberate food choices of consumers alone; instead, the shift necessitates a transformation of food systems, encompassing cultural and economic dimensions beyond health and environmental sustainability. Realigning food systems to deliver healthy and sustainable diets is among the most important global challenges of the 21st century [1]. Food systems are integral to the production, aggregation, processing, distribution, consumption, and disposal of food products that originate from agriculture, forestry, or fisheries [68]. Sustainable food systems ensure food security and nutrition for all, while preserving economic, social, and environmental resources for future generation; these are preconditions for sustainable diets [68]. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair, and affordable; nutritionally adequate, safe, and healthy; while optimizing natural and human resources [68]. From this definition it becomes clear that a sustainable diet involves a multifaceted array of factors, notably encompassing dimensions such as the economic aspects associated with food and diet costs, and the role of accessible and affordable foods such as processed foods.

Acceptable and affordable diets

In recent years, an increasing number of studies have been conducted to design sustainable diets, but failed to include crucial components such as feasibility, acceptability, and diet costs. An example of a proposed diet is the planetary health diet developed by the EAT-lancet commission, containing considerable amounts of vegetables, fruits, whole grains, legumes, and nuts and fewer amounts of meat, dairy and cheese [1]. The major food groups are in line with groups included in many FBDGs, however, the recommended amounts vary greatly. Since most of the Dutch population falls short of meeting national dietary guidelines, the gap between current and proposed diets such as the planetary health diet will become even larger [69]. For instance, the planetary health diet recommends a daily consumption of 300g vegetables and Dutch dietary guidelines 200g, while the average daily consumption is approximately 130g [1, 69, 70]. This raises questions about the feasibility and acceptability of such patterns.

Diet costs and affordability are key barriers for the adoption of healthy and environmentally sustainable diets [71]. Research shows that animal-based foods, and fresh fruits and vegetables are more expensive than unhealthy, energy-dense foods, high in fat, sugar, and salt [72, 73], with a growing price gap between healthy and unhealthy foods [74, 75]. Furthermore, previous studies have linked diet costs to diet quality and nutritional outcomes [71, 73, 76, 77]. This is particularly pronounced among low-income individuals who are most sensitive to and impacted by food costs [78]. While the costs of food are an important determinant of food choices [79], diet costs are often not addressed in nutritional research. Particularly costs associated with transitioning to healthier and more sustainable diets are often lacking, despite being fundamental to the adoption of healthy and environmentally sustainable diets.

The role of ultra-processed foods

In addition to the transition towards a less animal-based and more plant-based diet, reducing the consumption of unhealthy foods high in fat, sugar and salt is required to improve health [36]. In the past few decades ultra-processed foods (UPF) and drinks (UPD), generally energy-dense and nutrient-poor, have entered our diets at the expense of more nutrient-rich whole foods [80, 81]. The consumption of ultra-processed foods and drinks (UPFD) has been studied according to the NOVA classification (no acronym), and showed associations between the availability and consumption of UPFD and an increased energy intake, weight gain [82], higher risk of obesity, type 2 diabetes, CVD, cancer, and all-cause mortality [82-86]. While the concept of ultra-processing and the NOVA classification itself have been prone to criticism [87], it is widely applied and allows for comparison. The NOVA classification runs from unprocessed and minimally processed foods and drinks (NOVA 1) to ultra-processed foods and drinks (NOVA 4) and classifies foods to the nature, purpose, and extent of processing [88].

Food processing is fundamental in sustainable food systems; it enhances food safety, extends shelf life, and reduces food waste. However, certain foods are extensively processed or formulated [89], whereby they surpass these fundamental roles of food processing. The steps for food processing require substantial resources, energy, water, transportation, and packaging, which extend the food chain and contribute to environmental impacts [90, 91]. In general, UPFD are efficiently produced from cost-effective ingredients with minimal environmental impact [91]. Processing of UPFD generates and uses waste, and UPFD waste in households is generally low [91]. While there is a growing focus on the detrimental health effects of UPFD, their environmental impact on food level and contribution to overall dietary environmental impact remain largely unquantified.

Food processing and the use of cost-effective ingredients, make UPFD affordable for consumers and profitable for the food industry [91]. Therefore, the industry does not only benefit from processing and selling such foods, but they also contribute significantly to maintain the current state of unhealthiness. Previous studies have linked low-costs diets to energy-dense and nutrient poor diets [72, 92], which may contribute to the rise in overweight and obesity. Furthermore, the role of industry in the transition towards a more plant-based diet is evident. The industry has responded to this transition by introducing a wide array of processed plant-based foods. Many of these plant-based foods are highly processed, and are often automatically perceived as healthy by consumers due to the use of terms such as ‘plant-based’ [93]. In the Netherlands, there has been an increase in the supply and sales of products such as pre-packaged meat substitutes [94, 95], and the trend will likely continue. Yet, the nutritional and health impacts of these processed plant-based alternatives have been underexplored [93]. While ingredients have been approved by food safety authorities, the absence of substantial data on long-term health effects of ultra-processed plant-based foods, makes it easy for the food industry to introduce these products into the market ahead of regulatory and policy oversight. The role of UPFD in our dietary patterns and implications for the environment, health, and affordability needs to be further explored.

Enabling healthy and environmentally sustainable food choices

Dietary change, as emphasized by (inter)national agendas and evidence, holds significant potential for mitigating environmental change and improving public health. The Dutch government, bound by its constitutional duty to safeguard the health of the Dutch population, must prioritize primary disease prevention, and is obligated to maintain the country habitable and to protect and improve the environment [96, 97]. Furthermore, the EU Climate Law and the national Climate Agreement call for a substantial reduction in CO2 emissions to be achieved by 2030, with the latter specifically emphasizing food-related agreements. Consequently, the government also bears the responsibility to align its efforts in the food domain.

The government has a key role in shaping a healthy and sustainable food environment, thereby encouraging healthy and sustainable dietary choices among the Dutch population [98]. However, the formulation of current policies falls short in enabling the consumption of healthy, environmentally sustainable, and affordable diets. For example, given the ample evidence supporting the dietary shift to benefit public health and the environment, hardly any public policies explicitly aim to lower the consumption of animal-based foods [99]. In addition, shifting the responsibility primarily onto individual consumers for dietary change is deemed undesirable, given that individual dietary change tends to yield minimal impact. Notably, current food environments strongly shape dietary choices by influencing what individuals buy, including factors such as availability, affordability, and cultural influences [76, 77]. Therefore, food environments significantly influence consumers, yet remains largely unregulated. Given that dietary changes can have major benefits for the environment and public health, the case for the government to enable the adoptions of healthy, environmentally sustainable, and affordable diets by consumers and healthy and environmentally sustainable food production by agri-food sector gets even stronger. A fundamental shift in the food system is imperative.

Aim and outline of this thesis

The overall aim of this thesis is to provide a comprehensive understanding of the associations between dietary choices, health, environmental sustainability, and economic factors within Dutch diets, including the role of ultra-processed foods and drinks (UPFD).

The research aims to contribute to scientific evidence that can underpin effective governmental policies to promote healthier and more sustainable diets while considering the economic implications.

The specific objectives of the research are:

Part I – Health, environmental sustainability, and costs of current and future diets

- To evaluate the Dutch food consumption patterns for GHG emissions and blue water use, its association with healthiness of diets according to the Dutch Healthy Diet index 2015.
- To explore the role of diet costs and affordability in the transition to healthier and more sustainable diet for low, intermediate, and high educated Dutch adults.

Part II – The role of ultra-processed foods and drinks in healthy and environmentally sustainable diets

- To evaluate the nutritional quality, environmental sustainability and economic aspects of ultra-processed foods and drinks and its consumption in the Dutch population.
- To investigate the association between the consumption of ultra-processed foods and drinks, environmental sustainability, and all-cause mortality.
- To investigate the nutritional profile of plant-based ultra-processed foods in the out-of-home environment.

Part III – Enabling healthy and environmentally sustainable food choices in retail food environments

- To measure the effect of a fiscal measure, informative nudge, and the combination on meat purchases in a Dutch virtual supermarket via a randomized controlled trail.

Part I of this thesis focusses on health, environmental sustainability, and costs of current and future diets. Within this part, **chapter 2** assesses the GHG emissions and blue water use of the Dutch diet using data from the Dutch National Food Consumption Survey (DNFCS) 2012-2016. It also examines the relationship between the environmental indicators and adherence to the Dutch dietary guidelines, operationalized through the Dutch Healthy Diet 2015 index. Using a mathematical optimization model, a more environmentally sustainable and healthier diet for Dutch adults is constructed based on current diets from DNFCS 2019-2021 in **chapter 3**. Furthermore, it describes the diet costs associated with the current and optimized diet for Dutch adults across socio-economic position**. Part II** focusses on the role of ultra-processed foods and drinks in healthy and environmentally sustainable diets. In **chapter 4** the nutritional quality, environmental sustainability, and economic aspects of ultra-processed foods and drinks and their consumption in the Dutch population based on the DNFCS 2012-2016 is evaluated. **Chapter 5** describes a longitudinal cohort study, examining the impact of ultra-processed food and beverage consumption on environmental impact and all-cause mortality. The nutritional profile of ultra-processed plant-based foods available in out-of-home settings is presented in **chapter 6. Part III** focusses on the effectiveness of different policy measures on meat purchases in a virtual supermarket was, investigated in a randomized controlled trial (RCT), presented in **chapter 7**. **Chapter 8** summarizes the main findings of the studies included in this thesis. Methodological consideration and implications for policy and future steps and conclusions are provided.

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Part I

Health, environmental sustainability, and costs of current and future diets

Chapter 2

Greenhouse gas emissions and blue water use of Dutch diets and its association with health

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Abstract

Food consumption patterns affect the environment as well as public health, and monitoring is needed. The aim of this study was to evaluate the Dutch food consumption patterns for environmental (greenhouse gas (GHG) emissions and blue water use) and health aspects (Dutch Healthy Diet index 2015), according to age, gender, and consumption moments. Food consumption data for 4313 Dutch participants aged 1 to 79 years were assessed in 2012 to 2016, by two non-consecutive 24-h recalls. The environmental impact of foods was quantified using a life cycle assessment for, e.g., indicators of GHG emissions and blue water use. The healthiness of diet, operationalized by the Dutch Healthy Diet index 2015, was assessed for 2078 adults aged ≥19 years. The average daily diet in the Netherlands was associated with 5.0 ± 2.0 kg CO_2-equivalents of GHG emissions and 0.14 ± 0.08 m^3 of blue water use. Meat, dairy and non-alcoholic beverages contributed most to GHG emissions, and non-alcoholic beverages, fruits, and meat to blue water use. More healthy diets were associated with a lower GHG emission and higher blue water use. Different associations of environmental indicators (GHG emissions and blue water use) with health aspects of diets need to be considered when aligning diets for health and sustainability.

Keywords: food consumption; environmental impact; life cycle assessment; diet quality; greenhouse gas emission; blue water use

Introduction

The effect of diet on health and the environment has led to growing concerns [1,2] and should be addressed globally as well as on national and regional levels [3,4]. The link between diet and human health is well established while the link between diet and a sustainable food system is less known but of major importance [1]. A growing body of evidence shows the impact current western dietary patterns and global food production systems have on our environment [5].

The production and consumption of foods is responsible for 30% of total greenhouse gas (GHG) emissions [6]. Moreover, it is a major determinant of biodiversity loss, land use [7], and freshwater use [8]. Blue (surface water and ground water) and green (soil moisture) water resources are considered scarce due to human activities [9,10]. Agriculture consumes the largest amount of water and is responsible for 70% of global freshwater withdrawal [10]. Changes in our food system need to be made, aiming to reduce the impact on planetary boundaries (climate change, biodiversity loss) while optimizing nutritional quality of diets (taking into account the population growth and “expansion” of nutritional-related chronic diseases) [1,11].

Numerous studies have been conducted in recent years to assess the environmental impact of diets [12,13]. Earlier research has highlighted the positive associations between animal-based foods (meat and dairy), beverages and GHG emissions [5,12,14,15,16]. Moreover, positive associations between energy intake and GHG emissions were identified [17]. In contrast, lower emissions were found for plant-based food such as vegetables, legumes, and fruits [18,19]. Those studies most often operationalized environmental impact of diets via climate change, however associations between diet and other indicators, e.g., blue water use, are less known.

Next to associations between environmental impact and diet, the health aspects of diets need to be considered as well. Methods to quantitatively assess dietary quality or adherence to (county specific) dietary guidelines are widely used. The knowledge, however, of how those can be applied within a sustainable food system is still limited. Previous studies have investigated the environmental impact of healthy and sustainable diets, however most were often assessed by GHG emissions [12]. Associations between blue water use of diets and health are not yet assessed in detail. A systematic review and meta-analysis of Harris et al., (2019) shows that shifting towards a healthier diet, and by reducing animal-based foods, the water footprint decreases, however evidence is not clear for the blue water footprint [20]. In healthy patterns, fruits, nuts, and vegetables contributed most to water use [20].

Food consumption patterns and consumption moments differ according to gender, age, and other factors such as lifestyle factors and socio-economic factors [21]. Insights about different environmental impact indicators of food consumption by e.g., gender, age, and consumption moments are needed and can help to develop useful interventions, food policy, and dietary guidelines towards a more sustainable and healthy food consumption pattern.

Therefore, the aim of this study was to evaluate the Dutch food consumption patterns for greenhouse gas emission and blue water use according to age and gender, food groups, and consumption moments, and the association with healthiness of diets according to the Dutch Healthy Diet index 2015.

Materials and Methods

Study Population

Data for this present analysis were obtained from the Dutch National Food Consumption Survey (DNFCS) 2012–2016 [21]. The survey aimed to gain insight into diets of children and adults living in the Netherlands. Dutch children and adults aged 1–79 years were drawn from a representative consumer panel. The response rate was 65%. Pregnant and lactating women and people who were institutionalized or those without adequate command of the Dutch language were excluded. For the current cross-sectional study, the target population for analysis comprised 4313 Dutch children and adults aged 1–79 years of which 1192 boys and girls aged 1–8 years, 1043 boys and girls aged 9–18 years, 1043 men and 1035 women, both aged 19–79 years. A full explanation and description of this survey is described elsewhere [21].

General Questionnaire

Participants were asked to fill in an age dependent general questionnaire, which covered questions about various background factors, such as educational level, working status and family composition, and various lifestyle factors such as patterns of physical activity, smoking, and use of alcoholic beverages. The educational level concerned the highest completed educational level of the participants or, in case of participants under the age of 19 years, of the head of household. Educational level was categorized as low (primary education, lower vocational education, advanced elementary education), moderate (intermediate vocational education, higher secondary education) and high (higher vocational education and university). Information on region and degree of urbanization was provided by the market research agency. Region was categorized as North, East, South, and West. The degree of urbanization was divided into high urbanized (1500 or more addresses/km^2), moderately urbanized (1000–1500 addresses/km^2) and hardly or not urbanized (fewer than 1000 addresses/km^2).

Information on body composition was gathered in different ways depending on age. Height was not measured for adults aged 71–79 y due to practical reasons. Body Mass Index (BMI) was calculated as the average body weight (in kg) divided by average height (in m) squared (kg/m^2). Categories for BMI were underweight (<20), normal weight (20–25), overweight (>25–30), and obese (>30).

Description of Study Population

Reported population descriptives were weighted for demographic properties, season, and combination of both consumption days (week or weekend). Among 2235 Dutch children aged 1-18 years, fifty percent were boys (Supplementary Table S1). Mean age was 5 ± 1 years (mean ± SD) and 13 ± 2 years (mean ± SD) for children aged 1-8 years and 9-18 years, respectively. Most children aged 1-8 years (82%) and 9-18 years (72%) had a normal weight. Both caregivers were higher educated for 61% and 45% of 1-8 and 9-18 year-old children. Almost half of the children lived in the Western part of the Netherlands and most of them lived in extremely or strongly urbanized areas.

Of the 2078 adults aged 19-79 years, 50% was male (Supplementary Table S1). Mean age was 48 ± 21 years (mean ± SD) for men and 48 ± 21 years (mean ± SD) for women. Respectively, 34% and 33% of the men and women (19-70 years; because for adults >70 years, height was not measured so BMI could not be calculated) had a normal weight and 40% of the adults (19-70 years) were overweight or obese. About 20% of the adults smoked. The percentage of higher education was higher in men (38%) than in women (28%). More than 40% of the adults lived in the western part of the Netherlands and almost half of the adults lived in strongly urbanized areas.

Dietary Assessment

Participants were interviewed by telephone or face-to-face by a trained dietitian to assess dietary intake based on two non-consecutive 24-h dietary recalls. The period between the two 24-h dietary recalls was about four weeks. Interview dieticians used the GloboDiet system, which is computer-controlled interview software that enables answers to be directly entered in a computer [22].

Food consumption data were linked to food composition data derived from the Dutch Food Composition Database in order to calculate energy and nutrients (NEVO-online version 2016/5.0) [23]. Originally, food consumption data were categorized according to 23 GloboDiet food groups [22] and were adapted into 16 main groups for analysis or were stratified (e.g., cheese was excluded from dairy because its important role in determining environmental impact) (Supplementary Table S2). Aggregated food groups were used to determine important groups during the consumption moments of breakfast, lunch, dinner, and in between meals (Supplementary Table S2).

Environmental Impact Assessment

To calculate the environmental impact throughout the life cycle of foods and beverages, the life cycle assessment (LCA) approach was applied. The LCAs had an attributional approach and hierarchical perspective and were performed following the ISO 14040 and 14044 guidelines. A time horizon of 100 years was used and GHG emissions were recalculated following IPCC-guidelines (2006) [24]. Blue water use, indicating the total amount of water sourced from surface or groundwater resources and that is evaporated, incorporated into products, transferred to other watersheds, or disposed into the sea was calculated based on Mekonnen and Hoekstra (2011) [25]. Life cycle inventories (LCI) representative of the Dutch situation were delivered by Blonk Consultants (Gouda, the Netherlands) for 242 foods and beverages, and are referred to as primary data [26]. These foods were selected based on frequency of consumption in the DNFCS and variation in types of food. The National Institute for Public Health and the Environment (RIVM) performed the life cycle impact assessment (LCIA) using ReCiPe-2016 [27] and SimaPro software (version 8.52) (PRe Consultancy B.V., Amersfoort, The Netherlands).

The functional unit used was 1 kg of prepared food at plate or drink. All life cycle stages from cradle till plate were included in the analyses, including phases from primary production, processing, primary packaging, distribution, retail, supermarket, storage, preparation by the consumer (e.g., cooking), and incineration of packaging waste. Transport between all phases, except from retail to the consumer was included. Food waste was included by using food group specific percentages for avoidable and unavoidable food losses throughout the food chain. Land use change was included as direct land use change [28]. Disinfectants in the processing phase, refrigerant use and losses, secondary and tertiary packaging materials, and surface albedo change were not included. Economic allocation was applied when production processes lead to more than one food product, except for milk, where physical allocation was used. The following midpoint indicators for environmental impact were incorporated: land use (m^2 * year), blue water use (m^3), greenhouse gas (GHG) emission (kg CO_2-eq), acidification (kg SO_2-eq), fresh water eutrophication (kg P-eq), and marine eutrophication (kg N-eq).

Primary LCA data was available for 242 foods covering 71% of all foods consumed in the DNFCS. The environmental impact of foods and beverages for which primary data were not available but that were consumed in the DNFCS 2012–2016 [23] were estimated using extrapolations from the primary data. These extrapolations were carried out by expert judgement of a panel of (nutritional) scientists (I.B.T, M.v.d.K, S.B, R.E.V) and were based on similarities in types of food, production systems and ingredient composition. For composite dishes, standardized recipes from the Dutch Food composition table (NEVO-online version 2016/5.0) were used where available and if not available, recipes were based on label information [23]. The panel of scientists crosschecked all extrapolations.

Correlation Environmental Impact Indicators

Spearman rank correlation coefficients based on the 242 foods and beverages with primary LCA data were obtained in order to examine the relationship between the indicators for environmental impact. Significant ($p < 0.0001$) correlation were found between primary LCA data for GHG emission and acidification, fresh water eutrophication, marine eutrophication and land use, ranging from 0.70–0.86 (Supplementary Table S3). Blue water use had a weak correlation with GHG emission (0.51; $p < 0.0001$). Further analyses therefore focused on GHG emission and blue water use. The supplemental material provides descriptive analyses, for all environmental indictors analyzed (Supplementary Table S6; GHG emission, acidification, fresh water eutrophication, marine eutrophication, land use, and blue water use).

Dutch Healthy Diet Index 2015

The Dutch Healthy Diet index 2015 (DHD15) was used to measure health aspects of diets of Dutch adults aged 19–79 years [29]. For children aged 1–18 years, no DHD15 scores were obtained due to different underlying nutritional guidelines for that age group. The method gives a ranking to dietary intake based on the level of adherence to Dutch dietary guidelines for a healthy diet for the components: vegetables, fruits, wholegrain products, legumes, nuts, dairy, fish, tea, fats and oils, coffee, red meat, processed meat, sweetened beverages and fruit juices, alcohol and sodium [30] (Supplementary Table S4).

Components were scored based on their type: adequacy, moderate, optimum, ratio, or quality. Adequacy components are vegetables, fruit, legumes, nuts, fish and tea and reflect the recommendation to consume the minimum mentioned quantity. Moderate components are red meat, processed meat, sweetened beverages and fruit juices, alcohol and sodium and are components of which consumption should be eaten in moderation. Fats and oils are a ratio component and reflect the ratio between consumption of desired food products and less desired food products. The wholegrain component is divided in two sub-components: an adequacy component for wholegrain consumption and a ratio component to reflect replacement of refined grain products by wholegrain products. Dairy is an optimum component, which reflects the consumption in an optimal range. Coffee is a quality component and scoring was based on quality, which was filtered or unfiltered coffee. However, the consumption data used in this study did not distinguish between filtered or unfiltered coffee and therefore the component coffee was excluded.

For all components average food consumption was determined over two days (Supplementary Table S5) and a score of 0 to 10 points was allotted based on type of component. Intakes between minimum and maximum values were scored proportionally. All components had a similar weight and were summed up for the overall DHD15 score. This resulted in a range of 0 to 140 points, whereby 0 points indicated minimal adherence and 140 points indicated maximal adherence to the Dutch dietary guidelines for a healthy diet in 2015.

Statistical Analysis

Daily means over two consumption days were calculated for each participant in order to investigate food consumption, GHG emissions, blue water use, DHD15 scores and associations. Participants were categorized into children aged 1–8 years, children aged 9–18 years, men aged 19–79 years, and women aged 19–79 years to explore differences according to age and gender. Sixteen main food groups were used to identify important food groups and four different consumption moments with nine aggregated food groups were used to determine important consumption moments (Supplementary Table S2).

Descriptive statistics are displayed for the entire population as well as stratified for gender and age. Numbers are displayed as mean (standard deviation (SD)) or number (proportion) where appropriate. Reported values were weighted for demographic properties, season, and combination of both consumption days (week or weekend).

Multiple regression models were applied to investigate associations between total DHD15 scores, individual DHD15 components, GHG emissions, and blue water use. GHG emissions and blue water use were the dependent variables in the models. The variables age (continuous), sex (male, female), and energy intake (kcal, continuous) were included in the models. Regression coefficients (β) and p-values obtained from the regression model were used to determine associations between DHD15 component and GHG emissions and blue water use. The statistical analysis was performed using SAS software, version 9.4 (SAS Institute Inc., Cary, NC, USA). A two sided p-value of < 0.05 was considered as statistically significant.

Results

Nutritional and Environmental Aspects

Nutritional aspects and GHG emissions in kg CO_2-eq and blue water use in m^3 per person per day of diets were assessed for the total population and for children aged 1–8 years, children aged 9–18 years, men and women (Table 1). The Dutch population consumed on average 3.1 kg of food per day of which 1.8 kg was (non-alcoholic and alcoholic) beverages

(Table 1). Mean protein intake was 79 g/d, and varied between 60 and 103 g/d (25th and 75th percentile). Current consumption patterns provided around 62% of the protein intake from animal-based foods.

Food Consumption According to Age and Gender

In older children (9–18 years), consumption of meat (+41 g/day) and sugary and savory discretionary foods was higher, compared with younger children (aged 1–8 years) (Table 2). Consumption of dairy (−50 g/day) and fruits (−42 g/day) was lower in older children. Circa half of non-alcoholic beverages consumed by children were soft drinks with 469 and 654 mL/day for younger and older children, respectively. Men consumed more animal-based foods, more plant-based foods (potatoes and cereals (+93 g/day) and nuts (+6 g/day)) but lower amounts of fruits (−26 g/day) than women. Men also drank more soft drinks (+113 mL/day), fruit- and vegetable juices (+14 mL/day) and alcoholic beverages (+193 mL/day) but less water (−189 mL/day), coffee and tea (−112 mL/day) compared to women.

Greenhouse Gas Emissions

The average daily GHG emission was 5.0 ± 2.0 kg CO_2-eq (mean ± SD) and varied between 3.0 kg CO_2-eq for children aged 1–8 years and 6.0 kg CO_2-eq for men aged 19–79 years (Table 1). For the total population, main contributing food groups to total GHG emissions were: meat (33%); dairy (14% (of which more than half are dairy drinks 8%)) and non-alcoholic beverages (9%). Dairy (26%) and sugary and savory foods (9%) were more important contributing food groups for children aged 1–8 years and children aged 9–18 years, respectively. Plant-based foods, such as vegetables (5%), fruits (3%), nuts (2%), and legumes (0.2%) contributed less to daily GHG emissions. The majority of beverages-related GHG emissions were from soft drinks for children (1–18 y). Emissions from coffee and tea were the most important beverages contributing to beverages-related emissions for adults. The GHG emission from alcoholic beverages was twice as high in men (0.27 kg CO_2-eq), compared to women (0.13 kg CO_2-eq).

Blue Water Use

Blue water use was on average 0.14 ± 0.08 m^3 (mean ± SD) per person per day for the Dutch population. Estimated blue water use was lower for younger and older children (1-18 years) compared to adults (Table 2). Non-alcoholic beverages (31%) and fruits (14%) mainly determined daily blue water use. Meat contributed 11% to daily water use, remaining animal-based foods contributed less, for instance dairy (4%) and cheese (2%). Of the beverages, fruit- and vegetable juices (13%) and coffee and tea (12%) consumption were associated with the highest use of blue water. For younger and older children, fruit and vegetable juices and soft drinks contributed most to beverage-related blue water use. Compared to adults, contribution from fruits was higher in children aged 1-8 years but contribution from nuts was lower in children aged 1-18 years. Men had higher daily blue water use from animal-based foods and plant-based foods (potatoes and cereals and nuts) compared to women. Contribution from fruits was lower for men (11%) than for women (17%).

Consumption Moments

On average, dinner contributes 47% to daily GHG emission. At dinner, animal-based foods (meat, fish and eggs (28%), dairy, and cheese (5%)) and potatoes and cereals (5%) contributed the most (Figure 1a). Twenty-three percent of the daily dietary emissions were in between meals. Important sources were non-alcoholic beverages (6%) and dairy and cheese (5%).

For blue water use the most important consumption moment was in between meals (38% of daily blue water use) (Figure 1b). Non-alcoholic beverages (16%) and vegetables, fruits and legumes (8%) were important food groups that contributed for more than half of blue water use within the consumption moment in between meals. Dinner contributed with 32% to daily blue water use and during dinner, animal-based foods (meat, fish and eggs (9%)) and vegetables, fruits and legumes (7%) were the most important sources.

Dutch Healthy Diet Index 2015

DHD15 scores (maximum 140) showed that women had a significantly higher adherence to DHD15 with 64 ± 24 points (mean ± SD) compared to men with 52 ± 22 points (mean ± SD) (Table 3). On 9 out of 14 components (fruit, nuts, tea, red meat, processed meat, sweetened beverages and fruit juices, alcohol, and sodium) women scored significantly higher compared to men. The DHD15 score was significantly inversely ($p < 0.0001$) correlated with GHG emissions and significantly positively correlated with blue water use (Figure 2a,b).

After adjustments for age, sex, and energy intake, DHD15 score was still significant inversely associated with GHG emissions and positively with blue water use (Table 4). Thus, when DHD15 score increases with 1 point, emissions decrease with 0.011 kg CO_2-eq and blue water use increases with 0.002 m^3 (~2 L). To further explore adherence to individual components, the 14 individual DHD15 components were included in a similar model. Inverse significant associations were found between GHG emissions and the components of red meat, ratio fats, ratio fats and alcohol. Implying that better adherence to these components was associated with lower emissions. The components vegetables, fruit, dairy, ratio fish and processed meat were significantly associated with higher emissions. No associations were found for legumes, nuts, tea, sugared beverages, and sodium.

Significant associations for lower blue water use were found for more adherence to the components of ratio grains, sugared beverages, and alcohol. The components of vegetables, fruit, nuts, ratio fish, tea, processed meat and sodium were positively associated with blue water use. No associations were found for blue water use with legumes, dairy, ratio fats, and red meat.

Discussion

In this study, the food consumption patterns for the Dutch population in general as well as for children, men and women separately, were evaluated for environmental impact (GHG emissions and blue water use) and healthiness of diet (measured with the Dutch Healthy Diet index 2015). Climate change potential (GHG emissions) and blue water use among 4313 Dutch children and adults was on average 5.0 ± 2.0 kg CO_2-eq and 0.14 ± 0.08 m^3 per person per day. Daily environmental impact varied between children and adults. Men had overall a higher environmental impact compared to women. Meat, dairy, non-alcoholic beverages, and the consumption moment dinner mainly determined daily GHG emissions. Non-alcoholic beverages, fruits, and meat were main determinants of blue water use, with main consumption in between meals. Healthier diets, as scored on the DHD15, were associated with lower GHG emissions but higher blue water use. Better adherence to Dutch healthy diet guidelines for red and processed meat (less consumption); vegetables (more consumption) determined the strongest association with GHG emissions. Better adherence to Dutch guidelines for nuts, vegetables, and fruits (more consumption) determined the association with blue water use.

These results highlight the importance of investigating several environmental indicators in relation to healthy diets. Most research to date was focused on associations between GHG emission and healthy diets. This study shows that this focus on GHG emissions ignores important effects of foods and beverages, which have opposing associations between GHG emissions, blue water use and healthy diets. As far as we know, this is the first study investigating healthiness of diet (DHD15) in relation to blue water use in Dutch diets. In our regression analysis, we found that better adherence to the Dutch dietary guidelines of plant-based foods (nuts, vegetables, and fruits) significantly led to higher blue water use. These guidelines advise to increase consumption of vegetables and fruits and to consume moderate intakes of unsalted nuts compared to the current consumption [29]. Thus, while those foods benefit human health, they are associated with higher blue water use. Therefore, shifting towards a more plant-based diet may decrease GHG emissions and increase blue water use based on current origin, production, and consumption of foods.

Our conclusions are in line with previous studies investigating daily blue water use of diets. Meier and Christen (2013) investigated environmental impact, including blue water use, of several dietary scenarios in a German population [31]. They found, similar to our findings, that diets associated with increased blue water use were caused by the consumption of higher quantities of plant-based foods such as vegetables, fruits, and nuts [31]. Moreover, Springmann et al., (2018) showed in a modelling study that increased water use was associated with vegetable and fruit (and legume) consumption [3]. In order to stabilize and/or reduce blue water use from foods and beverages while meeting dietary requirements, different food choices can be considered within food groups. Foods and beverages using less blue water, such as (local) apples instead of oranges or mangoes, or hazelnuts instead of cashew nuts, can improve health aspects of diets while limiting the increase of- or even reducing blue water use [26]. Besides, changing from more animal-based foods to more plant-based foods can reduce (green) water footprint [20].

A body of literature evaluating dietary GHG emissions exists, which confirm our results. Meat, dairy (products), cheese, and beverages were shown to be major contributors to daily GHG emissions [5,12,14,15,16]. In the previous Dutch National Food Consumption Survey (DNFCS) 2007–2010, Temme et al., (2015) investigated GHG emissions in Dutch diets among a population aged 9–69 years and showed that younger children and women had a lower GHG emissions compared to men, similar to the current study [32]. The comparison of absolute GHG emissions of previous and current diets according to the DNFCS is not in the scope of this study. We used updated LCA data, included more age groups, and the current DNFCS was conducted in a different sample of the Dutch population. However, consumed quantities of animal-based foods (meat (−8%) and dairy and cheese (−12%)), alcoholic beverages (−19%) and sugar containing beverages decreased and plant-based foods (vegetables (+3%), legumes (+8%) and fruits (+8%) increased [21].

In the literature there is some inconsistency concerning the association between health aspects of diets and GHG emission [1,5,12,14,15,17,32,33,34,35]. Apart from the association between healthy diets (DHD15) and the environmental indicators, we investigated individual DHD15 components to evaluate the impact of underlying Dutch dietary guidelines on GHG emissions and blue water use. Biesbroek et al., (2017) found in a Dutch cohort (EPIC-NL) that had better adherence to the Dutch dietary guidelines, assessed with DHD15, was associated as well with lower GHG emission [33] but did not investigate individual components of the DHD15. Studies investigating individual components of dietary quality scores [36] were not comparable with our results due to underlying country specific dietary guidelines [37].

This study also has some limitations that should be addressed. First, in our study the environmental impact was estimated using primary LCA data and extrapolations.

Extrapolations can affect the results due to data uncertainty. However, primary LCA data covered 71% of consumed foods and beverages. The remaining contribution of extrapolated LCA data was small and did not influence the ranking of contributing foods in our study. As a result, our LCA data is more complete, which enables us to determine the entire daily food pattern and allows extended analyses in the future such as scenario analyses.

Secondly, food consumption data was based on two 24-h dietary recalls following the guidelines of the European Food and Safety Authority (EFSA) [38]. Although it is methodologically valid to obtain food consumption data this way, misreporting, underreporting, or overreporting occurs [21]. The amount of misreporting is unknown and not corrected for in this study thus the actual environmental impact might be influenced by misreporting. The estimation of the DHD15 score was based on the average of two 24-h dietary recalls and not on the habitual daily intake, and therefore the actual DHD15 score might be influenced as well.

Lastly, although we found that healthier diets (DHD15) were associated with lower emissions but higher blue water use, associations depend on the underlying method to define healthy and sustainable diets [2]. Our results concerning the association between the environmental impact indicators and health aspects of diets is based on DHD15, but this instrument was initially developed to assess adherence to Dutch dietary guidelines for foods associated with health [29]. Dietary quality scores, such as the DHD15, are suited to combine health aspects of diets and environmental impact, but choosing the most suitable method is of major importance because it can influence the results [2]. Previous studies showed inverse associations between food-based diet quality scores and GHG emissions [33,36,39,40], and no clear association between nutrient-based diet quality scores and GHG emissions [13,41,42]. In our study, we used a food-based quality score to investigate the association between health aspects of diet and GHG emissions. This food-based dietary quality score method assesses whole foods and easily categorizes specific foods as animal-based or plant-based, which may influence the association. Nutrient-based scores do not consider nutrient sources of foods and this could explain why no clear associations were found using nutrient-based scores [40]. The DHD15 is currently not yet a sufficient instrument to qualify healthy as well as the sustainable aspects of diets. Underlying Dutch dietary guidelines should be updated first in order to capture a healthy and sustainable diet.

For the development of healthy and sustainable dietary guidelines, advice and policies, research should not only address the proportion of animal-based foods in diets [43] but also other dietary aspects such as overconsumption and other foods and beverages that significantly contribute to environmental impact. Indeed, the ratio of animal- versus vegetable protein should shift in favor of vegetable protein, and intake of animal protein should also decrease (except for the elderly due to higher protein requirements) because in high-income countries, such as the Netherlands, total protein intake is often easily exceeding recommendations [44]. However, this is socially and culturally difficult to target because drivers for the consumption of animal-based foods are influenced by an inter-related system of culture, taste, costs, religion, gender, and socio-economic status [44]. Therefore, addressing other dietary aspects, overconsumption is important because regardless of the source, energy intake is associated with higher environmental impact [17] and discretionary foods [45]. Our results showed that the consumption of discretionary foods, that do not contribute to human health, such as sweet and savory snacks (and salted nuts), soft drinks, and alcoholic beverages (adults only) consumed by the entire population, certainly contribute towards daily environmental impact. Targeting those foods could lower environmental impact and benefit human health. This is in line with results from a modelling study in the Netherlands showing that reducing the consumption of soft and alcoholic drinks throughout the day leads to significantly lower dietary GHG emissions of people in the Netherlands, while also having health benefits [46]. In addition to this, our results suggest that reducing the consumption of non-alcoholic beverages, such as coffee and tea and fruit- and vegetable juice, during the day could decrease blue water use.

Overall, when aligning dietary recommendations, the aspects of sustainability should be included. In order to capture healthy and sustainable dietary guidelines and diets, total protein intake, overconsumption, and consumption of discretionary foods should be included next to the shift from animal-based toward plant-based diets. Those aspects should be accounted for in improved methods, such as diet quality scores to evaluate healthy and sustainable food patterns. Further research is needed to investigate methods to assess healthy and sustainable diets.

To conclude, environmental impact varied between age and gender. Meat, dairy, and cheese and non-alcoholic beverages, and the consumption moments dinner and in between meals determined the daily GHG emission of Dutch diets mostly. For blue water use, non-alcoholic beverages, fruits and meat were main contributors, and foods with high blue water impacts were consumed mostly in between meals. The DHD15 score includes food groups associated with health and does not (yet) give the full association of all food consumed and associated environmental impacts. Besides, different associations of environmental indicators with health aspects of diets need to be considered when aligning diets for health and sustainability.

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Tables and figures

Table 1. Daily mean (standard deviation) nutritional (in grams per day) and environmental aspects (per day) for total population and for children aged 1–8 years, children aged 9–18 years, men and women aged 19–79 years derived from the Dutch National Food Consumption Survey 2012–2016. [a]

	Total Population (n = 4313)		**Children, 1–8 y (n = 1192)**		**Children, 9–18 y (n = 1043)**		**Men, 19–79 y (n = 1043)**		**Women, 19–79 y (n = 1035)**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Nutritional aspects										
Quantity	3053	989	1682	228	2393	440	3427	1161	3192	1127
Energy	2126	717	1495	222	2120	423	2543	954	1860	656
Carbohydrates	236	84	201	30	266	53	270	117	202	84
Fat	84	36	52	11	81	21	102	50	75	34
Protein	79	28	48	8	69	17	95	36	72	26
Animal protein	48	22	28	7	41	14	58	30	45	24
Vegetable protein	30	12	20	4	29	7	37	17	27	13
Fiber	20	7	14	2	18	4	23	10	18	9
Environmental impact										
Greenhouse gas emission (kg CO_2-eq)	4.96	1.99	2.95	0.68	4.36	1.17	5.98	2.60	4.58	2.02
Blue water use (m^3)	0.14	0.08	0.07	0.02	0.10	0.04	0.16	0.11	0.15	0.11

SD, standard deviation; CO_2-eq, carbon dioxide equivalents.

[a] reported values weighted for demographic properties, season, and combination of both consumption days.

Table 2. Daily means of greenhouse gas emissions in kg CO_2-equivalents and blue water use in m^3 by food group for total population and for children aged 1–8 years, children aged 9–18 years, men and women aged 18–79 years, derived from the Dutch National Food Consumption Survey 2012–2016. [a]

	Total Population (n = 4313)			Children, 1–8 y (n = 1192)			Children, 9–18 y (n = 1043)			Men, 19–79 y (n = 1043)			Women, 19–79 y (n = 1035)		
Food Group	**g**	**$kgCO_2eq$**	**m^3**	**g**	**$kgCO_2eq$**	**m^3**	**g**	**$kgCO_2eq$**	**m^3**	**g**	**$kgCO_2eq$**	**m^3**	**g**	**$kgCO_2eq$**	**m^3**
Animal based foods															
Meat	97	1.66	0.016	52	0.82	0.008	93	1.52	0.015	121	2.11	0.020	83	1.44	0.014
Red processed meat	43	0.69	0.006	31	0.44	0.004	45	0.69	0.006	54	0.86	0.008	36	0.58	0.005
Red unprocessed meat	32	0.74	0.007	12	0.28	0.002	27	0.61	0.005	43	0.98	0.009	28	0.65	0.006
White processed meat	5	0.04	0.001	3	0.02	0.000	6	0.05	0.001	5	0.04	0.001	5	0.04	0.001
White unprocessed meat	17	0.19	0.003	6	0.07	0.001	15	0.18	0.002	20	0.23	0.003	16	0.18	0.003
Dairy	310	0.70	0.006	368	0.78	0.007	318	0.72	0.006	328	0.74	0.006	276	0.64	0.006
Dairy drinks	201	0.41	0.003	282	0.57	0.005	227	0.48	0.004	211	0.42	0.003	164	0.33	0.003
Cheese	33	0.38	0.003	15	0.17	0.001	22	0.25	0.002	40	0.47	0.004	33	0.38	0.003
Fish	16	0.13	0.001	6	0.05	0.000	7	0.06	0.001	19	0.16	0.001	18	0.15	0.001
Eggs	13	0.05	0.001	7	0.03	0.001	10	0.04	0.001	15	0.07	0.002	12	0.05	0.001
Plant-based foods															
Potatoes and cereals	266	0.40	0.010	178	0.26	0.006	267	0.44	0.009	323	0.48	0.012	230	0.35	0.009
Vegetables	131	0.23	0.010	66	0.12	0.005	89	0.16	0.007	142	0.25	0.011	147	0.25	0.012
Fruits (and olives)	120	0.15	0.020	138	0.16	0.017	94	0.12	0.013	108	0.13	0.017	134	0.19	0.025
Nuts and seeds	10	0.12	0.008	5	0.04	0.002	7	0.09	0.003	14	0.15	0.010	8	0.11	0.010
Legumes	5	0.01	0.000	2	0.00	0.000	3	0.01	0.000	5	0.01	0.000	5	0.01	0.000
Beverages															
Non-alcoholic beverages	1708	0.47	0.043	728	0.20	0.018	1261	0.39	0.031	1801	0.55	0.046	1973	0.46	0.049
Soft drinks	355	0.18	0.006	469	0.15	0.006	654	0.30	0.012	357	0.20	0.006	240	0.13	0.004
Coffee and tea	708	0.20	0.017	43	0.01	0.002	130	0.03	0.005	814	0.24	0.016	926	0.25	0.026
Fruit and vegetable juice	55	0.07	0.019	43	0.04	0.009	49	0.06	0.014	65	0.08	0.023	51	0.07	0.018
Water	589	0.02	0.001	173	0.00	0.000	428	0.01	0.001	566	0.02	0.001	755	0.02	0.001
Alcoholic beverages	139	0.16	0.005	0	0.00	0.000	28	0.02	0.000	268	0.27	0.007	75	0.13	0.005
Miscellaneous															
Sweets and snacks	92	0.30	0.008	69	0.22	0.005	112	0.39	0.009	105	0.34	0.009	79	0.25	0.007
Fats and oils	22	0.11	0.009	14	0.06	0.003	19	0.09	0.005	28	0.14	0.010	19	0.10	0.009
Broth, sauces and cond.	78	0.06	0.003	23	0.04	0.001	54	0.05	0.002	96	0.09	0.004	79	0.05	0.002
Other	15	0.02	0.001	10	0.01	0.000	9	0.01	0.000	12	0.02	0.000	21	0.03	0.001

SD, standard deviation; CO_2-eq, carbon dioxide equivalents [a] reported values weighted for demographic properties, season, and combination of both consumption days.

Table 3. Means (standard deviations) for Dutch Healthy Diet index 2015 scores and individual components for 2078 men and women aged 19–79 years derived from the Dutch National Food Consumption Survey 2012–2016. [a]

	Men, 19–79 y (n = 1043)		**Women, 19–79 y (n = 1035)**	
	Mean	**SD**	**Mean**	**SD**
DHD15 score total	51.8	22.4	64.2 ***	23.6
DHD15 Components b				
Red meat	4.2	5.5	6.2 ***	5.3
Processed meat	3.2	4.9	4.3 ***	5.2
Ratio dairy	4.8	4.8	5.2	4.7
Ratio fish	1.7	4.2	1.7	4.3
Ratio grains	4.7	3.8	4.6	3.9
Vegetables	6.2	3.8	6.2	4,0
Fruit	4.1	5.1	4.9 **	5,0
Nuts	0.8	3.1	1.1 *	3.7
Legumes	0.7	3.3	0.9	3.7
Sugared beverages and fruit juices	3.7	5.4	4.7 ***	5.5
Tea	3.5	5.2	6.0 ***	5.4
Alcohol	6.7	5.4	8.3 ***	4.5
Ratio fat	2.2	4.6	2.4	4.9
Sodium	5.2	4.6	7.8 ***	3.5

SD, standard deviation; DHD15, Dutch Healthy Diet index 2015. [a] reported values weighted for demographic properties, season, and combination of both consumption days. [b] 0 points indicates minimal adherence to dietary guidelines, 10 points indicates maximal adherence to dietary guidelines. Level of significant difference of men and women *** <0.0001, ** <0.01, * <0.05.

Table 4. Regression coefficients for adjusted Dutch healthy diet scores and individual components and greenhouse gas emissions and blue water use for 2078 men and women derived from the Dutch National Food Consumption Survey 2012–2016. [a]

	GHG Emission	**Blue Water Use**
Model 1 DHD15 [a,b]	β	β
DHD15 score	−0.011 ***	0.002 ***
Model 2 DHD15 Components [a,b]		
Red meat	−0.168 ***	−0.001
Processed meat	0.020 *	0.001 *
Dairy	0.023 **	−0.001
Ratio fish	0.020 *	0.002 ***
Ratio grains	−0.025 **	−0.001 **
Vegetables	0.090 ***	0.005 ***
Fruit	0.022 **	0.004 ***
Nuts	−0.001	0.008 ***
Legumes	−0.015	0.001
Sugared beverages	−0.000	−0.003 ***
Tea	−0.003	0.004 ***
Alcohol	−0.021 **	−0.002 ***
Ratio fats	−0.026 **	0.001
Sodium	0.003	0.002 **

GHG, greenhouse gas; DHD15, Dutch Healthy Diet index 2015. [a] models were weighted for demographic properties, season, and combination of both consumption days. [b] models were adjusted for age (continuous), sex (male, female) and energy intake (kcal continuous). Level of significance *** <0.0001, ** <0.01, * <0.05.

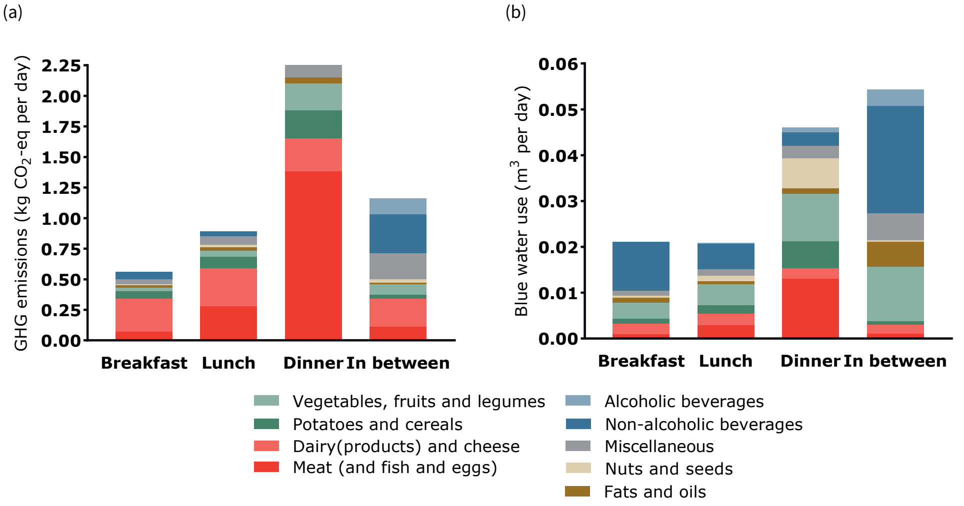

Figure 1. (a) Average greenhouse gas emission in kg CO_2-equivalents and (b) average blue water use in m^3 by consumption moment of 4313 Dutch children and adults derived from the Dutch National Food Consumption Survey 2012–2016, weighted for demographic properties, season, and combination of both consumption days.

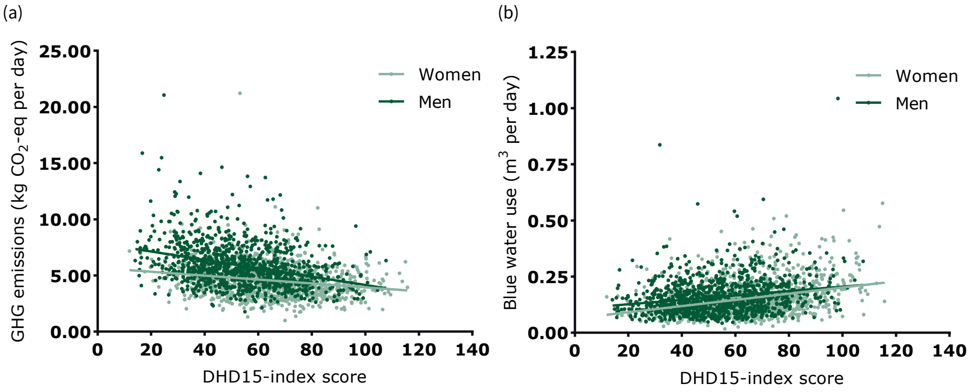

Figure 2. (a) Scatterplot illustrating the relation between the Dutch Healthy Diet index 2015 score and daily greenhouse gas emissions in kg CO_2-equivalents for 2078 Dutch men and women aged 19–79 years derived from the Dutch National Food Consumption Survey 2012–2016. (b) Scatterplot illustrating the relation between the Dutch Healthy Diet index 2015 scores and daily blue water use in m^3 for 2078 Dutch men and women aged 19–79 years derived from the Dutch National Food Consumption Survey 2012–2016.

Supplemental files

Supplemental table 1. Population characteristics for 4,313 Dutch participants aged 1-79 y derived from the Dutch National Food Consumption Survey 2012-2016.

Supplemental table 2. Categorization and shortened names for 16 main groups and 9 aggregated groups for analysis adapted from GloboDiet.

Supplemental table 3. Spearman correlation coefficients for greenhouse gas emission and acidification, fresh water eutrophication, marine eutrophication, land use and water use for 242 foods with primary life cycle analysis data.

Supplemental table 4. Components and recommendations (threshold and cut-off) of the Dutch Healthy Diet index 2015 and their minimum and maximum scores.

Supplemental table 5. Mean (standard deviation) food consumption per component of the Dutch Healthy Diet index 2015 for 2,078 Dutch men and women aged 19-79 y derived from the Dutch National Food Consumption Survey 2012-2016

Supplemental table 6. Environmental impact of daily diets and nutritional aspects for total population (n=4,313) aged 1-79 y derived from the Dutch National Food Consumption Survey 2012-2016.

Supplemental table 1. Population characteristics for 4,313 Dutch participants aged 1-79 y derived from the Dutch National Food Consumption Survey 2012-2016.[a] SD, standard deviation; CO_2-eq, carbon dioxide equivalents [a] reported values weighted for demographic properties, season, and combination of both consumption days.

	Total population (n=4,313)		Children, 1-8y		Children, 9-18y (n=1,043)		Men, 19-79y (n=1,043)		Women,19-79	
Characteristics	**N, mean**	**(%),SD**	**(n=1,192)**	**(%),SD**	**N, mean**	**(%),SD**	**N, mean**	**(%),SD**	**(n=1,035)**	**(%),SD**
Gender										
Male	2165	(50)	593	(50)	529	(51)	1043	(100)	0	0
Female	2148	(50)	599	(50)	514	(49)	0	0	1035	(100)
Age (y)	40	21	5	1	13	2	48	21	48	21
DHD15							51.8	22.4	64.2	23.6
BMI[b]										
Underweight	226	(5)	92	(8)	105	(10)	13	(1)	16	(2)
Normal weight	2414	(56)	973	(82)	751	(72)	354	(34)	336	(32)
Overweight	793	(18)	98	(8)	155	(15)	293	(28)	247	(24)
Obese	361	(8)	26	(2)	32	(3)	124	(12)	179	(17)
Level of education[c]										
Low	809	19	73	(6)	137	(13)	241	(23)	358	(35)
Moderate	1607	37	387	(32)	432	(41)	406	(39)	382	(37)
High	1888	44	732	(61)	468	(45)	395	(38)	293	(28)
Degree of urbanization										
Extremely, strongly	1996	(46)	543	(46)	475	(46)	494	(47)	484	(47)
Moderately	871	(20)	255	(21)	204	(20)	200	(19)	212	(20)
Hardly, not	1446	(34)	394	(33)	364	(35)	349	(33)	339	(33)
Region										
West	1931	(45)	542	(45)	481	(46)	454	(44)	454	(44)
North	459	(11)	129	(11)	112	(11)	109	(10)	109	(11)
East	949	(22)	261	(22)	223	(21)	235	(23)	230	(22)
South	974	(23)	260	(22)	227	(22)	245	(23)	242	(23)
Smoking[d]										
Yes	413	(10)					206	(20)	207	(20)
No	1654	(38)					831	(80)	823	(80)

SD, standard deviation; DHD15, Dutch healthy diet index 2015; BMI, body mass index

[a] reported values weighted for demographic properties, season and combination of both consumption days.

[b] ,BMI not obtained for adults ≥71 y [c] missing data for 9 participants, [d] missing data for 11 participants

Supplemental table 2. Categorization and shortened names for 16 main groups and 9 aggregated groups for analysis adapted from GloboDiet.

Main groups	Aggregated groups	GloboDiet groups
Animal based foods		
Meat total	Meat, fish and eggs	'07' Meat and meat products (excl. '07-06' meat replacers)
Red processed meat	Meat, fish and eggs	'07-04' Meat products and processed meat and 'red'[a]
Red unprocessed meat	Meat, fish and eggs	'07-00' Meat miscellaneous; '07-01' Fresh meat; '07-03' Game and ' 07-05' Oval meat
White processed meat	Meat, fish and eggs	'07-04' Meat products and processed meat and 'white'[1]
White unprocessed meat	Meat, fish and eggs	'07-02' Poultry
Dairy	Dairy and cheese	'05' Dairy (excl. '05-05' Cheese; '05-02' Dairy replacers and '05-07-02', '05-08-02' both non-dairy based products)
Dairy drinks	Dairy and cheese	'05-01' Dairy drinks
Cheese	Dairy and cheese	'05-05' Cheese
Fish	Meat, fish and eggs	'08' Fish, shellfish and amphibians
Eggs	Meat, fish and eggs	'09' Eggs and egg products
Plant-based foods		
Potatoes and cereals	Potatoes and cereals	'01' Potatoes and other tubers and '06' Cereals and cereal products
Vegetables	Vegetables, fruits and legumes	'02' Vegetables
Fruits	Vegetables, fruits and legumes	'04' Fruits, olives (excl. 04.02)
Nuts and seeds	Nuts and seeds	'04-02' Nuts, peanuts, seeds and nut spread
Legumes	Vegetables, fruits and legumes	'03' Legumes
Beverages		
Non-alcoholic beverages	Non-alcoholic beverages	'13' Non-alcoholic beverages
Soft drinks	Non-alcoholic beverages	'13-02' Lemonade, soft drinks
Coffee and tea	Non-alcoholic beverages	'13-03' Coffee, tea and herbal tea
Fruit and vegetable juice	Non-alcoholic beverages	'13-01' Fruit and vegetable juice
Water	Non-alcoholic beverages	'13-04' Water
Alcoholic beverages	Alcoholic beverages	'14' Alcoholic beverages
Miscellaneous		
Sugar, confectionery, cakes, biscuits and savoury	Miscellaneous	'11' Sugar and confectionery; '12' Cakes and sweet biscuits and '18' Savoury snacks.
Fats and oils	Fats and oils	'10' Fats and oils
Broth, sauces and condiments	Miscellaneous	'15' Condiments, spices, sauces and yeast and '16' Soups and stocks
Other	Miscellaneous	'17' Miscellaneous; '07-06' meat replacers; '05-02' Dairy replacers and '05-07-02', '05-08-02' both non-dairy based products

[a] GloboDiet group '07-04' Processed meat was categorized as red or white meat. Poultry was considered as white meat, remaining meats were categorized as red meat.

Supplemental table 3. Spearman correlation coefficients for greenhouse gas emission and acidification, fresh water eutrophication, marine eutrophication, land use and water use for 242 foods with primary life cycle analysis data.

Environmental impact indicator	rho[a]	p-value
GHG emission (kg CO_2-eq/kg)	1.00	
Acidification (kg SO_2-eq/kg)	0.86	<0.0001
Fresh water eutrophication (kg P-eq/kg)	0.72	<0.0001
Marine eutrophication (kg N-eq/kg)	0.75	<0.0001
Land use ($m^2 * $ year/kg)	0.70	<0.0001
Water use (m^3/kg)	0.51	<0.0001

GHG, greenhouse gas, CO_2-eq, carbon dioxide equivalents; SO_2-eq, sulfur dioxide; P, phosphor equivalents; N-eq, nitrogen equivalents;

[a] Correlations based on primary life cycle assessment data per kg foods

Supplemental table 4. Components and recommendations (threshold and cut-off) of the Dutch Healthy Diet index 2015 and their minimum and maximum scores.

Component	Dutch dietary guidelines 2015	Minimum score (0 points)	Maximum score (10 points)
Vegetables	Eat at least 200 g of vegetables daily	0 g/d	≥200 g/d
Fruit	Eat at least 200 g of fruit daily	0 g/d	≥200 g/d
Wholegrain products[a]	a.Eat at least 90 g of wholegrain products daily	0 g/d	≥90 g/d
	b.Replace refined cereal products by wholegrain products	No consumption of wholegrain products OR Ratio of wholegrains to refined grains ≤0.7	No consumption of refined products OR ratio of whole grains to refined grains ≥11
Legumes	Eat legumes daily	0 g/d	≥10 g/d
Nuts	Eat at least 15 g of unsalted nuts daily	0 g/d	≥15 g/d
Dairy[b]	Eat a few portions dairy products daily, including milk or yoghurt	0 g/d OR ≥ 750 g/d	300-450 g/d
Fish[c]	Eat one serving of fish weekly, preferably oily fish	0 g/d	≥15 g/d
Tea	Drink three cups of black or green tea daily	0 g/d	≥450 g/d
Fats and oils	Replace butter, hard margarines and cooking fats by soft margarines, liquid cooking fats and vegetable oils	No consumption of soft margarines, liquid cooking fats and vegetables oils OR ratio of liquid cooking fats to solid cooking ≤0.6	No consumption of butter, hard margarines and cooking fats OR ratio of liquid cooking fats to solid cooking fats ≥13
Coffee[d]	Replace unfiltered coffee by filtered coffee	Any consumption of unfiltered coffee	Consumption of only filtered coffee OR no coffee consumption
Red meat	Limit consumption of red meat	≥100 g/d	≤45 g/d
Processed meat	Limit consumption of processed meat	≥50 g/d	0 g/d
Sweetened beverages and fruit juices	Limit consumption of sweetened beverages and fruit juices	≥250 g/d	0 g/d
Alcohol	If alcohol is consumed at all, intake should be limited to one Dutch unit (10 g ethanol) daily	Women ≥20 g ethanol/day Men ≥30 g ethanol /day	Women ≤10 g ethanol/d Men ≤10 g ethanol/d
Salt	Limit consumption of table salt to 6 g daily	≥3-8 g Na/d	≤1.9 g/d

[a] This component comprises two sub-components (a and b) and each sub-component has a maximum score of 5 points. [b] A maximum of 40 g cheese can be included. [c] A maximum of 4 g lean fish can be included. [d] No information was gathered with regard to coffee consumption therefore this component is excluded. Source: Looman, M., Feskens, E. J., de Rijk, M., Meijboom, S., Biesbroek, S., Temme, E. H., ... & Geelen, A. (2017). Development and evaluation of the Dutch Healthy Diet index 2015. Public Health Nutrition, 1-11.

Supplemental table 5. Mean (standard deviation) food consumption per component of the Dutch Healthy Diet index 2015 for 2,078 Dutch men and women aged 19-79 y derived from the Dutch National Food Consumption Survey 2012-2016[a].

	Men, 19-79y (n=1,043)		Women, 19-79y (n=1,035)	
DHD15 component	**Mean**	**SD**	**Mean**	**SD**
Red meat (g/day)	96	90	64	66
Processed meat (g/day)	59	69	40	51
Dairy (g/day)	241	313	204	257
Cheese (g/day)	40	45	33	36
Fish (total) (g/day)	8	29	7	28
Fatty fish (g/day)	7	28	7	28
Lean fish (g/day)	1	2	1	2
Wholegrain products(g/day)	109	109	82	79
Refined grain products(g/day)	124	135	85	92
Vegetables (g/day)	142	119	147	136
Fruit(g/day)	100	147	125	171
Nuts (g/day)	3	15	3	12
Legumes (g/day)	5	26	5	29
Tea (g/day)	242	482	509	749
Sweetened beverages and fruit juices (g/day)	380	605	252	427
Alcohol(g/day)	17	29	6	16
Fat, solid(g/day)	16	20	11	13
Fat, liquid(g/day)	13	18	10	14
Sodium(mg/day)	2885	1296	2172	973

SD, standard deviation;DHD15, Dutch Healthy Diet index 2015.

[a] reported values weighted for demographic properties, season and combination of both consumption days.

Supplemental table 6. Environmental impact of daily diets and nutritional aspects for total population (n=4,313) aged 1-79 y derived from the Dutch National Food Consumption Survey 2012-2016[a].

Environmental indicator	Mean	SD	P5	P25	P50	P75	P95
GHG emission (kg CO_2-eq/day)	4.96	1.99	2.37	3.63	4.69	5.94	8.35
Land use (m^2 ∗ year/day)	2.91	1.11	1.35	2.16	2.76	3.51	4.91
Water use (m^3/day)	0.14	0.08	0.05	0.09	0.12	0.18	0.30
Acidification (kg SO_2-eq/day)	0.049	0.029	0.019	0.031	0.044	0.060	0.096
Marine eutrophication (kg N-eq/day)	0.0083	0.0051	0.0034	0.0053	0.0074	0.0101	0.0161
Fresh water eutrophication (kg P-eq/day)	0.0004	0.0002	0.0002	0.0003	0.0003	0.0004	0.0006
Nutritional aspects							
Quantity(g/day)	3053	989	1553	2370	2984	3630	4760
Energy(kcal/day)	2126	717	1167	1636	2015	2531	3435
Carbohydrates(g/day)	236	84	123	180	226	280	383
Fat(g/day)	84	36	37	59	79	104	148
Protein(g/day)	79	28	40	60	75	93	128
Animal protein(g/day)	48	22	18	33	45	60	88
Vegetable protein(g/day)	30	12	15	22	29	36	53
Fibre(g/d)	20	7	10	15	19	24	33

SD, standard deviation; P, percentile; GHG, greenhouse gas; CO_2-eq, carbon dioxide equivalents; SO_2-eq, sulfur dioxide ; N-eq, nitrogen equivalents; P, phosphor equivalents.

[a] reported values weighted for demographic properties, season and combination of both consumption days

Chapter 3

Diets optimized for environmental sustainability and health: Implications for diet costs across socio-economic positions for Dutch adults

Submitted:
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Abstract

Universal access to healthy, safe, environmentally sustainable, and affordable diets is imperative for individuals across all socio-economic positions. The aim of this modelling study was to investigate how dietary patterns can be improved among Dutch adults with different socioeconomic backgrounds, and how these changes affect the costs of their diets. Food consumption data for 1747 adults were derived from the Dutch National Food Consumption Survey 2019–2021. Participants were categorized according to their highest attained educational level (low, intermediate, high) as proxy for socio-economic position. For each individual the diet was minimized for greenhouse gas (GHG) emissions and maximized for diet quality according to the Dutch Healthy Diet 2015 (DHD15) index. Optimized diets were made using a benchmark approach, involving linear combinations of current diets, either within or across the three educational subgroups. Constraints limited individual dietary changes to within 33% of current consumption, except for less commonly consumed food groups. Diet costs were compared between current and optimized diets. Secondary outcomes included nutritional aspects and additional environmental impact indicators. For all educational subgroups, the optimized diets had on average a 19-24% lower GHG emission and a 52-56% improvement in DHD15 index compared to current diets, and the median diet costs remained similar. Depending on the educational subgroup, selected optimal diets contained more vegetables (6%), fruits (8-16%), nuts (37-89%), legumes (100-133%), and fish (59-66%), and less grains (-8-5%), dairy (-17-12%), meat (-27-25%), cheese (-11-6%), soft drinks (-45-42%), and juices (-56%-18%). More pronounced improvements were found when the optimization was not stratified by educational level. Across all socio-economic subgroups modest dietary changes can improve healthiness and environmental impacts of diets, without affecting diet costs. Furthermore, socio-economic disparities in diet quality can be reduced without additional diet costs, provided these educational subgroups are willing and facilitated to adopt diets divergent from their peer group.

Key-words: affordability, diet optimization, sustainable diets, greenhouse gas emissions, diet costs

Introduction

Food production and consumption significantly contribute to global environmental change and health burden [1, 2]. Animal-based foods have been identified as the main dietary contributors to environmental impacts [3, 4]. In the average Dutch diet, meat and dairy products contribute with about 50% to dietary greenhouse gas (GHG) emissions, land use, acidification, and eutrophication [5, 6]. Current meat consumption levels exceeds national dietary guidelines [5], while the consumption of fruit, vegetables, and legumes, known to prevent non-communicable diseases (NCDs) and associate with lower environmental impacts, remain generally insufficient [5]. Shifting towards more healthy and environmentally sustainable dietary patterns, including reduced meat and increased plant-based foods, is recommended to simultaneously improve public health and the environment [1]. In The Netherlands, the protein intake and proportion animal/plant protein has not materially changed since 1987 [7]. In the pursuit of sustainability goals, the Dutch government aims to transition from the current 60/40 animal to plant protein intake ratio towards an 50/50 ratio by 2030 [8].

Food costs are among the most important facilitating or inhibiting factors of dietary choices, though often neglected in nutritional research. In general, healthier foods such as fresh vegetables and fruits are more expensive compared to less healthy foods such as energy-dense, nutrient poor staple foods [9, 10]. Therefore, the consumption of healthier diets in general, as well as the transition to a more environmentally sustainable diet, might be counteracted by the higher costs of healthier foods [11]. Additionally, the rising food prices resulting from both inflationary pressures and population growth-induced scarcity have become an area of significant concern, and poses a major challenge for the adoption of healthy and environmentally sustainable diet, that is affordable for all [11, 12]. This challenge arises as policy goals, for instance in the Netherlands, commonly strive for universal access to affordable dietary patterns. Additionally, individuals with lower socio-economic positions (SEP), such as lower education, occupation or income, experience a higher prevalence of unhealthy diets [13, 14], diet-related chronic diseases [15], and health care expenditure [16] compared to higher SEP individuals. These socio-economic disparities, underscore the role of food costs in shaping divergent food consumption patterns across individuals with different socio-economic backgrounds.

Mathematical optimization models that optimize diets by making combinations of foods or food groups, providing optimal diets according to sustainability and nutritional objectives and constrains, have gained popularity [17, 18]. These studies have shown trade-offs between health and environmental sustainability, as prioritizing environmental outcomes may lead to unhealthy food substitutions [19], while prioritizing health may not always be environmentally sustainable nor affordable [17, 18]. Constructing feasible diets is often a challenge in optimization. Therefore, Kanellopoulos et al., (2020) developed an alternative mathematical model, in which optimized diets were derived as linear combinations of current diets of peers, i.e. benchmarking [20]. Consequently, the modelled diets closely align with existing food consumption patterns, as demonstrated by previous studies [21, 22]. While there is a growing body of research conducted utilizing such models [17, 18], the majority of studies only considered GHG emissions and diet quality, neglecting factors related to diet costs, affordability, other environmental indicators, and dietary disparities across SEP.

Universal access to healthy, safe, environmentally sustainable, and affordable diets is imperative for individuals across all socio-economic positions. Therefore, the aim of this modelling study is to investigate how dietary patterns can be improved for GHG emissions and DHD15 index among Dutch adults with different socio-economic backgrounds, and how these changes affect the costs of their diets.

Materials and methods

Study population

Data were derived from the Dutch National Food Consumption Survey 2019-2021. The survey aimed to gain insight into diets of children and adults living in the Netherlands. A full explanation is described elsewhere [23]. In short, Dutch children and adults aged 1–79 years were drawn from a consumer panel by Kantar and constitute a representative sample based on age, gender, education (for children, the education of their parents), region, and level of urbanization in the Netherlands. At baseline participants completed a digital questionnaire which provided information on height, weight and education, among other details. Information on body composition was gathered in different ways depending on age. Height was not measured for adults aged 71–79 y due to practical reasons. Body Mass Index (BMI) was calculated as the average body weight (in kg) divided by average height (in m) squared (kg/m^2). Categories for BMI were underweight or normal weight (<25 kg/m^2) and overweight or obese (>25 kg/m^2). For the current study, the target population for analysis comprised 1747 Dutch adults aged 18–79 years.

Dietary assessment and food composition

Participants were interviewed by telephone or face-to-face by a trained dietitian to assess dietary intake based on two non-consecutive 24-h dietary recalls. The period between the two 24-h dietary recalls was about four weeks. Interview dieticians used the GloboDiet system, which is computer-controlled interview software that enables answers to be directly entered in a computer. The Dutch Food Composition database (NEVO) was used to estimate energy-intake and macro and micronutrients (NEVO-online version 2021/7) [24].

Assessment of socio-economic position

Socio-economic position is a multifaceted concept, often captured by three proxy measures: education, occupation, and income [25]. As data on income are not available from DNFCS educational level was as the proxy to determine SEP. The educational level concerned the highest completed educational level of the participants. Educational level was categorized as low (primary education, lower vocational education, advanced elementary education), intermediate (intermediate vocational education, higher secondary education) and high (higher vocational education and university).

Assessment of dietary costs and affordability

Individual food and diet costs were derived using established methods [26]. Dutch food retail prices were linked to individual food consumption data from DNFCS 2019-2021. Food prices at barcode level were collected by Questionmark Intelligence B.V. using web-scraping techniques (n = 32135 products). This technique depends on webpage content and therefore data were cross-checked with the Dutch branded food database [27]. Food prices at barcode level from 1 Jan 2020 to 1 Jan 2021 were derived from seven supermarket chains. Data were collected every two weeks to take into account seasonality. Price promotions were reported but not included. For all barcodes the lowest retail prices were selected. The barcodes were accordingly categorized as generic food product, and therefore the prices of individual barcodes were summarized as minimal (lowest), mean and median food costs. Outliers were removed by excluding food prices above and below 1.5 times the interquartile range based on food product level. The generic food prices per food product level were linked to generic food items of NEVO database [28]. For home-made dishes and composite dishes, ingredients were separately reported in DNFCS, and prices were linked at ingredient level. In case recipes were available from NEVO, these recipes were used. For example, for 'fruit citrus average', the underlaying citrus fruits were attributed based on NEVO recipes [28]. All prices were adjusted for preparation and waste and were expressed in euros per edible portion. Based on the minimal price per barcodes, we determined minimal food costs and used it to estimate median diet costs. The variable obtained for each participant was the minimum costs value of their habitual diet in euros per day. Sensitivity analyses were performed using instead of the minimal costs of the aggregated food prices, the mean and median costs of the aggregated food prices.

Assessment of environmental sustainability

The environmental impact of food consumption was evaluated for greenhouse gas (GHG) emission (kg CO_2-eq), land use (m^2 * year), blue water use (also known as irrigation water) (m^3), acidification (kg SO_2-eq), fresh water eutrophication (kg P-eq), and marine eutrophication (kg N-eq). A full description is available elsewhere [5, 29, 30]. In short, environmental impacts were based on Life cycle analysis (LCA) methodology, which quantified quantifies the environmental impact through the foods' entire life cycle.

The LCAs performed had an attributional approach and hierarchical perspective and were performed following the ISO 14040 and 14044 guidelines. GHG emissions were recalculated following the guidelines of the Intergovernmental Panel on Climate Change (IPCC) (2006)) [31]. Economic allocation was applied when production processes led to more than one food product, except for milk, for which bio-physical allocation was used. The functional unit used was 1 kg of prepared food or drink on the plate. The LCA food database provided primary data for approximately 250 foods and drinks, which cover 75% of food consumption in the Netherlands [5, 29, 30]. The environmental impact of foods and beverages for which primary data were not available but that were consumed were previously for older versions of the DNFCS matched with similar foods, according to established methods [5, 30], and were for the DNFCS 2019-2021 extended. Briefly, foods were matched by expert judgement of a panel of scientists and were based on similarities in types of food, production systems and ingredient composition. For composite dishes, standardized recipes from the Dutch Food composition table (NEVO-online version 2021/7) were used where available and if not available, recipes were based on label information. More detailed information on the use of the database can be found elsewhere [5, 29, 30].

Assessment of healthiness of diet

The healthiness of the diets was assessed by means of the Dutch Healthy Diet 2015 index (DHD15) [32]. In short, this index assesses the adherence to the Dutch dietary guidelines. The method gives a ranking to dietary intake based on the level of adherence to Dutch dietary guidelines for a healthy diet for the components: vegetables, fruits, wholegrain products, legumes, nuts, dairy, fish, tea, fats and oils, coffee, red meat, processed meat, sweetened beverages and fruit juices, alcohol and sodium. For all components average food consumption was determined over two days and a score of 0 to 10 points was allotted based on type of component. Intakes between minimum and maximum values were scored proportionally. All components had a similar weight and were summed up for the overall DHD15 index. The coffee component was omitted from the index as no information was available on type of coffee consumption (e.g. filtered or unfiltered). This resulted in a range of 0 to 140 points, whereby 0 points indicated minimal adherence and 140 points indicated maximal adherence to the Dutch dietary guidelines for a healthy diet in 2015.

Data-analysis

To identify more environmentally sustainable, healthier, and preferred acceptable diets, the SHARP (Sustainable, Healthy, Affordable, Realistic and Preferrable) model was applied [20-22]. In short, this model generates improved diets for each individual person within a population, guided by predefined objectives and constraints. The optimization makes linear combinations of current diets that are benchmarked for higher DHD15 index and or lower GHG emissions than the index person. Using linear combinations of the diets of peers within the population eliminates the need to formulate explicit expert-based acceptability constraints. Consequently, the optimized diets do not surpass the best dietary options present within the target population, while they stay within the range of options that are acceptable in the cultural food context of the population. For the optimization, first the food consumption, GHG emissions, and DHD15 components were calculated based on individual dietary intake data, representing the current diet. Secondly, the current diets were optimized while adhering to a set of constraints. The primary objective was to minimize GHG emissions, and improving DHD15 index, which resulted in trade-offs between minimizing GHG emissions and maximizing the DHD15 (**Supplemental file 1**). Each individual’s diet was optimized in five models , in which each model GHG emissions was minimized, while a constraint on the minimum DHD15 index was increased gradually (**Supplemental file 1**). The difference of the DHD15 index between the first (model 1) and the fifth optimization (model 5) was assessed for each individual. The lower bound of the DHD15 index was defined by minimizing GHG emissions, setting this minimum GHG emissions as maximum constraint and consequently maximizing the DHD15 index. The upper bound was defined by maximizing the DHD index. The five models were run separately for the three levels of SEP, and in a secondary analysis the five models were run without stratifying for SEP. All optimizations were subject to the following additionally constraints: 1) energy and protein intake were set to be within ±5% of the current intake to maintain current energy and protein levels rather than substantially altering them, and 2) acceptability constraints were set with a range of ±33% based on individuals’ food group intake, except when the intake was 0. For zero intakes, food consumption generally should increase and therefore no constraints were set (e.g. legumes, nuts and fish). For presentation purposes food consumption for the optimized diets was aggregated in food groups and subgroups. Primary outcomes were GHG emission, DHD15 index, and diet costs. Secondary outcomes include energy and protein intake, proportion of plant protein, environmental impact indicators: land use, eutrophication, acidification and blue water consumption, food consumption according to food groups, and the nutrients: sodium, vitamin A, B2, B6, B12, calcium, iron, iodine, zinc and EPA/DHA.

Results are displayed as numbers or proportions, mean (standard deviation (SD)) or median (25th – 75th percentile) where appropriate. Characteristics of the population and their current diets and its characteristics were summarized for the total population and stratified by level of education. Differences in participants baseline characteristics and diets were assessed for trend using a Cochran-Armitage test for categorical data, regression for parametric continuous data and, Jonckheere-Terpstra test for non-parametric continuous data. All reported P-values are two-tailed, and $P < 0.05$ was considered significant. SAS statistical software version 9.4 (SAS Institute Inc., Cary, NC, USA) was used to estimate current diets and its characteristics, and to summarize outcomes of the optimization. FICO Xpress version X was used to determine the optimized diets. Outcomes from the five models were summarized using descriptive statistics. The primary outcomes GHG emission

DHD15 index and diet costs were plotted for each individual and summarized, for the current diets and five models. Relative differences in diet costs between the current and optimized diets were summarized using descriptive statistics and visualized by a graph. Food consumption and secondary outcomes for the optimized diet were summarized using descriptive statistics.

Results

Population and dietary characteristics

Of the 1747 Dutch participants aged 18-79 years, 50% was female (**Table 1**) with a mean age of 55 y (SD=15) and BMI of 26.7 kg/m^2 (SD=5.1). Among the participants, 25% had a low educational level (LEL), 36% had an intermediate educational level (IEL), and 38% had a high educational level (HEL). Participants with LEL were more likely to be female (56%), of higher age (60.8 y), and had a higher BMI (27.7 kg/m^2), compared to participants with IEL and HEL. The proportion of overweight or obese was 69% among participants with LEL, and respectively 60% and 47% among IEL and HEL.

Diets of participant with LEL, had compared IEL and HEL a lower DHD15 index (respectively 70, 73, and 77 points), contained on average less energy (respectively, 1977, 2061, and 2111 kcal), and had a lower plant protein proportion (respectively, 36%, 38%, and 42%) (**Table 1**). The median (25th-75th percentile) daily diet costs were with €3.15 (2.43-4.02) lower for participants with LEL than for those with IEL (€3.26 (2.56-4.17)), and HEL (€3,48 (2.67-4.58)). The median dietary environmental impacts of participants with LEL were comparable to those of IEL and HEL, except for usage of blue water; which was lower, with respectively 0.13, 0.15, and 0.17 m^3 per day.

Participants with LEL consumed lower amounts of vegetables (-47g, -15%), grains and grain-based products (-8g, -54%), fruits and olives (-34g, -21%), meat substitutes (4g, -62%) and dairy substitutes (-12g, -122%), nuts and seeds (-7g, -39%), cheese (-7g, -17%), fish (-5g, -25%), water (-155g, -19%), , juices (-8g, -23%), and alcoholic beverages (-27g, -20%) compared to those with HEL (**Table 2**). Participants with LEL consumed more dairy (+49g, +17%), meat (+27g, +34%), potatoes (+12g, +19%), and soft drinks (+35g, +21%) than those with HEL. The consumption of legumes, eggs, fats and oils, sugar and confectionery, biscuits and pastries, condiments and sauces, soups and bouillon, and savoury snacks were approximately similar (± 5 g/d) across the subgroups.

Participants with LEL allocated a relatively higher proportion of their expenditure to animal-based food, in contrast to those with IEL and HEL (respectively, 43%, 41%, and

37%) (**Table 3**). Additionally, they allocated a relatively lower proportion of their spending to plant-based food(respectively, 32%, 34%, and 38%)

Diet costs of optimizing diets for GHG emissions and Dutch Healthy Diet 2015 index

For participants with LEL, optimizing current diets for GHG emissions while improving the DHD15 index in model 1 resulted in a reduction of 24% in GHG emissions to 3.65 kg CO_2-eq and an increase of 30% in the DHD15 index to 92 points compared to current diets (**Figure 1a).** This diet had also the lowest costs (€3.02). The less stringent models 2-4 showed lower benefits for GHG emissions while the DHD15 index increased, and were less expensive than current diets. The fifth model had the highest GHG emissions of the modelled diets, but also the highest DHD15 index, with 4.49 kg CO_2-eq (-6%) and 116 points (66%), respectively. This diet was also most expensive of all diets (€ 3.28). The fourth model was selected as the preferable model, as it balanced GHG emissions and DHD15. This selected model showed a 20% reduction in GHG emissions to 3.83 kg CO_2-eq and a 56% increase in the DHD15 index to 109 points. Diet costs of the selected model were €3.14, and were approximately similar to costs of current diets (€3.15). Similar trends were found for optimized diets for IEL and HEL. For participants with IEL, the selected model showed a 24% reduction in GHG emissions to 3.64 kg CO_2-eq and a 52% increase in the DHD15 index to 111 points compared to current diets (**Figure 1b**). Diet costs were with €3.30 approximately similar to costs of current diets (€3.26). For participants with HEL, the selected model showed a 19% reduction in GHG emissions to 3.81 kg CO_2-eq and a 53% increase in the DHD15 index to 118 points compared to current diets (**Figure 1c**). Diet costs for the selected diet were with €3.36 slightly lower than costs of current diets (€3.48).

A secondary analyses addressed how the stratification for educational peer subgroups influenced the results. Using the total population as peers instead of using educational subgroups as peers, increased the options for making linear combinations of diets. The results consistently showed more pronounced reductions in GHG emissions and increases in DHD15 index for diets of all educational subgroups, while the diet costs were still similar compared to current diets (**Figure 2**). In the selected diets, DHD15 index were 121, 119 and 122, and GHG emissions were 3.48, 3.56 and 3.56 kg CO_2-eq respectively for participants with LEL, IEL and HEL.

The distribution of the relative (%) differences between costs of current and the optimized diets were approximately similar for all educational subgroups **Figure 3a-c**).

Diet composition of selected diets

The selected optimized diets for participants with LEL, contained more fruits (increase of 16%, in total 152g per day), vegetables (6%, 159g), nuts (89%, 21g, especially unsalted nuts), legumes (89%, 15g), fish (66%, 25g, with a shift from non-fatty to fatty fish), and eggs (13%, 18g) (**Figure 4**). Conversely, their diets contained less grains (-8, 153g) while shifting from refined to whole grains, dairy (-13%, 301g), and meat (-25%, 78g). The diets contained more water (13%; 807g) and less soft drinks (-42%; 116g) and juices (-51%; 13g). For participants with IEL the selected diets contained more fruits (8%; 145g), nuts (70%; 25g, especially unsalted nuts), legumes (136%; 17g), fish (60%; 27g, especially fatty fish), and eggs (19%; 21g). This was accompanied by lower amounts of grains (-5%; 178g), potatoes (-5%; 68g), dairy (-17%; 257g), and meat (-25%; 71g), and less cheese (-9%; 32g). The diets contained more water (16%; 1080g) and less soft drinks (-45%; 117g) and juices (-18%; 30g). The selected diets for participant with HEL contained more fruits (10%; 181g), potatoes (7%; 68g), nuts (37%; 25g, especially unsalted nuts), legumes (100%; 15g), and fish (59%; 32g, mainly fatty fish). However, the diet contained lower amounts of grains (-8%; 181g, with a shift from refined to whole grain), dairy (-12%; 262g), meat (-27%; 57g) and g cheese (-11%; 34g). Diets contained less soft drinks (-45% ;90g), juices (-56%;15 g) and alcoholic beverages (-15%; 113 g).

Secondary environmental and nutritional outcomes of selected diets

The environmental indicators land use, acidification, and eutrophication of both freshwater and marine water, were lower in the selected diets compared to current diets for all educational subgroups (**Supplemental file 2**). In contrast, blue water usage of the selected diets increased by 15%, 7%, and 12%, respectively for participants with LEL, IEL and HEL. Protein intake shifted towards more plant protein, with a most pronounced proportion of 45% for participants with HEL. Although protein intake was set as a constraint at ±5% the total protein intake only decreased with 3-4% (**Supplemental file 2**). Across all educational subgroups, the selected diets contained less energy, (saturated) fat, mono and disaccharides, and sodium, whereas more EPA, DHA, dietary fibre. Modest reductions of approximately 5% in micronutrients were observed (**Supplemental file 4**).

Sensitivity analysis

Sensitivity analyses addressed the use of aggregated median and mean food prices instead of the minimal food prices, based on the lowest prices of barcodes. Using mean and median food prices instead of the minimal food prices to calculate daily diet costs, did not alter our conclusions (**Supplemental file 6).**

Discussion

In this study, the median diet costs for the selected optimal diet model were similar to the costs of current diets, across all educational subgroups. The diets of low, intermediate and high educational subgroups had lower GHG emissions (respectively, 20%, 24%, and 19%) and higher diet quality according to the Dutch Healthy Diet 2015 (DHD15) index (respectively, 56%, 52%, and 53%). The selected diets of lower educational subgroups contained more vegetables (6%), while diets across all educational subgroups contained more fruit (10 to 16%) and less grains (-5 to -8%), with a shift towards whole grains. Moreover, all diets contained approximately 50g less dairy (-12 to -17%) and around 20-25g less red and processed meat (-25 to -27%), whereas more unsalted nuts, legumes, and eggs as alternative protein sources. In diets of low and intermediate educational subgroups soft drinks and juices were partially substituted with water, while diets of high educational subgroups contained less alcoholic beverages. Although diets substantially improved, the gap in diet quality between the educational subgroups remained in the optimized diets, which was largely due to lower amounts of vegetables and fruits and higher amounts of meat in the lower vs higher educational subgroups. Larger gains in environmental sustainability and diet quality are possible for low and intermediate educational subgroups, still without affecting diet costs, if the educational subgroups would be willing and able to adopt diets from outside their educational subgroup.

We demonstrated that without restricting the model to choose low-costs diets, it is possible to achieve more environmentally sustainable and healthier diets without increased diet costs. Similar to our study, Perignon did not apply cost constraints, and showed a significant 30% reduction in GHG emissions of French diets while maintaining nutritional adequacy and diet expenses [33]. More pronounced reductions in GHG emissions were accompanied by lower diet costs, but led to lower diet quality [33]. This was in line with our results, as the pursuit of the healthiest diets yielded less pronounced reductions in GHG emissions compared to the selected optimal diets, accompanied with increased diet costs. Previous research indicated that optimizing diets for nutritional adequacy or diet quality increased diet costs, and not consistently reduce GHG emissions [17, 18]. On the other hand, optimizing diets for environmental sustainability or adding cost constraints, led to lower diet quality [17, 18, 34, 35]. In the current study, the optimization for environmental sustainability combined with health constraints did not increase diet costs, aligning with previous research [36], and our estimated diet costs were comparable to those reported in earlier studies [30, 37]. Nevertheless, as potential trade-offs may arise among health, environmental sustainability, and costs, it becomes essential to thoroughly consider these aspects to prevent any aspect from being overlooked or neglected, resulting in unintended effects of dietary change.

The improvement in both environmental sustainability and diet quality, while simultaneously maintaining diet costs, can be attributed a shift in diet composition, primarily transitioning from meat to more plant-based foods. This is in alignment with previous findings [33, 36]. Animal-based foods, such as meat and fish, and fresh fruits and vegetables are often associated with higher expenses [9, 10, 38, 39]. Therefore, considering their contribution to daily diets alongside their elevated costs, these food groups are the most financially burdensome dietary components, as observed in our study and supported by earlier research [40]. The similar diet costs between the current and selected diets can be rationalized by the shift from costs attributed to meat to those attributed to increased quantities of fruits and vegetables. This reallocation in the selected diets resulted in a net-zero effect across the socio-economic subgroups.

Despite the selected optimized diets showed substantial improvements across all educational subgroups, the disparity in dietary quality persisted. This is in general observed between different levels of SEP [13, 14]. Lower SEP individuals tend to select processed meats, refined grains, and energy-dense foods and drinks [41], while higher SEP individuals tend to select more varied foods with a higher proportion of high-quality meats, fish, vegetables, and fruit [42]. In the current study, the selected optimized diets for lower educated subgroups contained for instance lower amounts of vegetables (159g) and higher amounts of red and processed meat (78g), than diets of higher educated subgroups (respectively, 197g vegetables and 57g meat). This was also reflected in the corresponding DHD15 index with respectively, 108, 111 and 118 for low, intermediate and high educated subgroups (range 10 points). Nonetheless, the secondary analyses with the total population as peers, virtually nullified the disparities in diet quality between the educational subgroups, with respectively, 121, 119 and 122 DHD15 points for low, intermediate and high educated subgroups (range 3 points). Using the total population as peers instead of using the educational subgroups as peers, increased the options for making linear combinations of diets. This resulted in higher diet quality for the low and intermediate educational subgroups, mainly due to higher amounts of vegetables and fruits and lower amounts of meat in the optimized diets. As this may require larger changes in food consumption of individuals with lower educational levels, this may therefore be less acceptable.

Previous research has shown that differences in diet quality between SEP can largely be attributed to food costs [13, 14, 43], resulting in low-income individuals and households having limited access to healthier foods [13, 14]. When considering the diet costs and affordability, the percentage of income spent on food would be a more objective indicator, yet data on income is lacking in the DNFCS. Based on income statistics of The Netherlands, low income households spend 19% (approximately €10,- per household) on food compared to 14% for the highest income households (approximately €23,- per household) [44, 45], supporting the concept that socio-economic differences are of major importance to diet quality. Beyond economics, food accessibility, and socio-cultural factors influence diet quality across SEP [13, 14]. Lower SEP individuals may face unhealthier food environments, limited access to healthier options [13, 14], while cultural traditions and social support both challenge and aid in maintain healthy diets [13, 46].

Diet optimization models are valuable tools to understand the socio-cultural, economic, and environmental synergies and trade-offs for the shift to sustainable diets. Their validity, however, depends on thoughtful formulation of model objectives and constraints [17, 18]. Firstly, the determination of diet acceptability was conducted objectively, considering the percentage deviation from current diets. While there is no agreed definition on how acceptability should be determined, deviation from current diets is assumed to be the best way to model acceptable diets [17]. Moreover, although diet models in general may simplify real-world situations, by studying subgroups with different SEP, aspects that are related to SEP such as food preferences, economical, behavioural or psychological factors that influence food choices, could be taken into account [13, 14]. Furthermore, educational level was used as proxy for SEP, which is multidimensional construct of occupation, education and income [25]. This leads to misclassification as individuals with lower levels of education may be engaged in high-earning professions, whereas individuals with higher levels of education may still be pursuing their studies and consequently possess lower incomes. Nevertheless, convincing economic principles [47] and previous studies have consistently shown the relationship between measures of SEP and diet quality, but due to the cross-sectional design of nutritional studies they do formally not allow to infer causality [13, 14]. Therefore, further research employing longitudinal and more comprehensive methodologies may deepen the understanding of the complex interplay between socioeconomic factors and dietary patterns.

Ensuring equitable access to healthy and sustainable diets to all is a pivotal responsibility of governments in Western countries. While we demonstrate the feasibility of a shift to more sustainable and still affordable diet, the promotion of such diets necessitates a facilitating food environment. In line with our study, research consistently shows healthier foods remain more expensive than unhealthy options, posing a barrier to improving food choices [9, 10]. To achieve the beneficial effects of the needed dietary shift among individuals with different socio-economic backgrounds, policy interventions, preferably disincentives and incentives, may improve wider access to such diets [13]. Furthermore, as dietary changes were not consistent across SEP, tailored policies may target specific food and consumer groups. For example, to reduce alcoholic beverage consumption among individuals with higher SEP, while increasing vegetable consumption among individuals with lower SEP. In addition, individuals with lower SEP may encounter difficulties with respect to the understanding of health campaigns and information, the use of tailored policies may improve their understanding [13]. While it may be possible to achieve large improvements in diets without additional expenses , monitoring food prices and diet cost is essential as higher prices may hinder for the adoption of healthier diets, particularly for those with lower SEP. At last, despite the substantial potential improvements, our findings indicate that the optimized diets fell short of the 2030 planetary boundaries target for GHG emissions [1] and plant/animal protein proportion objective of 50/50 from the Dutch government [8]. Achieving these targets would require larger dietary change, likely to be less acceptable to consumers.

To conclude, environmental sustainability and diet quality of Dutch dietary patterns can be improved, across all educational levels, without increasing diet costs. Environmental impact was reduced by 19-24% and adherence to dietary guidelines by 52-56%. Moreover, our analysis supports that factors associated with socio-economic position do contribute to the disparities in dietary quality.

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Tables and figures

Table 1. Population and dietary characteristics for 1747 Dutch adults aged 18-79 years with low, intermediate and high educational level, from the DNFCS 2019-2021.

	Total		**Low educational level**		**Intermediate educational level**		**High educational level**		
	n=1747		**n=445**	**(25%)**	**n=633**	**(36%)**	**n=669**	**(38%)**	**p-trend**
Demographics									
Sex									p<0.001
Females	867	(50%)	250	(56%)	317	(50%)	300	(45%)	
Men	880	(50%)	195	(44%)	316	(50%)	369	(55%)	
Age	55,0	(15,49)	60,8	(14,61)	52,5	(15,53)	53,4	(15,04)	p<0.001
BMI (kg/m2)	26,6	(5,08)	27,7	(5,02)	27,1	(5,61)	25,5	(4,31)	p<0.001
Weight status									p<0.001
Normal weight (BMI < 25 kg/m2)	746	(43%)	138	(31%)	253	(40%)	355	(53%)	
Overweight and obese (BMI ≥ 25 kg/m2)	1001	(57%)	307	(69%)	380	(60%)	314	(47%)	
Diet expenses									
Diet costs (€/day)	3,31	(2,56-4,26)	3,15	(2,43-4,02)	3,26	(2,56-4,17)	3,48	(2,67-4,58)	p<0.001
Dietary pattern									
Diet quality (DHD15 index)	74	(62-86)	70	(59-84)	73	(62-84)	77	(66-89)	p<0.001
Energy (kcal)	2059	(608)	1977	(565)	2061	(619)	2111	(619)	p<0.001
Protein (g)	81	(25)	80	(24)	81	(27)	81	(24)	0.61
Protein (En%)	16	(4)	16	(4)	16	(3)	16	(3)	p<0.001
Ratio plant/animal protein	40/60		36/64		38/72		42/58		p<0.001
Environmental impact									
GHG emission (kg CO2-eq/d)	4,77	(3,87-5,93)	4,80	(3,91-6,01)	4,78	(3,89-5,87)	4,72	(3,84-5,96)	0.55
Land use (m2*yr/d)	2,92	(2,35-3,55)	2,93	(2,37-3,58)	2,92	(2,35-3,56)	2,88	(2,37-3,47)	0.63
Freshwater eutrophication (g P-eq/d)	0,35	(0,28-0,43)	0,34	(0,28-0,42)	0,35	(0,29-0,43)	0,35	(0,28-0,43)	0.22
Marine water eutrophication (g N-eq/d)	7,34	(5,51-10,01)	7,73	(5,74-10,34)	7,44	(5,5-9,99)	7,12	(5,43-9,46)	p<0.001
Acidification (g SO2-eq/d)	43,92	(32,63-60)	46,17	(34,4-63,21)	44,20	(32,75-60,05)	41,83	(31,55-57,5)	p<0.001
Blue water (m3/d)	0,15	(0,11-0,21)	0,13	(0,1-0,18)	0,15	(0,11-0,21)	0,17	(0,12-0,24)	p<0.001

Values are presented as proportions, means (SD) and medians (25th-75th percentile).
DHD15; Dutch Healthy Diet 2015 index ;

Table 2. Mean food intake for current diet (grams per day and %), for 1747 Dutch adults aged 18-79 years with low, intermediate and high educational level, from the DNFCS 2019-2021.

	Total (n=1747)		Low educational level (n=445)		Intermediate educational level (n=633)		High educational level (n=669)		
	(gram)	(%)	(gram)	(%)	(gram)	(%)	(gram)	(%)	p-trend[1]
Grains and grain-based products	186	5,6%	167	5,3%	188	5,6%	196	5,7%	0.03
Vegetables	171	5,1%	150	4,7%	157	4,7%	197	5,7%	p<0.001
Fruit and olives	145	4,3%	131	4,1%	135	4,0%	165	4,8%	p<0.001
Potatoes	70	2,1%	76	2,4%	72	2,1%	64	1,9%	p<0.001
Nuts and seeds	15	0,5%	11	0,4%	15	0,4%	18	0,5%	p<0.001
Legumes	7	0,2%	7	0,2%	7	0,2%	8	0,2%	0.90
Dairy	314	9,4%	347	11,0%	309	9,2%	297	8,6%	p<0.001
Meat	91	2,7%	104	3,3%	95	2,8%	78	2,3%	0.03
Cheese	36	1,1%	32	1,0%	35	1,0%	39	1,1%	p<0.001
Fish	18	0,5%	15	0,5%	17	0,5%	20	0,6%	0.08
Eggs	17	0,5%	16	0,5%	18	0,5%	16	0,5%	0.30
Dairy replacers	11	0,3%	6	0,2%	12	0,4%	14	0,4%	0.01
Meat replacers	5	0,1%	3	0,1%	3	0,1%	7	0,2%	p<0.001
Soup and bouillon	22	0,6%	22	0,7%	18	0,5%	25	0,7%	0.31
Biscuits and pastries	40	1,2%	42	1,3%	38	1,1%	40	1,2%	0.10
Condiments and sauces	35	1,1%	34	1,1%	35	1,0%	36	1,1%	0.62
Sugar and confectionary	23	0,7%	21	0,7%	24	0,7%	24	0,7%	0.90
Fats and oils	23	0,7%	23	0,7%	22	0,7%	22	0,7%	0.04
Savoury snacks	16	0,5%	12	0,4%	19	0,6%	16	0,5%	0.42
Miscellaneous	2	0,1%	1	0,0%	3	0,1%	3	0,1%	0.31
Coffee and tea	898	26,8%	898	28,4%	852	25,3%	940	27,4%	0.60
Water	855	25,6%	713	22,5%	927	27,5%	881	25,6%	0.03
Soft drinks	191	5,7%	199	6,3%	212	6,3%	164	4,8%	0.02
Fruit and vegetable juice	33	1,0%	26	0,8%	37	1,1%	34	1,0%	0.18
Alcohol beverages	121	3,6%	106	3,3%	120	3,6%	132	3,8%	0.05

[1] p-trend is for %

Table 3. Average diet expenses (in %) of the current diet per food group for 1747 Dutch adults aged 18-79 years with low, intermediate and high educational level, from the DNFCS 2019-2021.

	Total (n=1747)	Low educational level (n=445)	Intermediate educational level (n=633)	High educational level (n=669)	p-trend
Grains and grain-based products	**7,2%**	**6,9%**	**7,4%**	**7,3%**	**0.07**
Vegetables	12,9%	11,6%	12,1%	14,4%	p<0.001
Fruit and olives	10,5%	9,3%	10,0%	11,7%	p<0.001
Potatoes	2,1%	2,2%	2,1%	1,9%	0.004
Nuts and seeds	2,2%	1,7%	2,2%	2,6%	p<0.001
Legumes	0,2%	0,2%	0,2%	0,3%	0.67
Dairy	8,6%	10,0%	8,5%	7,7%	p<0.001
Meat	18,8%	22,4%	19,7%	15,6%	p<0.001
Cheese	6,4%	6,0%	6,3%	6,8%	0.01
Fish	4,2%	3,6%	4,0%	4,7%	0.02
Eggs	1,5%	1,6%	1,7%	1,4%	0.16
Dairy replacers	0,4%	0,2%	0,4%	0,4%	0.04
Meat replacers	0,8%	0,5%	0,6%	1,3%	p<0.001
Soup and bouillon	0,2%	0,2%	0,2%	0,2%	0.54
Biscuits and pastries	2,6%	2,9%	2,5%	2,5%	0.09
Condiments and sauces	2,2%	2,0%	2,2%	2,4%	0.05
Sugar and confectionary	1,9%	1,6%	2,0%	2,0%	0.06
Fats and oils	1,6%	1,6%	1,4%	1,7%	0.22
Savoury snacks	2,0%	1,6%	2,4%	1,8%	0.72
Miscellaneous	0,3%	0,1%	0,4%	0,3%	0.49
Coffee and tea	4,6%	5,3%	4,6%	4,0%	p<0.001
Water	0,6%	0,6%	0,7%	0,6%	0.68
Soft drinks	2,8%	3,2%	2,9%	2,4%	0.01
Fruit and vegetable juice	1,1%	0,9%	1,1%	1,2%	0.24
Alcohol beverages	4,4%	3,8%	4,2%	4,9%	0.006

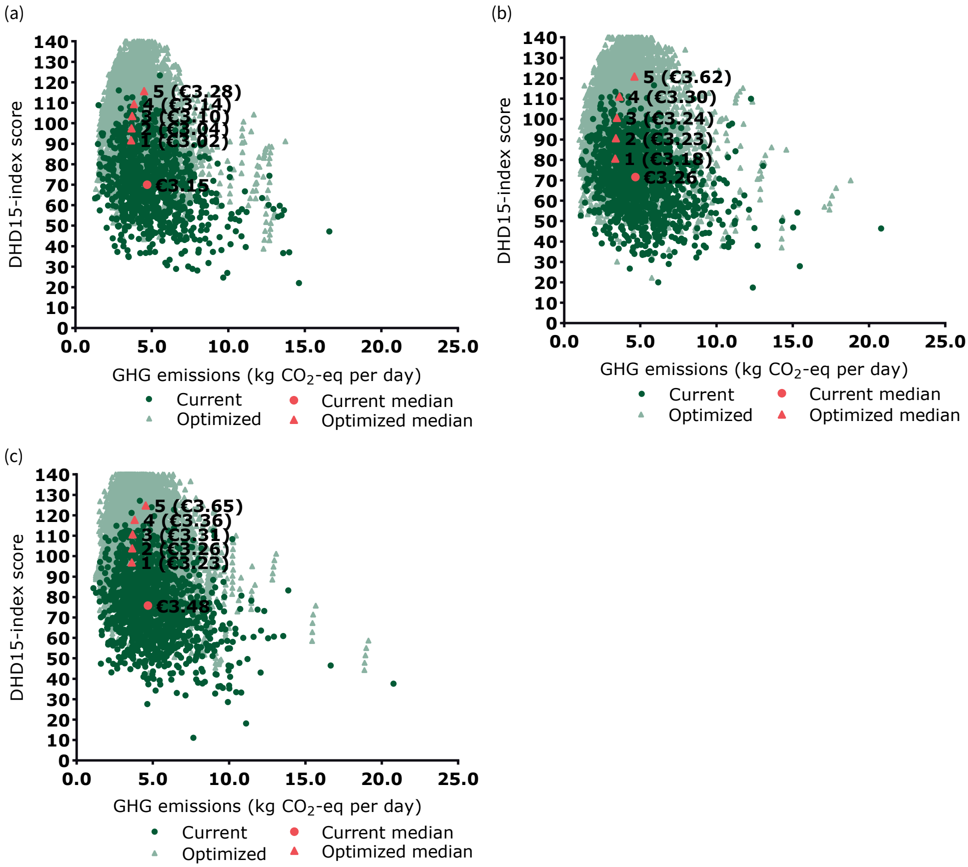


Figure 1a-c. Trade-off between minimizing greenhouse gas (GHG) emission and maximizing Dutch Healthy Diet index 2015 for 1747 Dutch adults aged 18-79 years with low (a), intermediate (b) and high (c) educational levels, from the DNFCS 2019-2021. Values are presented as medians. Dark green circles represent the individual data of current diets and the light green triangles for the optimized diets for all five models (1 to 5). The star indicates the median of current diets, the triangles numbered 1 to 5, represent the median of the models, with median prices. Supplemental file 2 contains the descriptive data.

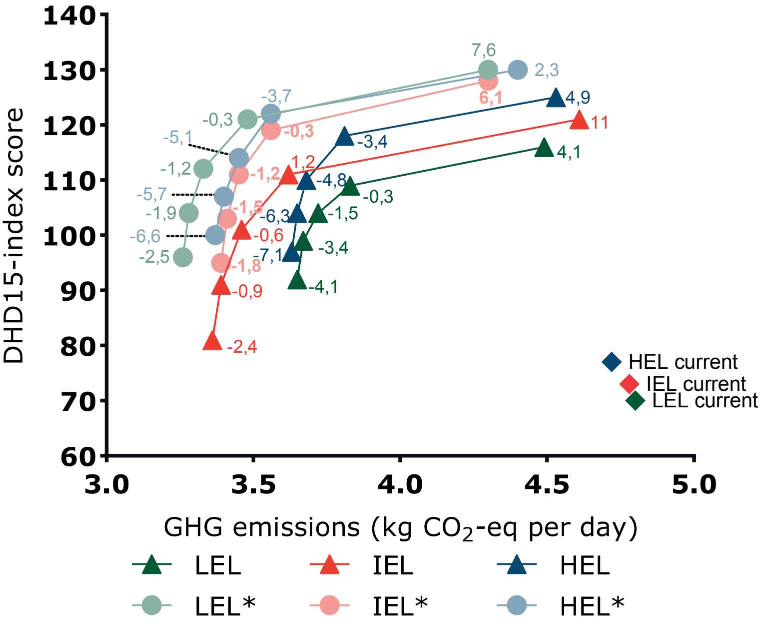


Figure 2. Greenhouse gas (GHG) emission and the Dutch Healthy Diet index 2015 for optimized diets of 1747 Dutch adults aged 18-79 years with low, intermediate and high educational level, from the DNFCS 2019-2021. The horizontal and vertical axis show the absolute GHG emissions and DHD15 index. The numbers at each point represent the percent difference in diet costs between current and optimized diets. Filled diamonds represent the GHG emissions and DHD15 index of current diets. Filled triangles represent optimization with educational groups as peers. *Filled rounds represent results of the secondary analysis using the total population as peers, showing larger reductions in GHG emissions and larger improvements in dietary quality (DHD15). For all models and educational subgroups, the most healthy diet has the highest GHG emissions and highest diet costs. LEL, low educational level; IEL, intermediate educational level; HEL, high educational level. Supplemental file 6 contains descriptive data related to the secondary analysis in which models were not stratified for educational subgroups.

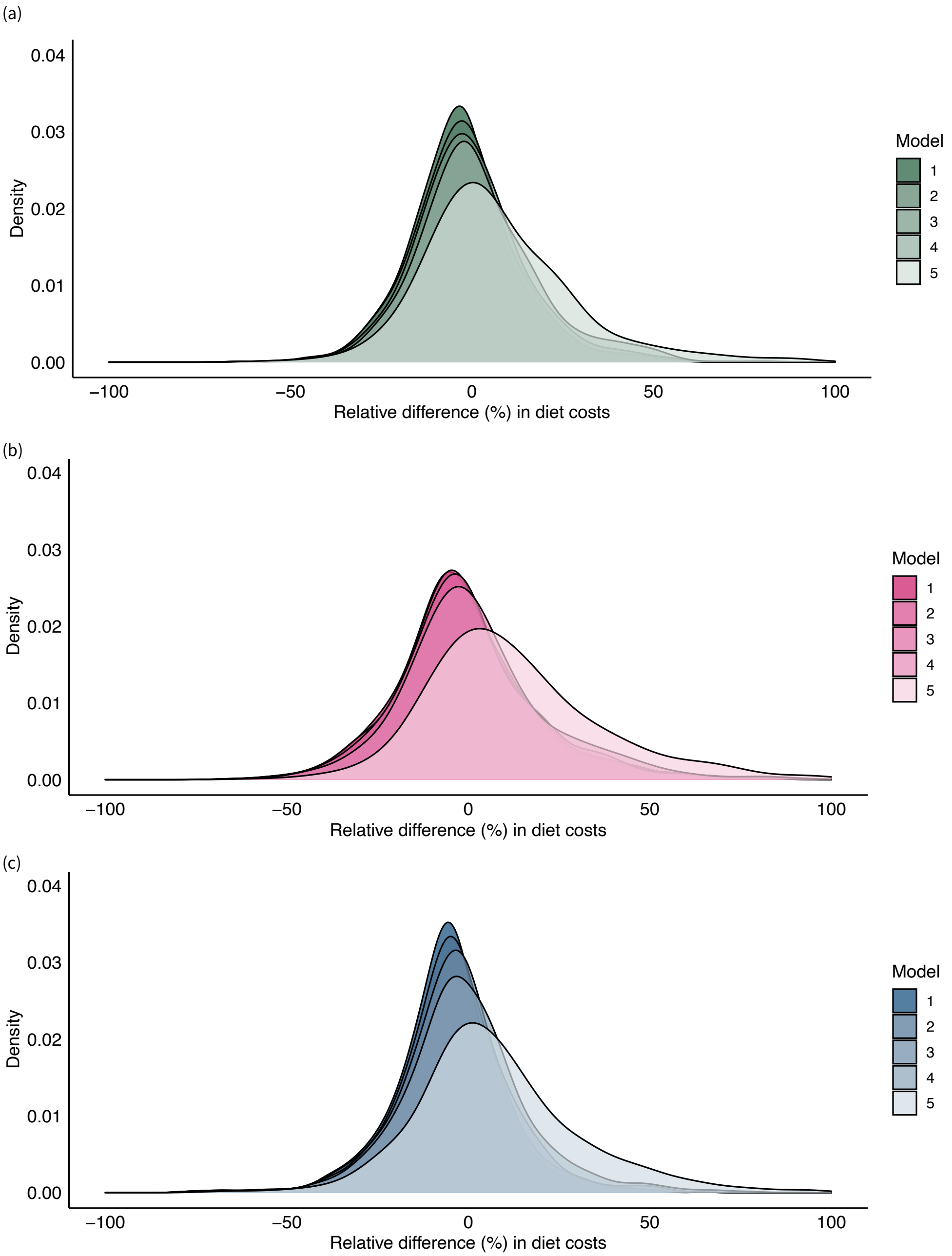


Figure 3a-c. Relative (%) difference in diet costs between current and optimized diets (model 1 to 5) for 1747 Dutch adults aged 18-79 years with low (a), intermediate (b) and high (c) educational level. Supplemental file 5 contains the distribution of the diet costs for the current and optimized diets.

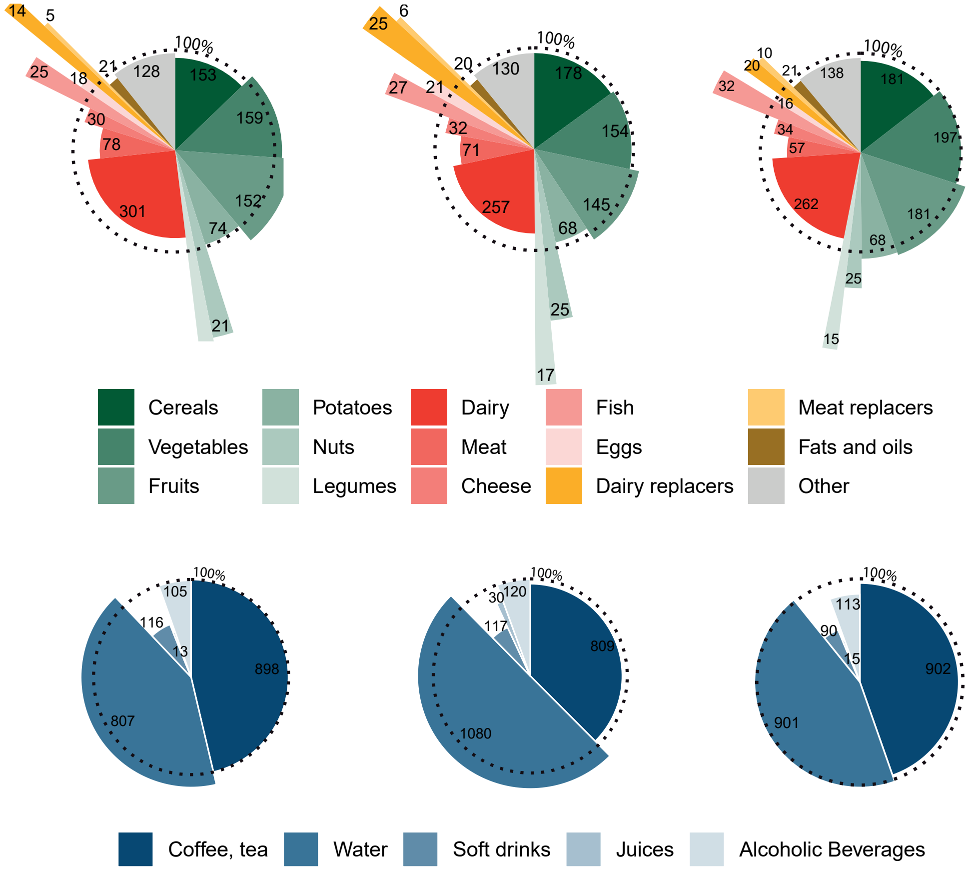


Figure 4. Share of foods (top) and beverages (bottom) in daily diets for the selected diets for 1747 Dutch adults aged 18-79 years. The size of the sectors represent the amount of food in the selected diets, whereas the radius represent the magnitude of relative difference between current and selected diets for low (a), intermediate (b) and high (c) educational subgroups. The dotted round circle represent the current diet. Sectors outside the dotted circle indicate increased amounts, whereas sectors inside the dotted grey line represents decreased amounts compared to current diets. Values presented in the sectors display the absolute amounts of foods (in g) in the diets. Supplemental file 3 contains descriptive data on food consumption in grams per day and relative differences for the current diet compared to optimized diets.

Supplementary files

Supplemental file 1. SHARP model

Supplemental file 2. Summary output for optimized diets

Supplemental file 3. Food consumption and differences between current and optimized diets

Supplemental file 4. Macro and micronutrients for current and optimized diets

Supplemental file 5. Distribution of diet costs for current and optimized diets

Supplemental file 6. Outcomes diet optimization for secondary analysis, using the total population as peers

Supplemental file 1 SHARP model

Supplemental file 1.1. Explanation SHARP model

The objective functions, the main constraints, and the constraints used to calculate the diet quality index (Dutch Healthy Diet index 2015 (DHD15)) are presented and explained below. This model is used iteratively to calculate an optimal diet for each of the individuals in the sample. From now on the evaluated diet is indicated with an index *j'*.

Objective functions

Equation *(1)* is an objective function of the model, which minimizes the total GHG emissions of the optimized diet, expressed as a linear combination of GHG emissions of current diets.

$$min\left\{F_{ghge} = \sum_{j} ghge_j \cdot L_j\right\} \tag{1}$$

Where $\mathrm{F}_{\mathrm{ghge}}$ is the total greenhouse gas (GHG) emissions of the optimized diet, $\mathrm{ghge}_{\mathrm{j}}$ is the GHG emissions of diet j, and L_{j} is the share of diet j in the optimized diet.

Objective function *(2)* maximizes the Dutch Healthy Diet index 2015 (DHD15-index) which is selected to be the health index in this study [1].

$$max\left\{F_{heal} = \sum_{c} S_c\right\} \tag{2}$$

Where $\mathrm{F}_{\mathrm{heal}}$ is the health quality index of the optimized diet, and S_{c} is the partial health index score of food component *c*.

Main constraints

Constraints *(3)* are used to calculate the absolute deviation between food group consumption of the optimized and the current diet.

$$\sum_{j} q_{g,j} \cdot L_j - D_g^+ + D_g^- = q_{g,j'} \qquad \forall\, g \tag{3}$$

Where $\mathrm{q}_{\mathrm{g,j}}$ is the consumption of food group *g* in diet *j*, $\mathrm{q}_{\mathrm{g,j'}}$ is the consumption level of food group *g* in the evaluated diet j', $\mathrm{D}_{\mathrm{g}}^{+}$ is the positive deviation between the food group consumption of the optimized diet (i.e. $\Sigma_{\mathrm{j}} q_{g,j} \cdot L_j$) and the current diet ($q_{g,j'}$), D_g^{-} is the negative deviation between the food group consumption of the optimized diet and the current diet.

Equations *(4)* impose that for each food group the sum of the deviations is smaller than 33% of the mean current consumption in consumers, ensuring that the optimized diet remains within realistic ranges.

$$D_a^+ + D_a^- \leq 0.33 * \ mean_a \qquad \forall\, g \qquad (4)$$

Where $\mathrm{mean_g}$ is the average current consumption of food group *g* in consumers (i.e. consumption>0).

Equation *(5)* is the add up constraint imposing that the sum of the shares of current diets *j* in the optimized diet does not exceed 1.

$$\sum_j L_j = 1 \qquad (5)$$

Constraints *(6)* impose that the partial health index scores of each food component in the optimized diet are larger or equal to the partial health index scores of the same food component in the current diet, i.e. ensuring the diet will be at least as healthy as the current diet in each food component.

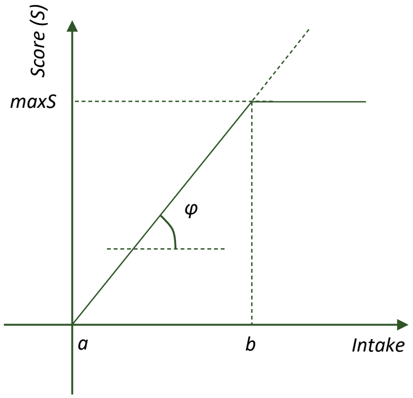
$$S_c \geq s_c \qquad \forall\, c \qquad (6)$$

Where $\mathrm{S_c}$ is the food component score that corresponds to the optimized food component intake, $\mathrm{S_c}$ is the food component score that corresponds to the current food component intake.

Modelling the partial health scores

The DHD15 index exists of 15 food components. There are four types of calculating the score for a food component in the DHD15 index, which are explained below.

The score of the components of the DHD15-index like the one presented in Supplemental figure 1 are modelled using constraints *(7)* and *(8)*. The components vegetables, fruit, whole grain products, legumes, nuts, fish (including 4g lean fish), and tea are of this type. Constraint *(7)* imposes that the score increases from the minimum possible score (0) with a slope of φ. Constraint *(8)* imposes that the score of the component *c* is restricted to the maximum score of the specific component.

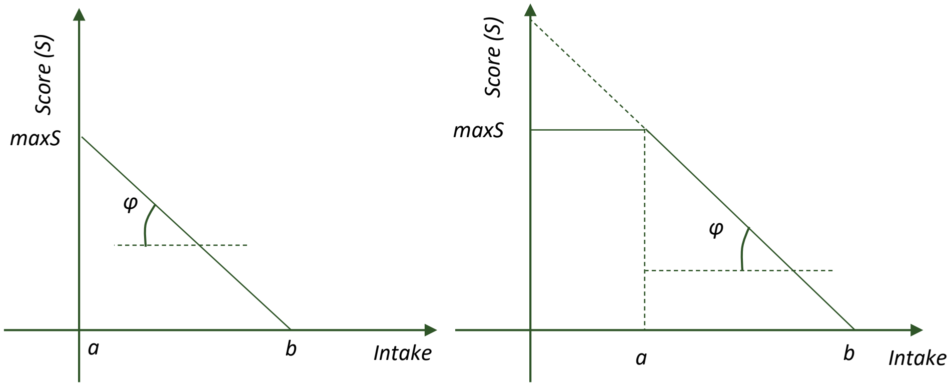


Supplemental figure 1. Scoring function for food components of the Dutch Healthy Diet index 2015 that have a minimum intake level.

$$S_c \leq \varphi_c * intake_c \quad (7)$$
$$S_c \leq maxS_c \quad (8)$$

Where a_c is the maximum food component intake level with the minimum individual health score, b_c is the smallest intake level that receive an individual health score of 10, φ_c is the rate of change of the score between food component intake levels a_c and b_c, $\mathrm{maxS_c}$ is the maximum possible individual score of the component (i.e. either 5 or 10), $\mathrm{intake_c}$ is the intake in gram of the component *c* in the optimized diet.

The score of the components of the DHD15 index like the one presented in Supplemental figure 2 are modelled using constraints *(9)-(12)*. The components red meat, processed meat, sweetened beverages and fruit juices, alcohol, and sodium are of this type.



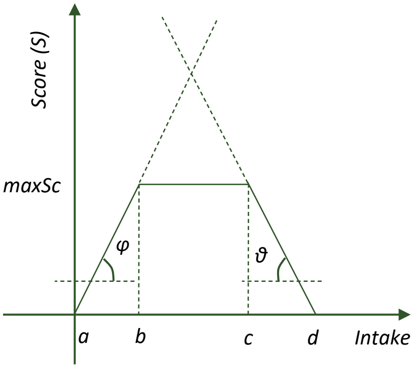
Supplemental figure 2. Scoring function for food components of the Dutch Healthy Diet index 2015 that have a maximum intake level. The maximum intake level can be either 0 (left) or some positive amount a (right).

$$Intake_c - b_c \leq bigM \cdot B_c \quad (9)$$
$$S_c \leq maxS_c - \varphi_c(intake_c - a_c) + bigN \cdot B_c \quad (10)$$
$$b_c - intake_c \leq b_c \cdot (1 - B_c) \quad (11)$$
$$S_c \leq maxS_c \cdot (1 - B_c) \quad (12)$$

Where a_c is the maximum food component intake level with the maximum individual health score, b_c is the smallest intake level that receive the minimum individual health score, B_c is a binary variable that takes the value of 1 if the food component intake becomes larger than b_c (and 0 otherwise), and *bigM* and *bigN* are very large numbers.

If the binary variable B_c becomes 1 then constraints *(9)* and *(10)* become not binding while constraints *(11)* and *(12)* become binding and impose that the intake is greater than b_c and the individual health score is set to 0. On the contrary if B_c becomes 0 then constraints *(11)* and *(12)* become not binding. Constraint *(9)* imposes that the food component intake is lower than b_c and constraint *(10)* imposes that the score decreases from the maximum possible individual score with a slope φ_c. For food component levels lower than a the right hand side of constraint *(10)* become more than the maximum possible individual food component score. However because of constraint *(12)* the score value is restricted to the maximum possible score of the specific component.

The score of the components of the DHD15 index like the one presented in Supplemental figure 3 are modelled using constraints *(13)-(17)*. The component dairy (including 40g cheese) is of this type.



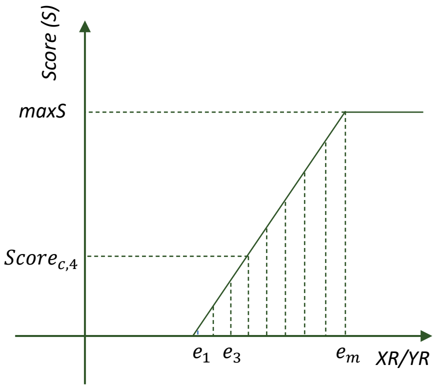
Supplemental figure 3. Scoring function for food components of the Dutch Healthy Diet index 2015 that have an optimum intake level.

$$Intake_c - d_c \leq bigM \cdot B_c \quad (13)$$
$$S_c \leq maxS_c - \theta_c(intake - c_c) + bigN \cdot B_c \quad (14)$$
$$d_c - intake \leq d_c \cdot (1 - B_c) \quad (15)$$
$$S_c \leq maxS_c \cdot (1 - B_c) \quad (16)$$
$$S_c \leq \varphi_c * intake_c \quad (17)$$

Where c_c is the maximum food component intake level with the maximum individual health score, and d_c is the minimum food component intake level with the minimum individual health score.

If the binary variable B_c becomes 1 then constraints *(13)* and *(14)* become not binding while constraints *(15)* and *(16)* become binding and impose that the intake is greater than d_c and the individual health score is set to 0. On the contrary if B_c becomes 0 then constraints *(13)* and *(14)* become not binding. Constraint *(13)* imposes that the food component intake is lower than d_c and constraint *(14)* imposes that the score decreases from the maximum possible individual score with a slope θ. For food component levels lower than c_c the right hand side of constraint *(14)* become more than the maximum possible individual food component score. However because of constraint *(16)* the score value is restricted to the maximum possible score of the specific component *c*. Constraint *(17)* imposes that the score increases from the minimum possible score (0) with a slope of φ_c, again restricted by constraint *(16)* to the maximum possible score of the specific component.

The DHD15 score comprises of ratio components like the 'Replace refined with wholegrain products' and 'Replace butter and hard fats with margarines and oils' component. The score of such components are presented in Supplemental figure 4 and are modelled using constraints *(18)-(20)*. To approximate ratio components in a mixed integer linear programming model we assumed that the individual score function of a ratio component remain the same between specific intake levels *(m)*. By increasing the number of intake levels we achieved a rather accurate approximation of the score function of such components.



Supplemental figure 4. Scoring function for food components of the Dutch Healthy Diet index 2015 that include a ratio.

$$e_{c,m} * YR_c - XR_c \leq bigM \; * (1 - Y_{c,m}) \qquad \forall\, m \tag{18}$$

$$\sum_m Y_{c,m} = 1 \tag{19}$$

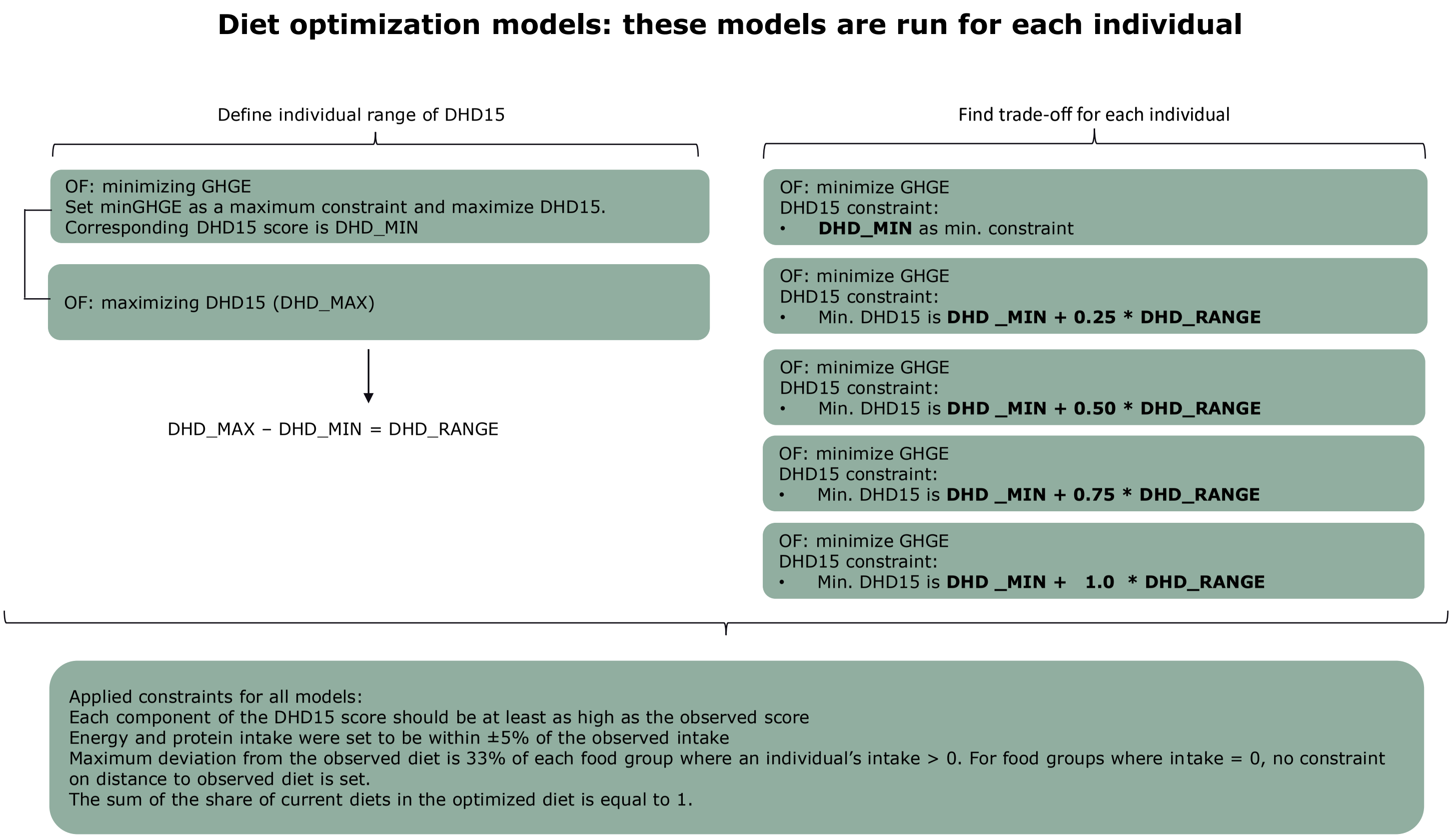
$$S_c = \sum_m Score_{c,m} \; * Y_{c,m} \tag{20}$$

Where XR is the intake of the nutrient or food group that is on the numerator of the ratio component (e.g. the intake of whole grains in the optimized diet), YR is the intake of the nutrient or food group that is on the denominator (e.g. the intake of refined grains in the optimized diet), e_m is the level of XR/YR that receives the $score_{c,m}$, $Y_{c,m}$ is a binary variable that takes the value of 1 if the value of the ratio component XR/YR is larger than e_m (and 0 otherwise).

Equation *(18)* imposes that the binary variable $Y_{c,m}$ becomes 1 if e_m is smaller than XR/YR. Equation *(19)* ensures that only one score level can be selected. Equation *(20)* calculates the score of ratio components of the DHD15 index.

Finally, constraints *(21)* are the domain specific constraints of the decision variables.

$$L_j \geq 0 \;\; \forall\, j, \quad D_g^+ \geq 0 \;\; \forall g, \quad D_g^- \geq 0 \;\; \forall g, \quad S_c \geq 0 \;\; \forall c\,, B_c \; \in (0,1) \;\; \forall c, \quad Y_{c,m} \in (0,1) \;\; \forall c, m \tag{21}$$



Diet optimization models: these models are run for each individual

Define individual range of DHD15

OF: minimizing GHGE
Set minGHGE as a maximum constraint and maximize DHD15.
Corresponding DHD15 score is DHD_MIN

OF: maximizing DHD15 (DHD_MAX)

DHD_MAX – DHD_MIN = DHD_RANGE

Find trade-off for each individual

OF: minimize GHGE
DHD15 constraint:
- **DHD_MIN** as min. constraint

OF: minimize GHGE
DHD15 constraint:
- Min. DHD15 is **DHD _MIN + 0.25 * DHD_RANGE**

OF: minimize GHGE
DHD15 constraint:
- Min. DHD15 is **DHD _MIN + 0.50 * DHD_RANGE**

OF: minimize GHGE
DHD15 constraint:
- Min. DHD15 is **DHD _MIN + 0.75 * DHD_RANGE**

OF: minimize GHGE
DHD15 constraint:
- Min. DHD15 is **DHD _MIN + 1.0 * DHD_RANGE**

Applied constraints for all models:
Each component of the DHD15 score should be at least as high as the observed score
Energy and protein intake were set to be within ±5% of the observed intake
Maximum deviation from the observed diet is 33% of each food group where an individual's intake > 0. For food groups where intake = 0, no constraint on distance to observed diet is set.
The sum of the share of current diets in the optimized diet is equal to 1.

OF, Objective function (what to maximize or minimize)

Supplemental figure 5. Steps of diet optimization models.

References

1. Looman M, Feskens EJ, de Rijk M, Meijboom S, et al. (2017). Development and evaluation of the Dutch Healthy Diet index 2015. *Public Health Nutrition* **20**(13): 2289-2299. DOI: 10.1017/S136898001700091X.

Supplemental file 2. Summary output for optimized diets

Table 2.1 Summary output for characteristics of optimized diets for 445 Dutch adults 18-79 years with low educational level, from the Dutch National Food Consumption Survey 2019-2021.

	Low educational level														
	Model 1			**Model 2**			**Model 3**			**Model 4**			**Model 5**		
Diet costs (€/day) based on															
Minimum price	3,02	(2,43-	3,72)	3,04	(2,46-	3,72)	3,10	(2,50-	3,77)	3,14	(2,57-	3,82)	3,28	(2,78-	3,92)
Mean price	7,05	(5,80-	8,64)	7,13	(5,89-	8,67)	7,21	(5,99-	8,76)	7,32	(6,13-	8,78)	7,74	(6,59-	9,05)
Median price	6,76	(5,57-	8,24)	6,85	(5,66-	8,26)	6,90	(5,75-	8,35)	7,02	(5,89-	8,41)	7,38	(6,29-	8,67)
DHD15 (points)	92	(79-	103)	98	(84-	109)	104	(90-	115)	109	(96-	121)	116	(101-	128)
Energy (kcal)	1900	(619)		1901	(618)		1904	(616)		1910	(614)		1932	(609)	
Protein (g)	76	(27)		77	(27)		77	(27)		78	(26)		79	(26)	
Plant protein (%)	41%			40%			0%			40%			38%		
GHG emission (kg CO_2-eq/d)	3,65	(2,97-	4,67)	3,67	(2,99-	4,69)	3,72	(3,02-	4,72)	3,83	(3,12-	4,82)	4,49	(3,62-	5,37)
Land use (m^2*yr/d)	2,42	(2,00-	3,04)	2,44	(2,01-	3,05)	2,46	(2,02-	3,05)	2,52	(2,08-	3,10)	2,73	(2,24-	3,32)
Freshwater eutrophication (g P-eq/d)	0,30	(0,25-	0,38)	0,30	(0,25-	0,37)	0,30	(0,25-	0,38)	0,31	(0,26-	0,38)	0,33	(0,28-	0,40)
Marine water eutrophication (g N-eq/d)	5,43	(4,40-	7,04)	5,47	(4,42-	7,05)	5,51	(4,45-	7,12)	5,62	(4,58-	7,30)	6,88	(5,39-	8,70)
Acidification (g SO_2-eq/d)	31,93	(25,01-	41,53)	32,09	(25,19-	41,80)	32,28	(25,38-	42,31)	33,12	(26,33-	43,33)	40,98	(31,77-	51,46)
Blue water (m^3/d)	0,13	(0,10-	0,18)	0,14	(0,10-	0,18)	0,14	(0,11-	0,19)	0,15	(0,12-	0,19)	0,17	(0,13-	0,20)
PREF	673	(450-	927)	688	(483-	932)	717	(501-	951)	743	(546-	982)	815	(609-	1046)

Values are presented as proportions, means (SD) and medians (25th-75th percentile).

DHD15, Dutch Healthy Diet 2015 index; PREF, preferences score based on deviation from current diets

Table 2.2. Summary output for characteristics of optimized diets for 663 Dutch adults 18-79 years with intermediate educational level, from the Dutch National Food Consumption Survey 2019-2021.

	Intermediate educational level														
	Model 1			**Model 2**			**Model 3**			**Model 4**			**Model 5**		
Diet costs (€/day) based on															
Minimum price	3,18	(2,66-	3,73)	3,23	(2,70-	3,75)	3,24	(2,69-	3,79)	3,30	(2,79-	3,87)	3,62	(3,08-	4,32)
Mean price	8,03	(6,80-	9,25)	7,98	(6,82-	9,17)	7,84	(6,64-	9,13)	7,79	(6,64-	9,15)	8,48	(7,29-	9,89)
Median price	7,71	(6,57-	8,95)	7,69	(6,59-	8,85)	7,55	(6,38-	8,73)	7,47	(6,33-	8,70)	8,08	(6,96-	9,41)
DHD15 (points)	81	(71-	91)	91	(81-	99)	101	(90-	109)	111	(100-	120)	121	(108-	131)
Energy (kcal)	1983	(675)		1985	(674)		1984	(673)		1987	(671)		2019	(660)	
Protein (g)	78	(29)		78	(29)		78	(29)		79	(29)		81	(29)	
Plant protein (%)	45%			45%			44%			43%			40%		
GHG emission (kg CO_2-eq/d)	3,36	(2,62-	4,37)	3,39	(2,65-	4,41)	3,46	(2,71-	4,47)	3,64	(2,88-	4,65)	4,61	(3,74-	5,64)
Land use (m^2*yr/d)	2,30	(1,78-	2,89)	2,32	(1,82-	2,91)	2,37	(1,86-	2,94)	2,48	(1,96-	3,05)	2,81	(2,27-	3,42)
Freshwater eutrophication (g P-eq/d)	0,29	(0,22-	0,37)	0,29	(0,23-	0,37)	0,30	(0,23-	0,37)	0,31	(0,25-	0,39)	0,35	(0,29-	0,43)
Marine water eutrophication (g N-eq/d)	4,84	(3,74-	6,37)	4,88	(3,80-	6,42)	4,97	(3,88-	6,53)	5,27	(4,14-	6,85)	6,96	(5,42-	8,69)
Acidification (g SO_2-eq/d)	27,91	(20,93-	37,71)	28,28	(21,10-	38,06)	28,66	(21,78-	38,45)	30,35	(23,17-	40,06)	40,95	(30,90-	52,08)
Blue water (m^3/d)	0,13	(0,10-	0,17)	0,14	(0,10-	0,18)	0,15	(0,11-	0,18)	0,16	(0,13-	0,20)	0,19	(0,16-	0,23)
PREF	921	(713-	1150)	919	(718-	1146)	912	(702-	1135)	908	(713-	1144)	940	(740-	1176)

Values are presented as proportions, means (SD) and medians (25^{th}-75^{th} percentile).

DHD15, Dutch Healthy Diet 2015 index; PREF, preferences score based on deviation from current diets

Table 2.3. Summary output for characteristics of optimized diets for 669 Dutch adults 18-79 years with high educational level, from Dutch National Food Consumption Survey 2019-2021.

	High educational level														
	Model 1			Model 2			Model 3			Model 4			Model 5		
Diet costs (€/day) based on															
Minimum price	3,23	(2,58 -	4,02)	3,26	(2,61 -	4,04)	3,31	(2,65 -	4,05)	3,36	(2,73 -	4,14)	3,65	(3,06 -	4,43)
Mean price	7,79	(6,40 -	9,56)	7,83	(6,51 -	9,60)	7,87	(6,57 -	9,63)	7,98	(6,66 -	9,76)	8,63	(7,37 -	10,35)
Median price	7,39	(6,09 -	9,12)	7,44	(6,17 -	9,14)	7,48	(6,25 -	9,17)	7,59	(6,35 -	9,32)	8,19	(7,02 -	9,85)
DHD15 (points)	97	(85 -	109)	104	(92 -	114)	111	(98 -	120)	118	(104 -	126)	125	(110 -	134)
Energy (kcal)	2011	(689)		2013	(686)		2012	(688)		2020	(691)		2046	(682)	
Protein (g)	77	(28)		77	(27)		77	(27)		78	(28)		80	(27)	
Plant protein (%)	45%			45%			45%			45%			43%		
GHG emission (kg CO_2-eq/d)	3,63	(2,93 -	4,62)	3,65	(2,95 -	4,66)	3,68	(2,98 -	4,70)	3,81	(3,07 -	4,82)	4,53	(3,65 -	5,47)
Land use (m^2*yr/d)	2,41	(1,96 -	2,95)	2,42	(1,97 -	2,97)	2,45	(2,00 -	3,00)	2,51	(2,05 -	3,06)	2,77	(2,28 -	3,30)
Freshwater eutrophication (g P-eq/d)	0,29	(0,24 -	0,36)	0,29	(0,24 -	0,36)	0,30	(0,24 -	0,37)	0,30	(0,25 -	0,37)	0,34	(0,28 -	0,41)
Marine water eutrophication (g N-eq/d)	5,15	(4,22 -	6,57)	5,16	(4,22 -	6,60)	5,20	(4,26 -	6,64)	5,30	(4,36 -	6,77)	6,42	(5,00 -	8,08)
Acidification (g SO_2-eq/d)	29,60	(23,12 -	38,94)	29,68	(23,24 -	39,03)	30,02	(23,57 -	39,32)	30,77	(24,27 -	40,22)	37,47	(28,43 -	48,50)
Blue water (m^3/d)	0,17	(0,13 -	0,21)	0,17	(0,14 -	0,21)	0,18	(0,14 -	0,22)	0,19	(0,15 -	0,22)	0,21	(0,18 -	0,25)
PREF	754	(515 -	991)	762	(544 -	1007)	796	(563 -	1025)	826	(590 -	1062)	885	(646 -	1148)

Values are presented as proportions, means (SD) and medians ($25^{th-}75^{th}$ percentile).

DHD15, Dutch Healthy Diet 2015 index PREF, preferences score based on deviation from current diet

Supplemental file 3. Food consumption and differences between current and optimized diets.

Supplemental table 3.1. Daily food consumption in grams and relative (%) difference with current diets, for 445 Dutch adults 18-79 years with low educational level, from the Dutch National Food Consumption Survey 2019-2021.

	Current	Model 1		Model 2		Model 3		Model 4		Model 5	
	Mean	Mean		Mean		Mean		Mean		Mean	
	(grams)	(grams)	Δ	(grams)	Δ	(grams)	Δ	(grams)	Δ	(grams)	Δ
Grains and grans based products											
Bread, rusks, wholegrain	79	89	14%	88	12%	87	11%	85	8%	80	2%
Bread, rusks, refined	35	25	-28%	24	-31%	23	-33%	22	-37%	21	-39%
Flours, rice, grains, refined	40	24	-39%	24	-40%	24	-40%	23	-42%	22	-44%
Flours, rice, grains, wholegrain	7	9	41%	10	55%	11	65%	12	76%	15	132%
Breakfast cereals, wholegrain	5	7	39%	8	45%	8	51%	8	63%	8	60%
Breakfast cereals, refined	2	2	9%	2	20%	2	23%	2	22%	2	-3%
Vegetables	150	146	-3%	149	-1%	153	2%	159	6%	169	13%
Fruit											
Fruit, other	50	53	8%	55	12%	58	17%	60	22%	64	29%
Apples and pears	35	38	8%	39	11%	40	15%	43	24%	45	29%
Citrus fruits	27	26	-4%	26	-4%	27	-2%	28	2%	31	12%
Berries	11	7	-37%	7	-34%	8	-31%	9	-23%	15	32%
Fruitcompote	5	5	0%	5	5%	6	10%	6	18%	7	37%
Mixed fruits and olives	3	4	43%	5	67%	5	86%	6	114%	7	148%
Potatoes and tubers	76	74	-2%	73	-3%	73	-3%	74	-2%	74	-3%
Nuts and seeds											
Nuts and seeds, not unsalted	6	9	45%	9	43%	9	39%	8	35%	9	35%
Nuts and seeds, unsalted	5	10	113%	11	124%	11	136%	13	154%	12	152%
Legumes	7	9	31%	11	71%	14	108%	15	127%	16	137%

Animal based foods										
Dairy										
Milk and yoghurtproducts, sugarfree	263	232	-12%	234	-11%	236	-10%	242	-8%	249	-5%
Milk and yoghurtproducts, sugared	16	8	-48%	8	-50%	8	-51%	7	-52%	7	-55%
Dairy, other	69	53	-22%	53	-23%	53	-23%	52	-24%	57	-17%
Meat											
Meat, hot meal, processed	30	21	-30%	21	-32%	20	-36%	17	-43%	13	-56%
Meat, cold meal, processed	24	15	-35%	15	-36%	15	-37%	14	-39%	12	-48%
Meat beef, unprocessed	17	6	-63%	6	-62%	7	-60%	7	-55%	16	-1%
Meat poultry, unprocessed	16	18	11%	18	13%	19	17%	20	24%	22	35%
Meat pork, unprocessed	14	16	12%	16	10%	16	11%	16	15%	14	1%
Meat mixed, unprocessed	3	1	-42%	1	-43%	1	-43%	2	-38%	2	-9%
Meat, other	3	2	-43%	2	-44%	2	-42%	2	-28%	3	2%
Cheese	32	30	-5%	30	-5%	30	-5%	30	-6%	31	-4%
Fish											
Fish, not fatty	9	8	-12%	8	-12%	8	-12%	8	-11%	8	-12%
Fish, fatty	6	12	110%	14	139%	15	168%	17	190%	17	193%
Eggs	16	18	13%	18	11%	17	9%	18	10%	18	15%
Dairy and meat replacers											
Dairy replacers	6	12	91%	12	91%	13	98%	14	117%	14	121%
Meat replacers	3	6	124%	6	109%	6	97%	5	90%	5	70%
Mixed foods											
Soups and bouillon	22	21	-6%	22	-2%	23	2%	23	5%	24	7%
Biscuits and sweet pastries	42	43	1%	42	0%	41	-2%	41	-3%	41	-3%
Contaminants, yeast and sauces	34	30	-14%	30	-14%	30	-13%	30	-14%	31	-11%

Sugar and confectionary										
Sugar, honey, jam, syrup, dessert sauce	11	10	-9%	10	-9%	10	-9%	10	-10%	10	-12%
Chocolat, candybars, chocolate bread toppings	8	9	14%	9	12%	9	11%	9	10%	8	7%
Sweets without chocolate, other bread toppings	2	4	63%	4	55%	4	49%	3	40%	3	39%
Fats and oils											
Fats and oils, soft	19	18	-3%	18	-3%	18	-3%	18	-3%	18	-6%
Fats and oils, hard	4	3	-33%	3	-33%	3	-32%	3	-33%	3	-34%
Savoury snacks											
Pretzels, chips, salty biscuits	6	6	-3%	6	-5%	6	-5%	5	-11%	5	-17%
Snacks, croquettes, snackrolls	6	7	1%	6	-1%	6	-4%	6	1%	8	22%
Non-alcoholic beverages											
Coffee and tea	898	848	-6%	852	-5%	865	-4%	898	0%	920	2%
Water	713	809	14%	811	14%	809	14%	807	13%	809	13%
Soft drinks, sugared	121	69	-43%	67	-45%	64	-47%	61	-49%	58	-52%
Soft drinks, sugarfree	61	33	-47%	33	-47%	33	-46%	35	-42%	48	-21%
Alcoholfree beverages	17	20	19%	20	18%	20	18%	20	14%	17	-4%
Juice, fruit	25	13	-49%	12	-49%	12	-50%	12	-51%	12	-50%
Juice, vegetables	2	1	-62%	1	-62%	1	-64%	1	-60%	1	-43%
Alcoholic beverages											
Beer	66	72	8%	70	6%	69	5%	70	6%	71	7%
Wine	34	23	-32%	25	-25%	27	-20%	29	-12%	40	19%
Alcohol, other than beer wine	6	5	-24%	5	-21%	5	-19%	5	-19%	5	-15%

Supplemental table 3.2. Daily food consumption in grams and relative (%) difference with current diets, for 663 Dutch adults 18-79 years with intermediate educational level, from the Dutch National Food Consumption Survey 2019-2021.

	Current	Model 1		Model 2		Model 3		Model 4		Model 5	
	Mean	Mean		Mean		Mean		Mean		Mean	
	(grams)	(grams)	Δ	(grams)	Δ	(grams)	Δ	(grams)	Δ	(grams)	Δ
Grains and grans based products											
Bread, rusks, wholegrain	83	79	-5%	80	-4%	81	-3%	80	-3%	74	-11%
Bread, rusks, refined	37	39	6%	37	2%	35	-4%	31	-16%	22	-39%
Flours, rice, grains, refined	50	43	-15%	41	-18%	41	-19%	42	-17%	39	-23%
Flours, rice, grains, wholegrain	8	9	11%	9	14%	10	22%	11	39%	21	151%
Breakfast cereals, wholegrain	7	10	32%	10	34%	10	32%	9	29%	9	23%
Breakfast cereals, refined	2	4	47%	4	51%	4	58%	4	62%	2	-18%
Vegetables	157	133	-16%	137	-13%	142	-9%	154	-2%	175	12%
Fruit											
Fruit, other	55	50	-9%	52	-6%	55	1%	60	10%	65	18%
Apples and pears	36	41	15%	43	19%	45	25%	48	34%	43	18%
Citrus fruits	22	18	-18%	19	-14%	19	-13%	21	-5%	21	-2%
Berries	15	5	-65%	6	-62%	7	-55%	9	-42%	27	75%
Fruitcompote	4	2	-47%	2	-46%	3	-40%	4	-8%	10	141%
Mixed fruits and olives	3	2	-24%	2	-17%	3	-7%	3	18%	5	99%
Potatoes and tubers	72	64	-10%	65	-10%	66	-8%	68	-5%	73	2%
Nuts and seeds											
Nuts and seeds, not unsalted	10	14	46%	14	45%	13	37%	12	28%	10	1%
Nuts and seeds, unsalted	5	6	12%	7	34%	9	80%	12	142%	14	182%
Legumes	7	12	60%	15	102%	16	119%	17	126%	16	116%

Animal based foods										
Dairy										
Milk and yoghurtproducts, sugarfree	232	182	-22%	185	-20%	193	-17%	206	-11%	223	-4%
Milk and yoghurtproducts, sugared	17	14	-19%	12	-26%	10	-38%	9	-48%	6	-63%
Dairy, other	60	40	-33%	40	-34%	40	-34%	42	-30%	58	-3%
Meat											
Meat, hot meal, processed	23	19	-21%	18	-25%	16	-33%	13	-44%	10	-56%
Meat, cold meal, processed	23	19	-17%	19	-17%	18	-18%	17	-24%	12	-46%
Meat beef, unprocessed	15	3	-81%	3	-81%	3	-80%	4	-76%	14	-9%
Meat poultry, unprocessed	19	21	14%	22	14%	23	20%	25	31%	24	28%
Meat pork, unprocessed	12	9	-23%	9	-22%	10	-16%	11	-1%	14	24%
Meat, other	4	1	-67%	1	-68%	1	-68%	1	-65%	3	-22%
Cheese	35	31	-12%	31	-12%	31	-11%	32	-8%	34	-3%
Fish											
Fish, not fatty	11	7	-34%	7	-34%	7	-34%	7	-31%	7	-29%
Fish, fatty	6	14	123%	16	154%	19	197%	20	212%	20	208%
Eggs	18	19	10%	19	10%	20	13%	21	17%	21	20%
Dairy and meat replacers											
Dairy replacers	12	35	188%	35	192%	35	192%	35	187%	25	111%
Meat replacers	3	6	77%	6	75%	6	73%	6	79%	5	63%
Mixed foods											
Soups and bouillon	18	18	3%	19	5%	19	7%	20	12%	20	11%
Biscuits and sweet pastries	38	37	-2%	37	-2%	38	-1%	37	-2%	36	-4%
Contaminants, yeast and sauces	35	30	-16%	30	-16%	30	-16%	30	-15%	31	-13%
Sugar and confectionary											

Sugar, honey, jam, syrup, dessert sauce	10	8	-24%	8	-24%	8	-24%	8	-22%	8	-18%
Chocolat, candybars, chocolate bread toppings	10	11	8%	12	12%	12	14%	12	12%	10	-6%
Sweets without chocolate, other bread toppings	4	5	39%	5	28%	4	16%	4	-3%	4	9%
Fats and oils											
Fats and oils, soft	19	18	-6%	18	-5%	18	-3%	19	-2%	19	-1%
Fats and oils, hard	3	2	-36%	2	-41%	2	-47%	2	-50%	2	-52%
Savoury snacks											
Pretzels, chips, salty biscuits	8	10	24%	10	17%	9	9%	8	1%	8	4%
Snacks, croquettes, snackrolls	11	12	10%	12	9%	12	8%	12	7%	12	8%
Non-alcoholic beverages											
Coffee and tea	852	620	-27%	653	-23%	709	-17%	809	-5%	956	12%
Water	927	1241	34%	1218	31%	1165	26%	1080	16%	947	2%
Soft drinks, sugared	106	88	-16%	78	-26%	68	-36%	54	-49%	40	-62%
Soft drinks, sugarfree	87	45	-48%	46	-47%	46	-47%	48	-44%	78	-10%
Alcoholfree beverages	20	13	-31%	14	-29%	14	-28%	15	-25%	23	19%
Juice, fruit	36	14	-61%	14	-61%	14	-60%	16	-56%	17	-52%
Juice, vegetables	1	0	-68%	0	-65%	0	-64%	0	-53%	2	98%
Alcoholic beverages											
Beer	72	89	23%	89	23%	88	21%	91	26%	91	25%
Wine	42	20	-52%	20	-52%	21	-50%	23	-45%	40	-4%
Alcohol, other than beer wine	6	8	17%	7	8%	7	1%	6	-7%	6	-5%

Supplemental table 3.3. Daily food consumption in grams and relative (%) difference with current diets, for 669 Dutch adults 18-79 years with high educational level, from the Dutch National Food Consumption Survey 2019-2021.

	Current	Model 1		Model 2		Model 3		Model 4		Model 5	
	Mean	Mean		Mean		Mean		Mean		Mean	
	(grams)	(grams)	Δ	(grams)	Δ	(grams)	Δ	(grams)	Δ	(grams)	Δ
Grains and grans based products											
Bread, rusks, wholegrain	86	98	14%	97	12%	95	10%	92	6%	82	-5%
Bread, rusks, refined	30	23	-23%	23	-25%	22	-27%	21	-31%	18	-42%
Flours, rice, grains, refined	54	40	-26%	38	-29%	36	-33%	33	-39%	27	-49%
Flours, rice, grains, wholegrain	13	13	7%	14	9%	14	13%	16	31%	26	109%
Breakfast cereals, wholegrain	10	15	45%	16	48%	16	51%	16	56%	15	46%
Breakfast cereals, refined	2	2	-24%	2	-23%	2	-21%	2	-17%	2	-30%
Vegetables	197	186	-6%	189	-4%	192	-3%	197	0%	206	5%
Fruit											
Fruit, other	67	67	1%	67	1%	68	2%	71	7%	84	26%
Apples and pears	46	50	7%	53	15%	56	22%	59	27%	55	19%
Citrus fruits	25	29	16%	30	18%	30	19%	32	25%	31	21%
Berries	19	10	-47%	10	-45%	11	-42%	12	-35%	22	18%
Fruitcompote	5	3	-41%	3	-40%	3	-38%	3	-32%	4	-23%
Mixed fruits and olives	3	4	15%	4	15%	4	15%	4	22%	4	12%
Potatoes and tubers	64	66	4%	67	5%	67	5%	68	6%	65	2%
Nuts and seeds											
Nuts and seeds, not unsalted	11	12	8%	11	3%	11	-1%	10	-5%	10	-7%
Nuts and seeds, unsalted	8	11	46%	12	58%	13	71%	14	92%	16	108%
Legumes	8	9	17%	12	53%	14	82%	15	94%	15	99%

Animal based foods										
Dairy										
Milk and yoghurtproducts, sugarfree	230	199	-13%	200	-13%	202	-12%	205	-11%	213	-7%
Milk and yoghurtproducts, sugared	12	8	-34%	8	-35%	7	-37%	7	-39%	5	-59%
Dairy, other	56	48	-14%	48	-14%	48	-14%	51	-9%	61	9%
Meat											
Meat, hot meal, processed	19	13	-29%	13	-32%	12	-36%	10	-46%	8	-59%
Meat, cold meal, processed	19	10	-46%	10	-47%	10	-48%	9	-51%	7	-63%
Meat beef, unprocessed	11	4	-66%	4	-65%	4	-64%	4	-62%	9	-23%
Meat poultry, unprocessed	17	21	23%	21	25%	22	30%	24	44%	26	56%
Meat pork, unprocessed	8	7	-9%	8	-8%	8	-8%	8	-2%	9	7%
Meat, other	4	1	-71%	1	-70%	1	-70%	1	-68%	3	-18%
Cheese	38	35	-9%	35	-9%	35	-10%	34	-11%	36	-7%
Fish											
Fish, not fatty	11	8	-28%	8	-28%	8	-28%	8	-28%	8	-26%
Fish, fatty	9	22	131%	23	147%	24	159%	24	161%	22	133%
Eggs	16	15	-5%	15	-5%	15	-5%	15	-3%	16	0%
Dairy and meat replacers											
Dairy replacers	14	22	54%	21	50%	21	46%	20	45%	25	75%
Meat replacers	7	10	40%	10	36%	10	34%	10	35%	12	63%
Mixed foods											
Soups and bouillon	25	25	-2%	25	1%	26	2%	26	1%	25	-1%
Biscuits and sweet pastries	40	38	-7%	38	-6%	38	-6%	39	-4%	40	-1%
Contaminants, yeast and sauces	36	33	-10%	33	-10%	33	-10%	33	-8%	35	-2%
Sugar and confectionary											

Sugar, honey, jam, syrup, dessert sauce	9	9	-1%	9	-1%	9	-2%	9	-4%	8	-13%
Chocolat, candybars, chocolate bread toppings	11	11	-4%	11	-7%	10	-9%	10	-10%	10	-9%
Sweets without chocolate, other bread toppings	3	4	6%	4	14%	4	18%	4	17%	4	26%
Fats and oils											
Fats and oils, soft	18	18	2%	18	2%	18	2%	18	2%	18	1%
Fats and oils, hard	5	3	-33%	3	-36%	3	-38%	3	-41%	3	-41%
Savoury snacks											
Pretzels, chips, salty biscuits	8	8	7%	8	5%	8	1%	7	-4%	7	-5%
Snacks, croquettes, snackrolls	9	9	9%	9	8%	9	5%	9	8%	10	20%
Miscellaneous	3	7	140%	6	110%	5	79%	4	44%	3	8%
Non-alcoholic beverages											
Coffee and tea	940	807	-14%	826	-12%	854	-9%	902	-4%	1004	7%
Water	881	980	11%	966	10%	940	7%	901	2%	828	-6%
Soft drinks, sugared	82	46	-44%	45	-46%	42	-49%	38	-54%	33	-60%
Soft drinks, sugarfree	61	36	-42%	35	-42%	36	-40%	38	-37%	60	-2%
Alcoholfree beverages	21	12	-41%	13	-39%	13	-37%	14	-32%	19	-11%
Juice, fruit	33	16	-52%	15	-54%	15	-55%	14	-58%	13	-61%
Juice, vegetables	1	1	-42%	1	-33%	1	-17%	1	7%	2	78%
Alcoholic beverages											
Beer	69	70	1%	69	1%	68	-1%	69	0%	75	9%
Wine	58	36	-38%	37	-36%	39	-34%	41	-30%	50	-13%
Alcohol, other than beer wine	5	3	-36%	3	-37%	3	-38%	3	-37%	4	-31%

Supplemental file 4. Macro and mirconutrients for current and optimized diets.

Supplemental table 4.1. Macro and micronutrient intake of diets for 445 Dutch adults 18-79 years with low educational level, from the Dutch National Food Consumption Survey 2019-2021.

	Observed	Model 1		Model 2		Model 3		Model 4		Model 5	
	Mean	**Mean**		**Mean**		**Mean**		**Mean**		**Mean**	
	unit	**unit**	**Δ**	**unit**	**Δ**	**unit**	**Δ**	**unit**	**Δ**	**unit**	**Δ**
Energy (kcal)	1977	1900	-4%	1901	-4%	1904	-4%	1910	-3%	1932	-2%
Protein (g)	80	76	-4%	77	-4%	77	-4%	78	-3%	79	-1%
Vegetable protein (g)	29	31	7%	31	7%	31	6%	31	6%	30	4%
Animal protein (g)	51	46	-11%	46	-10%	46	-10%	47	-8%	49	-3%
Fat (g)	84	82	-2%	82	-2%	82	-2%	83	-1%	84	0%
SFA (g)	31	28	-8%	28	-9%	28	-9%	28	-9%	29	-6%
EPA (g)	71	114	60%	126	78%	138	95%	147	107%	141	99%
DHA (g)	107	188	77%	211	98%	233	119%	249	134%	236	121%
Carbohydrates (g)	202	191	-5%	191	-5%	190	-6%	190	-6%	189	-6%
Mono and disaccarides (g)	91	85	-7%	84	-7%	85	-7%	85	-7%	85	-6%
Dietary fibre (g)	20	21	8%	21	9%	22	10%	22	11%	22	12%
Alcohol (g)	8	6	-17%	7	-15%	7	-13%	7	-9%	8	6%
Calcium (mg)	1020	969	-5%	971	-5%	973	-5%	983	-4%	1010	-1%
Iron (mg)	10	10	0%	10	0%	10	0%	10	0%	10	0%
Iron haem (mg)	1	0	-54%	0	-53%	0	-52%	1	-49%	1	-26%
Iron non-haem (mg)	9	9	6%	9	6%	9	6%	9	5%	9	4%
Iodine (mg)	169	162	-4%	161	-4%	160	-5%	159	-6%	159	-6%
Sodium (mg)	2285	2052	-10%	2040	-11%	2026	-11%	1999	-13%	1974	-14%
Zinc (mg)	10	9	-9%	9	-9%	9	-9%	10	-8%	10	-2%
ret (ug)	683	673	-1%	677	-1%	671	-2%	644	-6%	528	-23%
RAE (ug)	880	904	3%	920	5%	931	6%	915	4%	787	-11%
vitB2 (mg)	2	1	-7%	1	-7%	1	-7%	1	-7%	1	-5%
vitB6 (mg)	2	2	3%	2	3%	2	4%	2	5%	2	7%
vitB12 (ug)	5	4	-9%	4	-7%	4	-4%	5	-2%	5	2%

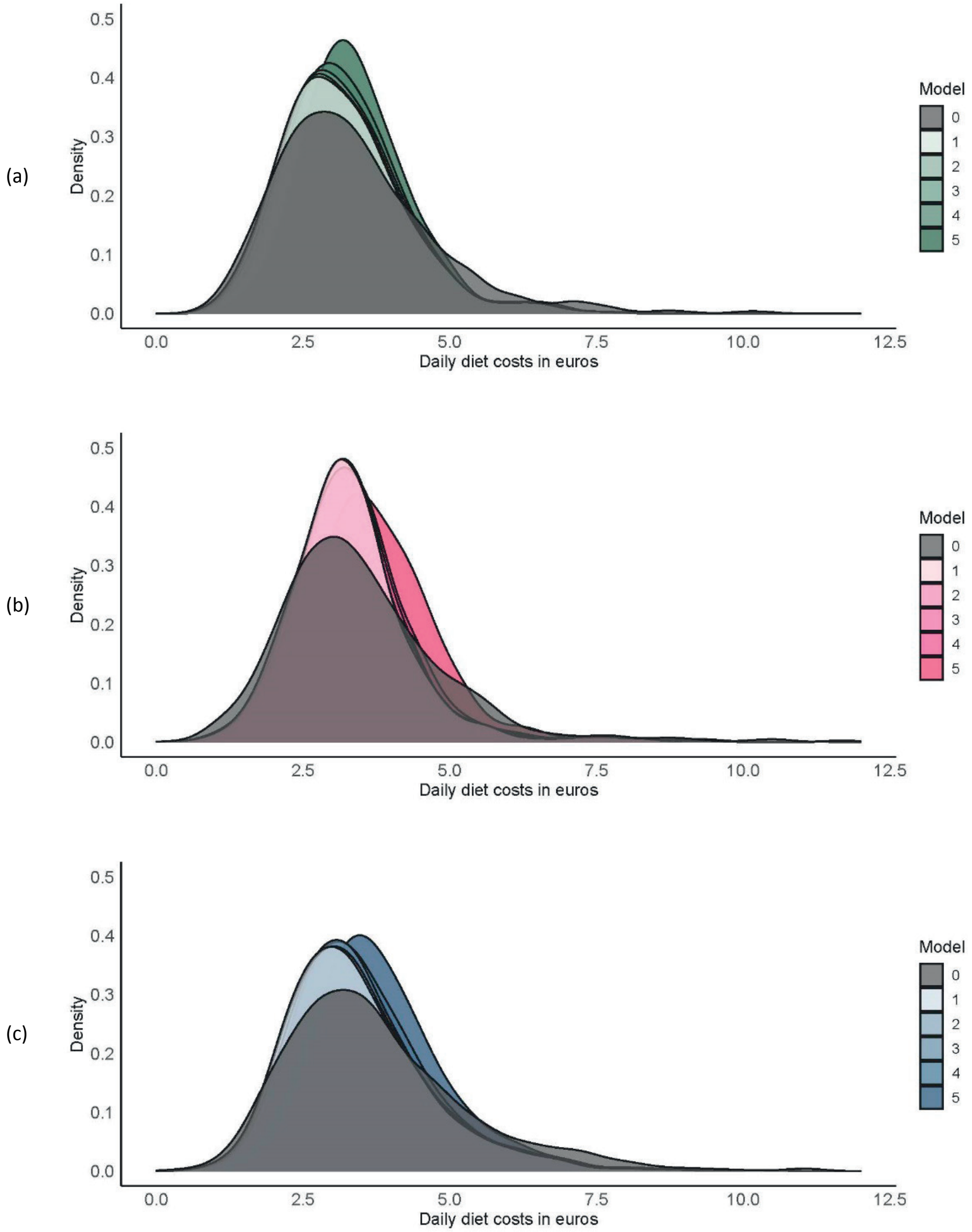
Supplemental table 4.2. Macro and micronutrient intake of diets for 663 Dutch adults 18-79 years with intermediate educational level, from the Dutch National Food Consumption Survey 2019-2021.

	Observed	Model 1		Model 2		Model 3		Model 4		Model 5	
	Mean	Mean		Mean		Mean		Mean		Mean	
	unit	unit	Δ	unit	Δ	unit	Δ	unit	Δ	unit	Δ
Energy (kcal)	2061	1983	-4%	1985	-4%	1984	-4%	1987	-4%	2019	-2%
Protein (g)	81	78	-4%	78	-4%	78	-4%	79	-3%	81	0%
Vegetable protein (g)	31	35	12%	35	12%	34	11%	34	9%	32	3%
Animal protein (g)	50	43	-14%	43	-14%	44	-13%	45	-11%	49	-2%
Fat (g)	87	82	-6%	83	-5%	84	-4%	85	-3%	88	1%
SFA (g)	31	28	-11%	28	-10%	28	-9%	28	-9%	29	-6%
EPA (g)	77	124	60%	139	79%	157	103%	166	114%	176	127%
DHA (g)	115	198	72%	223	94%	254	121%	267	131%	274	138%
Carbohydrates (g)	211	208	-2%	206	-2%	204	-3%	201	-5%	197	-7%
Mono and disaccarides (g)	91	85	-6%	85	-7%	84	-7%	84	-7%	86	-6%
Dietary fibre (g)	21	22	5%	22	7%	23	8%	23	8%	22	7%
Alcohol (g)	9	8	-10%	8	-13%	7	-14%	8	-13%	9	6%
Calcium (mg)	1005	967	-4%	965	-4%	960	-5%	967	-4%	1011	1%
Iron (mg)	10	11	7%	11	7%	11	4%	11	1%	11	1%
Iron haem (mg)	1	0	-54%	0	-53%	0	-50%	0	-48%	1	-21%
Iron non-haem (mg)	9	11	13%	11	12%	10	9%	10	5%	10	3%
Iodine (mg)	169	167	-1%	166	-2%	162	-4%	157	-7%	156	-8%
Sodium (mg)	2339	2252	-4%	2222	-5%	2179	-7%	2122	-9%	2025	-13%
Zinc (mg)	10	10	-7%	10	-7%	9	-8%	9	-8%	10	-1%
ret (ug)	570	642	13%	636	12%	610	7%	553	-3%	501	-12%
RAE (ug)	778	847	9%	856	10%	842	8%	792	2%	732	-6%
vitB2 (mg)	1	1	4%	1	3%	1	1%	1	-1%	1	1%
vitB6 (mg)	2	2	-1%	2	-1%	2	-2%	2	-1%	2	3%
vitB12 (ug)	4	4	0%	4	2%	5	4%	5	4%	5	10%

Supplemental table 4.3. Macro and micronutrient intake of diets for 669 Dutch adults 18-79 years with high educational level, from Dutch National Food Consumption Survey 2019-2021.

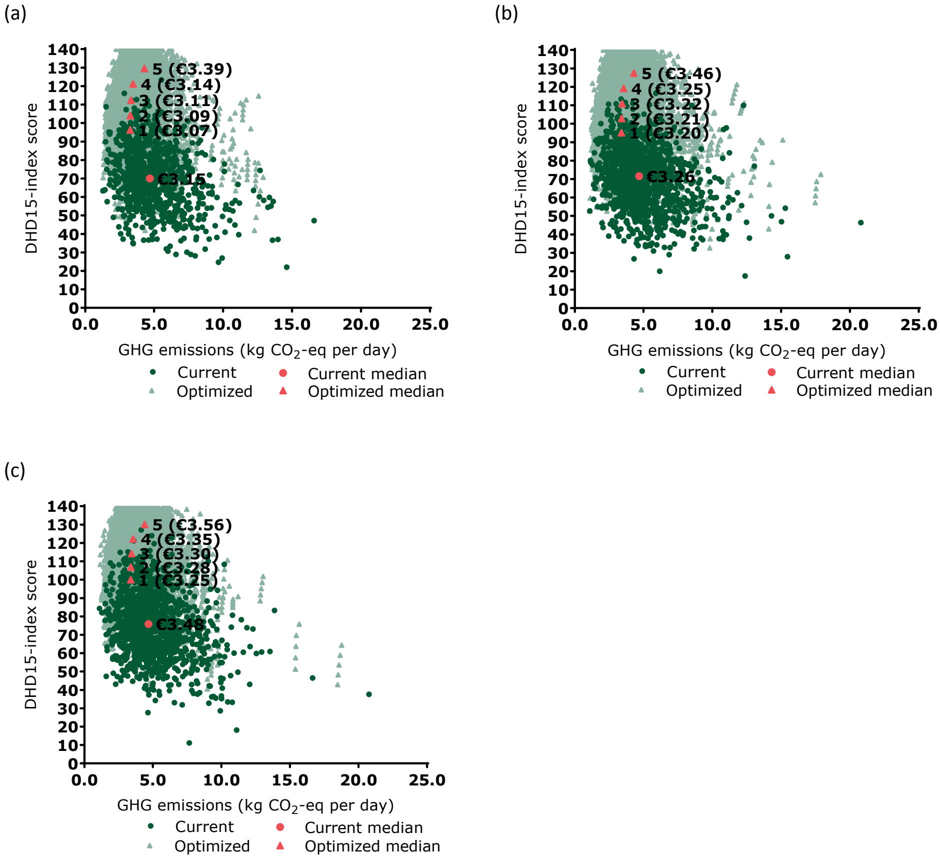
	Observed	Model 1		Model 2		Model 3		Model 4		Model 5	
	Mean	**Mean**		**Mean**		**Mean**		**Mean**		**Mean**	
	unit	**unit**	**Δ**	**unit**	**Δ**	**unit**	**Δ**	**unit**	**Δ**	**unit**	**Δ**
Energy (kcal)	2111	2011	-5%	2013	-5%	2012	-5%	2020	-4%	2046	-3%
Protein (g)	81	77	-5%	77	-5%	77	-5%	78	-4%	80	-2%
Vegetable protein (g)	34	35	4%	35	4%	35	4%	35	3%	34	1%
Animal protein (g)	47	41	-12%	42	-11%	42	-11%	43	-9%	45	-3%
Fat (g)	91	87	-4%	87	-4%	87	-4%	88	-3%	90	0%
SFA (g)	32	29	-10%	29	-11%	29	-11%	29	-10%	30	-7%
EPA (g)	99	191	93%	204	107%	214	116%	217	120%	190	92%
DHA (g)	150	321	114%	344	130%	361	141%	368	146%	319	113%
Carbohydrates (g)	213	204	-4%	203	-4%	202	-5%	201	-5%	198	-7%
Mono and disaccarides (g)	92	83	-10%	83	-10%	83	-10%	84	-9%	87	-6%
Dietary fibre (g)	23	25	5%	25	6%	25	7%	25	8%	25	7%
Alcohol (g)	10	7	-25%	7	-24%	8	-23%	8	-21%	9	-9%
Calcium (mg)	1040	970	-7%	969	-7%	971	-7%	980	-6%	1029	-1%
Iron (mg)	11	11	-2%	11	-2%	11	-1%	11	-1%	11	1%
Iron haem (mg)	1	0	-57%	0	-56%	0	-56%	0	-54%	0	-31%
Iron non-haem (mg)	10	10	2%	10	2%	10	3%	11	3%	11	3%
Iodine (mg)	168	163	-3%	163	-3%	162	-4%	161	-4%	156	-7%
Sodium (mg)	2287	2163	-5%	2150	-6%	2126	-7%	2083	-9%	2014	-12%
Zinc (mg)	11	10	-10%	10	-10%	10	-9%	10	-9%	10	-4%
ret (ug)	647	533	-18%	539	-17%	536	-17%	519	-20%	510	-21%
RAE (ug)	916	811	-11%	817	-11%	812	-11%	801	-12%	795	-13%
vitB2 (mg)	1	1	-5%	1	-5%	1	-5%	1	-4%	1	0%
vitB6 (mg)	2	2	-1%	2	-1%	2	1%	2	2%	2	6%
vitB12 (ug)	5	5	-1%	5	1%	5	3%	5	3%	5	7%

Supplemental file 5. Distribution of diet costs for current and optimized diets.



Supplemental figures 5.1a-c. Distribution of diet costs of current (0) and optimized diets (model 1 to 5) based on minimal costs for Dutch adults aged 18-79 years with low (a), intermediate (b) and high (c) educational level.

Supplemental file 6. Outcomes diet optimization for secondary analysis, using the total population as peers.



Supplemental figures 6.1a-c. Trade-off between greenhouse gas emission and Dutch Healthy Diet index 2015 for 1747 Dutch adults aged 18-79 years with low(a), intermediate(b) and high(c) educational level, from the DNFCS 2019-2021, results from the secondary analysis using total population as peers. Dark green circles represent the individual data of current diets and the light green triangles for the optimized diets for all five models (1 to 5). The star indicates the median of current diets, the triangles numbered 1 to 5, represent the median of the models, with median prices. This secondary analyses addressed how the stratification for educational peer subgroups influenced the results. Using the total population as peers instead of using educational subgroups as peers, increased the options for making linear combinations of diets. The results consistently showed more pronounced reductions in GHG emissions and increases in DHD15 index for diets of all educational subgroups, while the diet costs were still similar compared to current diets.

Supplemental table 6.1. Summary output for characteristics of current and optimized diets for 445 Dutch adults 18-79 years with low educational level, from the Dutch National Food Consumption Survey 2019-2021, results from the secondary analysis using total population as peers.

	Model 1			Model 2			Model 3			Model 4			Model 5		
Diet costs (€/day)															
Minimum of minimum price	3,07	(2,55 -	3,72)	3,09	(2,56 -	3,71)	3,11	(2,56 -	3,75)	3,14	(2,62 -	3,78)	3,39	(2,87 -	4,04)
Mean of minimum price	7,59	(6,42 -	8,96)	7,54	(6,36 -	8,99)	7,55	(6,32 -	8,98)	7,48	(6,30 -	8,98)	7,85	(6,90 -	9,32)
Median of minimum price	7,33	(6,20 -	8,67)	7,29	(6,10 -	8,64)	7,21	(6,07 -	8,57)	7,14	(6,02 -	8,58)	7,51	(6,55 -	8,90)
DHD15 (points)	96	(85 -	107)	104	(93 -	113)	112	(102 -	120)	121	(110 -	128)	130	(118 -	136)
Energy (kcal)	1908	(599)		1910	(600)		1914	(599)		1921	(596)		1953	(591)	
Protein (g)	77	(26)		77	(26)		77	(26)		78	(26)		80	(26)	
Plant protein (%)	43%			43%			43%			41%			39%		
GHG emission (kg CO_2-eq/d)	3,26	(2,72 -	4,17)	3,28	(2,73 -	4,19)	3,33	(2,77 -	4,24)	3,48	(2,87 -	4,37)	4,30	(3,49 -	5,33)
Land use (m^2*yr/d)	2,26	(1,87 -	2,80)	2,25	(1,88 -	2,82)	2,29	(1,91 -	2,86)	2,36	(1,98 -	2,93)	2,67	(2,23 -	3,26)
Freshwater eutrophication (g P-eq/d)	0,28	(0,23 -	0,34)	0,28	(0,23 -	0,35)	0,28	(0,23 -	0,35)	0,29	(0,24 -	0,36)	0,32	(0,27 -	0,40)
Marine water eutrophication (g N-eq/d)	4,76	(3,95 -	6,01)	4,79	(3,97 -	6,03)	4,88	(4,03 -	6,11)	5,02	(4,15 -	6,21)	6,31	(5,03 -	8,11)
Acidification (g SO_2-eq/d)	27,89	(22,68 -	35,88)	27,85	(22,84 -	36,10)	28,34	(23,15 -	36,50)	29,42	(23,89 -	37,51)	37,98	(29,35 -	48,98)
Blue water (m^3/d)	0,13	(0,10 -	0,17)	0,14	(0,11 -	0,17)	0,15	(0,12 -	0,18)	0,16	(0,13 -	0,19)	0,19	(0,15 -	0,22)
PREF	858	(657 -	1057)	855	(662 -	1058)	870	(686 -	1065)	901	(715 -	1099)	954	(766 -	1177)

Values are presented as proportions, means (SD) and medians (25^{th}-75^{th} percentile).

DHD15; Dutch Healthy Diet 2015 index ; PREF, preferences score based on deviation from current diets

Supplemental Table 6.2. Summary output for characteristics of current and optimized diets for 663 Dutch adults 18-79 years with intermediate educational level, from the Dutch National Food Consumption Survey 2019-2021, results from the secondary analysis using total population as peers.

	Model 1			**Model 2**			**Model 3**			**Model 4**			**Model 5**		
Diet costs (€/day)															
Minimum of minimum price	3,20	(2,61 -	3,82)	3,21	(2,64 -	3,82)	3,22	(2,66 -	3,84)	3,25	(2,71 -	3,89)	3,46	(2,94 -	4,15)
Mean of minimum price	7,84	(6,57 -	9,19)	7,84	(6,55 -	9,20)	7,81	(6,49 -	9,20)	7,76	(6,50 -	9,19)	8,16	(6,99 -	9,73)
Median of minimum price	7,58	(6,33 -	8,83)	7,54	(6,28 -	8,82)	7,51	(6,25 -	8,80)	7,44	(6,24 -	8,80)	7,77	(6,68 -	9,25)
DHD15 (points)	95	(85 -	107)	103	(93 -	113)	111	(101 -	120)	119	(109 -	128)	128	(116 -	136)
Energy (kcal)	1989	(666)		1991	(665)		1995	(663)		2001	(659)		2032	(652)	
Protein (g)	78	(29)		79	(29)		79	(29)		79	(29)		81	(29)	
Plant protein (%)	44%			44%			43%			43%			41%		
GHG emission (kg CO_2-eq/d)	3,39	(2,69 -	4,34)	3,41	(2,70 -	4,36)	3,45	(2,75 -	4,41)	3,56	(2,85 -	4,56)	4,30	(3,48 -	5,39)
Land use (m^2*yr/d)	2,33	(1,85 -	2,88)	2,33	(1,88 -	2,89)	2,35	(1,90 -	2,92)	2,44	(1,97 -	3,01)	2,72	(2,20 -	3,34)
Freshwater eutrophication (g P-eq/d)	0,29	(0,23 -	0,35)	0,29	(0,23 -	0,36)	0,29	(0,24 -	0,36)	0,30	(0,25 -	0,37)	0,33	(0,27 -	0,41)
Marine water eutrophication (g N-eq/d)	4,91	(3,91 -	6,25)	4,92	(3,91 -	6,30)	4,97	(3,94 -	6,33)	5,05	(4,08 -	6,52)	6,33	(4,93 -	8,10)
Acidification (g SO_2-eq/d)	28,16	(21,74 -	36,72)	28,31	(21,88 -	37,17)	28,48	(22,17 -	37,45)	29,28	(23,05 -	38,65)	37,43	(28,62 -	48,68)
Blue water (m^3/d)	0,14	(0,11 -	0,18)	0,15	(0,12 -	0,19)	0,16	(0,13 -	0,19)	0,17	(0,14 -	0,20)	0,19	(0,16 -	0,23)
PREF	865	(639 -	1095)	877	(651 -	1106)	873	(684 -	1112)	925	- (709	1157)	975	(761 -	1233)

Values are presented as proportions, means (SD) and medians (25^{th}-75^{th} percentile).

DHD15; Dutch Healthy Diet 2015 index; PREF, preferences score based on deviation from current diets

Supplemental table 6.3. Summary output for characteristics of current and optimized diets for 669 Dutch adults 18-79 years with high educational level, from Dutch National Food Consumption Survey 2019-2021 , results from the secondary analysis using total population as peers.

	Model 1			**Model 2**			**Model 3**			**Model 4**			**Model 5**		
Diet costs (€/day)															
Minimum of minimum price	3,25	(2,68 -	3,95)	3,28	(2,73 -	3,94)	3,30	(2,75 -	3,98)	3,35	(2,76 -	3,99)	3,56	(3,05 -	4,26)
Mean of minimum price	8,07	(6,87 -	9,58)	8,08	(6,84 -	9,55)	8,02	(6,83 -	9,55)	8,02	(6,78 -	9,59)	8,44	(7,27 -	10,06)
Median of minimum price	7,74	(6,61 -	9,15)	7,74	(6,60 -	9,14)	7,70	(6,57 -	9,13)	7,68	(6,50 -	9,14)	8,07	(6,93 -	9,54)
DHD15 (points)	100	(88 -	111)	107	(96 -	117)	114	(104 -	122)	122	(111 -	129)	130	(118 -	136)
Energy (kcal)	2032	(654)		2033	(653)		2036	(652)		2042	(648)		2069	(639)	
Protein (g)	78	(26)		78	(26)		78	(26)		79	(26)		81	(26)	
Plant protein (%)	46%			46%			46%			46%			43%		
GHG emission (kg CO_2-eq/d)	3,37	(2,77 -	4,37)	3,40	(2,78 -	4,39)	3,45	(2,83 -	4,46)	3,56	(2,92 -	4,61)	4,40	(3,45 -	5,40)
Land use (m^2*yr/d)	2,33	(1,90 -	2,88)	2,35	(1,92 -	2,88)	2,38	(1,94 -	2,92)	2,44	(1,99 -	3,00)	2,73	(2,19 -	3,30)
Freshwater eutrophication (g P-eq/d)	0,29	(0,24 -	0,36)	0,29	(0,24 -	0,36)	0,30	(0,24 -	0,36)	0,30	(0,25 -	0,37)	0,33	(0,27 -	0,41)
Marine water eutrophication (g N-eq/d)	4,86	(4,02 -	6,23)	4,88	(4,03 -	6,22)	4,91	(4,07 -	6,30)	5,05	(4,18 -	6,44)	6,21	(4,84 -	8,06)
Acidification (g SO_2-eq/d)	27,71	(21,99 -	36,47)	27,69	(22,12 -	36,63)	28,10	(22,44 -	37,11)	28,86	(23,15 -	38,27)	36,46	(27,54 -	47,84)
Blue water (m^3/d)	0,16	(0,12 -	0,21)	0,16	(0,13 -	0,21)	0,17	(0,14 -	0,21)	0,18	(0,15 -	0,22)	0,20	(0,17 -	0,24)
PREF	867	(668 -	1082)	875	(676 -	1089)	893	(695 -	1120)	935	(719 -	1152)	992	(779 -	1229)

Values are presented as proportions, means (SD) and medians (25^{th}-75^{th} percentile).

DHD15; Dutch Healthy Diet 2015 index; PREF, preferences score based on deviation from current diets

Supplemental table 6.4. Daily food consumption in grams and relative (%) difference with current diets, for 445 Dutch adults 18-79 years with low educational level, from the Dutch National Food Consumption Survey 2019-2021, results from the secondary analysis using total population as peers.

	Current	Model 1		Model 2		Model 3		Model 4		Model 5	
	Mean	Mean		Mean		Mean		Mean		Mean	
	(grams)	(grams)	Δ	(grams)	Δ	(grams)	Δ	(grams)	Δ	(grams)	Δ
Grains and grans based products											
Bread, rusks, wholegrain	79	91	16%	91	16%	91	15%	89	14%	81	3%
Bread, rusks, refined	35	23	-35%	22	-38%	21	-41%	18	-47%	14	-60%
Flours, rice, grains, refined	40	26	-35%	25	-38%	23	-42%	21	-48%	16	-60%
Flours, rice, grains, wholegrain	7	9	34%	10	43%	11	60%	13	99%	24	256%
Breakfast cereals, wholegrain	5	12	125%	12	126%	12	137%	14	163%	13	161%
Breakfast cereals, refined	2	2	26%	2	23%	2	24%	2	30%	2	-12%
Vegetables	150	151	0%	154	2%	159	6%	167	11%	181	20%
Fruit											
Fruit, other	50	56	12%	57	14%	59	18%	65	30%	74	49%
Apples and pears	35	46	31%	48	38%	51	46%	54	55%	52	49%
Citrus fruits	27	25	-10%	25	-8%	26	-4%	29	5%	28	1%
Berries	11	5	-52%	6	-50%	6	-47%	7	-39%	19	72%
Fruitcompote	5	3	-46%	3	-46%	3	-44%	3	-36%	6	11%
Mixed fruits and olives	3	3	0%	3	9%	3	18%	4	33%	5	87%
Potatoes and tubers	76	74	-2%	75	-1%	75	0%	76	1%	76	1%
Nuts and seeds											
Nuts and seeds, not unsalted	6	10	57%	10	53%	9	44%	9	37%	9	36%
Nuts and seeds, unsalted	5	10	102%	11	124%	13	162%	15	199%	15	206%
Legumes	7	9	36%	13	89%	15	123%	15	130%	16	134%

Animal based foods											
Dairy											
Milk and yoghurtproducts, sugarfree	263	224	-15%	225	-14%	227	-14%	231	-12%	247	-6%
Milk and yoghurtproducts, sugared	16	8	-51%	7	-56%	6	-61%	5	-68%	3	-80%
Dairy, other	69	51	-25%	51	-25%	52	-25%	54	-22%	58	-15%
Meat											
Meat, hot meal, processed	30	21	-31%	20	-33%	19	-38%	14	-52%	7	-75%
Meat, cold meal, processed	24	14	-40%	14	-41%	13	-43%	11	-52%	6	-73%
Meat beef, unprocessed	17	3	-83%	3	-83%	3	-82%	3	-80%	11	-32%
Meat poultry, unprocessed	16	23	39%	23	41%	25	51%	30	82%	33	104%
Meat pork, unprocessed	14	12	-15%	12	-14%	12	-13%	14	-3%	14	1%
Meat, other	3	1	-68%	1	-64%	1	-63%	2	-55%	4	23%
Cheese	32	28	-11%	28	-11%	28	-11%	28	-11%	30	-5%
Fish											
Fish, not fatty	9	5	-43%	5	-44%	5	-46%	5	-44%	6	-37%
Fish, fatty	6	18	222%	20	255%	22	284%	22	289%	20	256%
Eggs	16	16	0%	16	0%	16	1%	17	5%	19	19%
Dairy and meat replacers											
Dairy replacers	6	22	240%	22	245%	22	239%	20	217%	20	213%
Meat replacers	3	6	98%	5	87%	5	80%	5	87%	6	112%
Mixed foods											
Soups and bouillon	22	22	0%	23	5%	24	7%	25	12%	25	14%
Biscuits and sweet pastries	42	38	-10%	38	-10%	38	-11%	38	-9%	40	-6%
Contaminants, yeast and sauces	34	30	-13%	30	-12%	31	-11%	31	-10%	32	-7%
Sugar and confectionary											

Sugar, honey, jam, syrup, dessert sauce	11	9	-15%	9	-14%	9	-15%	9	-15%	9	-21%
Chocolat, candybars, chocolate bread toppings	8	9	18%	9	16%	9	15%	9	19%	10	24%
Sweets without chocolate, other bread toppings	2	4	68%	4	68%	4	64%	4	46%	4	44%
Fats and oils											
Fats and oils, soft	19	19	-1%	19	-1%	19	0%	19	0%	19	1%
Fats and oils, hard	4	2	-50%	2	-51%	2	-53%	2	-54%	2	-55%
Savory snacks											
Pretzels, chips, salty biscuits	6	7	16%	7	13%	6	5%	6	3%	6	-4%
Snacks, croquettes, snackrolls	6	8	23%	8	21%	8	21%	8	22%	9	39%
Non-alcoholic beverages											
Coffee and tea	898	727	-19%	748	-17%	782	-13%	844	-6%	931	4%
Water	713	1051	47%	1032	45%	1011	42%	956	34%	846	19%
Soft drinks, sugared	121	50	-59%	47	-61%	42	-65%	37	-70%	29	-76%
Soft drinks, sugarfree	61	28	-55%	29	-53%	29	-52%	32	-47%	60	-3%
Alcoholfree beverages	17	12	-28%	13	-24%	13	-23%	14	-16%	19	8%
Juice, fruit	25	7	-71%	7	-73%	6	-74%	6	-76%	5	-79%
Juice, vegetables	2	1	-65%	1	-63%	1	-62%	1	-54%	2	20%
Alcoholic beverages											
Beer	66	81	23%	80	21%	81	22%	80	22%	78	18%
Wine	34	16	-54%	16	-53%	17	-49%	19	-42%	35	4%
Alcohol, other than beer wine	6	4	-32%	4	-33%	4	-36%	4	-39%	5	-27%

Supplemental table 6.5. Daily food consumption in grams and relative (%) difference with current diets, for 663 Dutch adults 18-79 years with intermediate educational level, from the Dutch National Food Consumption Survey 2019-2021, results from the secondary analysis using total population as peers.

	Current	**Model 1**		**Model 2**		**Model 3**		**Model 4**		**Model 5**	
	Mean	**Mean**		**Mean**		**Mean**		**Mean**		**Mean**	
	(grams)	**(grams)**	**Δ**	**(grams)**	**Δ**	**(grams)**	**Δ**	**(grams)**	**Δ**	**(grams)**	**Δ**
Grains and grans based products											
Bread, rusks, wholegrain	83	91	10%	91	10%	91	9%	89	8%	81	-2%
Bread, rusks, refined	37	23	-38%	22	-41%	21	-44%	18	-50%	14	-62%
Flours, rice, grains, refined	50	26	-48%	25	-51%	23	-54%	21	-59%	16	-68%
Flours, rice, grains, wholegrain	8	9	9%	10	16%	11	30%	13	62%	24	189%
Breakfast cereals, wholegrain	7	12	58%	12	58%	12	66%	14	84%	13	83%
Breakfast cereals, refined	2	2	-4%	2	-6%	2	-5%	2	-1%	2	-33%
Vegetables	157	151	-4%	154	-2%	159	1%	167	6%	181	15%
Fruit											
Fruit, other	55	56	1%	57	3%	59	6%	65	18%	74	34%
Apples and pears	36	46	27%	48	33%	51	42%	54	51%	52	45%
Citrus fruits	22	25	13%	25	15%	26	21%	29	32%	28	27%
Berries	15	5	-64%	6	-63%	6	-61%	7	-55%	19	27%
Fruitcompote	4	3	-35%	3	-34%	3	-32%	3	-22%	6	34%
Mixed fruits and olives	3	3	1%	3	10%	3	19%	4	34%	5	89%
Potatoes and tubers	72	74	3%	75	4%	75	5%	76	6%	76	6%
Nuts and seeds											
Nuts and seeds, not unsalted	10	10	2%	10	0%	9	-6%	9	-11%	9	-11%
Nuts and seeds, unsalted	5	10	95%	11	116%	13	153%	15	188%	15	195%
Legumes	7	9	24%	13	72%	15	102%	15	109%	16	113%

Animal based foods										
Dairy										
Milk and yoghurtproducts, sugarfree	232	224	-4%	225	-3%	227	-2%	231	-1%	247	6%
Milk and yoghurtproducts, sugared	17	8	-55%	7	-59%	6	-63%	5	-70%	3	-81%
Dairy, other	60	51	-14%	51	-15%	52	-14%	54	-10%	58	-3%
Meat											
Meat, hot meal, processed	23	21	-10%	20	-13%	19	-19%	14	-38%	7	-68%
Meat, cold meal, processed	23	14	-37%	14	-38%	13	-40%	11	-50%	6	-72%
Meat beef, unprocessed	15	3	-81%	3	-81%	3	-80%	3	-77%	11	-24%
Meat poultry, unprocessed	19	23	21%	23	22%	25	31%	30	58%	33	77%
Meat pork, unprocessed	12	12	4%	12	5%	12	7%	14	19%	14	24%
Meat, other	4	1	-72%	1	-68%	1	-67%	2	-61%	4	8%
Cheese	35	28	-20%	28	-20%	28	-20%	28	-19%	30	-14%
Fish											
Fish, not fatty	11	5	-50%	5	-50%	5	-52%	5	-51%	6	-44%
Fish, fatty	6	18	190%	20	220%	22	245%	22	250%	20	220%
Eggs	18	16	-9%	16	-10%	16	-8%	17	-4%	19	8%
Dairy and meat replacers											
Dairy replacers	12	22	81%	22	84%	22	80%	20	69%	20	66%
Meat replacers	3	6	72%	5	62%	5	57%	5	63%	6	84%
Mixed foods											
Soups and bouillon	18	22	25%	23	31%	24	34%	25	40%	25	43%
Biscuits and sweet pastries	38	38	0%	38	-1%	38	-1%	38	0%	40	5%
Contaminants, yeast and sauces	35	30	-15%	30	-14%	31	-13%	31	-12%	32	-9%
Sugar and confectionary											

Sugar, honey, jam, syrup, dessert sauce	10	9	-9%	9	-8%	9	-9%	9	-9%	9	-15%
Chocolat, candybars, chocolate bread toppings	10	9	-11%	9	-13%	9	-14%	9	-11%	10	-7%
Sweets without chocolate, other bread toppings	4	4	8%	4	9%	4	6%	4	-6%	4	-7%
Fats and oils											
Fats and oils, soft	19	19	-2%	19	-2%	19	-2%	19	-2%	19	0%
Fats and oils, hard	3	2	-38%	2	-40%	2	-42%	2	-44%	2	-44%
Savory snacks											
Pretzels, chips, salty biscuits	8	7	-15%	7	-17%	6	-23%	6	-24%	6	-29%
Snacks, croquettes, snackrolls	11	8	-29%	8	-30%	8	-30%	8	-30%	9	-20%
Non-alcoholic beverages											
Coffee and tea	852	727	-15%	748	-12%	782	-8%	844	-1%	931	9%
Water	927	1051	13%	1032	11%	1011	9%	956	3%	846	-9%
Soft drinks, sugared	106	50	-53%	47	-55%	42	-60%	37	-65%	29	-73%
Soft drinks, sugarfree	87	28	-68%	29	-67%	29	-66%	32	-63%	60	-31%
Alcoholfree beverages	20	12	-36%	13	-33%	13	-32%	14	-26%	19	-5%
Juice, fruit	36	7	-80%	7	-81%	6	-82%	6	-84%	5	-85%
Juice, vegetables	1	1	-27%	1	-24%	1	-22%	1	-5%	2	148%
Alcoholic beverages											
Beer	72	81	12%	80	11%	81	11%	80	11%	78	8%
Wine	42	16	-63%	16	-62%	17	-59%	19	-53%	35	-16%
Alcohol, other than beer wine	6	4	-34%	4	-35%	4	-38%	4	-40%	5	-29%

Supplemental table 6.6. Daily food consumption in grams and relative (%) difference with current diets, for 669 Dutch adults 18-79 years with high educational level, from Dutch National Food Consumption Survey 2019-2021, results from the secondary analysis using total population as peers.

	Current	Model 1		Model 2		Model 3		Model 4		Model 5	
	Mean	Mean		Mean		Mean		Mean		Mean	
	(grams)	(grams)	Δ	(grams)	Δ	(grams)	Δ	(grams)	Δ	(grams)	Δ
Grains and grans based products											
Bread, rusks, wholegrain	86	92	7%	91	6%	91	6%	90	5%	83	-3%
Bread, rusks, refined	30	25	-17%	24	-19%	23	-23%	21	-29%	17	-45%
Flours, rice, grains, refined	54	35	-36%	33	-39%	32	-42%	28	-48%	23	-57%
Flours, rice, grains, wholegrain	13	10	-17%	11	-12%	12	-2%	15	20%	25	100%
Breakfast cereals, wholegrain	10	13	23%	13	24%	13	26%	14	35%	14	31%
Breakfast cereals, refined	2	3	14%	3	15%	3	13%	3	8%	2	-33%
Vegetables	197	154	-22%	156	-21%	160	-19%	167	-15%	179	-9%
Fruit											
Fruit, other	67	58	-14%	58	-12%	61	-9%	65	-3%	75	12%
Apples and pears	46	46	1%	49	6%	52	12%	54	18%	52	14%
Citrus fruits	25	24	-7%	24	-6%	25	-3%	27	6%	26	3%
Berries	19	6	-70%	6	-69%	6	-67%	7	-61%	19	-2%
Fruitcompote	5	3	-42%	3	-41%	3	-40%	3	-27%	5	17%
Mixed fruits and olives	3	3	-8%	3	0%	4	12%	5	31%	6	69%
Potatoes and tubers	64	73	14%	73	15%	74	16%	75	18%	76	20%
Nuts and seeds											
Nuts and seeds, not unsalted	11	12	10%	11	6%	11	1%	10	-5%	10	-6%
Nuts and seeds, unsalted	8	10	34%	11	51%	13	75%	15	101%	15	104%
Legumes	8	10	36%	13	77%	15	104%	16	109%	16	114%

Animal based foods											
Dairy											
Milk and yoghurtproducts, sugarfree	230	209	-9%	210	-9%	210	-9%	212	-8%	227	-1%
Milk and yoghurtproducts, sugared	12	7	-37%	7	-41%	6	-45%	5	-55%	3	-72%
Dairy, other	56	45	-19%	45	-19%	46	-17%	49	-11%	56	0%
Meat											
Meat, hot meal, processed	19	17	-8%	16	-11%	15	-19%	11	-40%	7	-64%
Meat, cold meal, processed	19	13	-28%	13	-29%	13	-31%	11	-41%	7	-63%
Meat beef, unprocessed	11	3	-73%	3	-73%	3	-72%	3	-70%	10	-13%
Meat poultry, unprocessed	17	23	38%	23	39%	25	47%	29	73%	33	95%
Meat pork, unprocessed	8	10	20%	10	25%	11	30%	12	49%	13	59%
Meat, other	4	1	-69%	1	-67%	1	-65%	2	-62%	4	-11%
Cheese	38	32	-17%	32	-17%	32	-17%	32	-17%	34	-12%
Fish											
Fish, not fatty	11	7	-33%	7	-32%	7	-34%	7	-31%	8	-29%
Fish, fatty	9	19	106%	21	123%	23	142%	23	146%	21	120%
Eggs	16	17	6%	17	7%	18	10%	18	14%	19	19%
Dairy and meat replacers											
Dairy replacers	14	26	86%	27	92%	26	87%	26	85%	24	74%
Meat replacers	7	6	-15%	6	-20%	6	-22%	6	-19%	7	-7%
Mixed foods											
Soups and bouillon	25	20	-22%	20	-19%	21	-17%	22	-14%	21	-15%
Biscuits and sweet pastries	40	37	-8%	37	-9%	37	-8%	37	-8%	39	-3%
Contaminants, yeast and sauces	36	31	-14%	31	-14%	31	-13%	32	-11%	33	-8%
Sugar and confectionary											

Sugar, honey, jam, syrup, dessert sauce	9	9	0%	10	2%	10	3%	10	2%	9	-9%
Chocolat, candybars, chocolate bread toppings	11	11	-2%	11	-3%	11	-5%	11	-3%	11	-3%
Sweets without chocolate, other bread toppings	3	5	40%	5	40%	5	37%	4	24%	4	31%
Fats and oils											
Fats and oils, soft	18	19	5%	19	4%	19	4%	19	6%	19	7%
Fats and oils, hard	5	2	-57%	2	-58%	2	-60%	2	-62%	2	-61%
Savory snacks											
Pretzels, chips, salty biscuits	8	8	7%	8	3%	8	0%	7	-3%	7	-4%
Snacks, croquettes, snackrolls	9	12	40%	12	37%	12	38%	12	36%	13	48%
Non-alcoholic beverages											
Coffee and tea	940	733	-22%	753	-20%	787	-16%	855	-9%	948	1%
Water	881	1149	31%	1127	28%	1096	24%	1043	18%	928	5%
Soft drinks, sugared	82	50	-40%	46	-44%	41	-50%	35	-58%	27	-67%
Soft drinks, sugarfree	61	36	-40%	36	-41%	37	-39%	40	-34%	65	7%
Alcoholfree beverages	21	15	-30%	16	-25%	17	-21%	18	-14%	21	-2%
Juice, fruit	33	10	-69%	10	-71%	9	-72%	9	-74%	8	-75%
Juice, vegetables	1	0	-72%	0	-69%	0	-66%	1	-56%	2	25%
Alcoholic beverages											
Beer	69	83	21%	83	21%	83	21%	84	22%	85	23%
Wine	58	20	-66%	20	-66%	21	-63%	24	-58%	37	-36%
Alcohol, other than beer wine	5	5	-1%	5	-5%	5	-4%	5	-9%	5	-6%

Part II

The role of ultra-processed foods and drinks in healthy and environmentally sustainable diets

Chapter 4

Evaluation of foods, drinks and diets in the Netherlands according to the degree of processing for nutritional quality, environmental impact and food costs

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Abstract

This study investigates nutritional quality, environmental impact and costs of foods and drinks and their consumption in daily diets according to the degree of processing across the Dutch population. The NOVA classification was used to classify the degree of processing (ultra-processed foods (UPF) and ultra-processed drinks (UPD)). Food consumption data were derived from the Dutch National Food Consumption Survey 2012–2016. Indicators assessed were nutritional quality (saturated fatty acids (SFA), sodium, mono and disaccharides (sugar), fibre and protein), environmental impact (greenhouse gas (GHG) emissions and blue water use) and food costs. Setting: The Netherlands. Participants: Four thousand three hundred thirteen Dutch participants aged 1 to 79 years. Per 100 g, UPF were more energy-dense and less healthy than unprocessed or minimally processed foods (MPF); UPF were associated with higher GHG emissions and lower blue water use, and were cheaper. The energy and sugar content of UPD were similar to those of unprocessed or minimally processed drinks (MPD); associated with similar GHG emissions but blue water use was less, and they were also more expensive. In the average Dutch diet, per 2000 kcal, ultra-processed foods and drinks (UPFD) covered 29% (456 g UPF and 437 g UPD) of daily consumption and 61% of energy intake. UPFD consumption was higher among children than adults, especially for UPD. UPFD consumption determined 45% of GHG emissions, 23% of blue water use and 39% of expenses for daily food consumption. UPFD consumption contributed 54% to 72% to daily sodium, sugar and SFA intake. Compared with unprocessed or minimally processed foods and drinks, UPF and UPD were found to be less healthy considering their high energy, SFA, sugar and sodium content. However, UPF were associated higher GHG emissions and with less blue water use and food costs. Therefore daily blue water use and food costs might increase if UPF are replaced by those unprocessed or minimally processed. As nutritional quality, environmental impacts and food costs relate differently to the NOVA classification, the classification is not directly applicable to identify win–win-wins of nutritional quality, environmental impact and costs of diets.

Introduction

Providing healthy and sustainable diets is one of the major challenges of this century. Considering global warming and the rise of nutrition-related non-communicable diseases (NCDs) [1], it is essential to identify, understand, and influence key drivers that contribute to unhealthy and unsustainable diets. In the last few decades, the global nutritional transition is characterized by a shift towards the consumption of ultra-processed foods (UPF) at the expense of basic, unprocessed foods [2, 3]. UPF are mostly or entirely created from substances extracted from foods or derived from food constituents and are transformed into unrecognizable, ready-to-eat foods that contain additives and high amounts of energy, sugar, fat and salt [4]. In contrast, unprocessed or minimally processed foods and drinks are those that are either fresh or slightly altered to increase food safety, accessibility or palatability.

Food processing should be an integral part of a sustainable food system [5, 6]. For instance, food processing makes food safer, enables preservation of foods, helps to overcome seasonal gaps, enables nose-to-tail consumption and encourages reuse of materials [6]. On the other hand, food processing steps such as manufacturing, packaging and distribution, contribute to GHG emissions [7]. Moreover, considerable amounts of energy, water and packaging materials are used for food processing. The latter significantly contributes to the plastic waste stream entering marine ecosystems [7].

Processes and ingredients that are used to manufacture UPF make them highly convenient for consumers and highly profitable for manufacturers [4]. Over the past years, it has been argued that unhealthy foods are less expensive compared with healthy foods while the price gap between them is growing [8]. Considering that food prices are an important determinant of food choices and nutritious diets, affordability of ultra-processed foods seems inevitably linked to its consumption, which may have implications for public health, health inequalities and food security, among others [9].

Recent studies link UPF with adverse health outcomes. Higher availability or consumption of UPF is associated with increased risk of overweight, obesity, cardiovascular diseases (CVD), cancer and all-cause mortality [10,11,12]. In food-based dietary guidelines, several countries recommend reducing UPF consumption (for example, in Brazil [13] and Canada [14]) or have set targets to reduce UPF consumption (for example, by 20% in France by 2022 [15]). Existing literature on UPF has primarily focused on nutrient profiles or health outcomes. Less is known about the association between UPF and environmental impact or food costs.

The NOVA classification is often used to categorize foods according to the degree of processing [4]. It could potentially be used to distinguish nutritional quality, environmental impact and cost of diets. If those indicators were consistently different in ultra-processed foods and drinks (UPFD) compared with unprocessed or minimally processed foods and drinks (MPFD), this would facilitate a win–win-win scenario for the transition towards a healthy and sustainable diet. Therefore, this study examines the nutritional quality (via energy, saturated fatty acids (SFA), sodium, fibre, mono and disaccharides (sugar) and protein), environmental impact (via GHG emissions and blue water use) and food costs for UPFD compared with MPFD, as well as their consumption across a representative Dutch population.

Methods

Population and dietary data

Data for 4,313 Dutch children and adults aged 1 to 79 years were derived from the Dutch National Food Consumption Survey (DNFCS) 2012−2016 [16]. Food consumption data was obtained using two 24-h non-consecutive dietary recalls and reported in Globodiet software (IARC©; former EPIC-Soft) [17]. Background information such as date of birth, urbanisation level and educational level was collected by the market research agency who was responsible for the representativeness. Information on body composition was gathered in different ways depending on age: body weight and height of 1−15-year-olds were measured, for 16−70-year-olds they were self-reported and body weight of < 70-year-olds was measured by a trained dietician. Height was not measured for adults aged 71–79-years due to practical reasons. Body Mass Index (BMI) was calculated as the average body weight (in kg) divided by average height (in m) squared (kg/m^2). A full explanation and description of this survey are reported elsewhere [16]. For the current study, participants were classified into subgroups based on age (1–3, 4–8, 9–18, 19–30, 31–50 and 51–79 year-olds), weight status (underweight (BMI < 18.5 kg/m^2), normal weight (BMI 18.5– < 25 kg/m^2), overweight (BMI 25– < 30 kg/m^2), and obese (BMI ≥ 30 kg/m^2), level of education, and degree of urbanization. The level of education was classified as low (primary education, lower vocational education, advanced elementary education), moderate (intermediate vocational education, higher secondary education) or high (higher vocational education and university). The educational level concerned the participants' highest completed educational level or, in the case of participants under the age of 19 years, of the head of household. The degree of urbanization was classified as hardly urbanized (fewer than 1,000 addresses/km^2), moderately urbanized (1000–1500 addresses/km^2) and highly urbanized (1,500 or more addresses/km^2) [16].

Degree of food processing

The NOVA food classification system was applied to determine the degree of food processing [4]. NOVA categorizes foods and drinks according to the nature, extent, and purpose of the industrial processing they undergo. The classification distinguishes four categories: unprocessed or minimally processed foods, processed culinary ingredients, processed foods, and ultra-processed foods, which are described in detail elsewhere [4]. In the current study, foods and drinks were classified into separate categories. Via facet descriptions from Globodiet, all unique foods and drinks reported by participants were identified and systematically categorized into one of the four NOVA categories. Ingredients of composite dishes were individually reported. The following facets descriptions were used: conservation method (e.g. fresh, pasteurization, canned, frozen); production (e.g. industrial, ready-to-eat, fresh); medium (e.g. in oil, in brine, in syrup); salt content (e.g. salted or not salted); sugar content (e.g. not sweetened or sweetened with sugar and/or artificial sweeteners) and where appropriate consistency/shape (e.g. powder, liquid, sliced). Food groups were based on Globodiet. Food group-specific categorization can be found in Supplemental Table S1. In short, fresh or plain foods and drinks or slightly altered (dried, frozen, steamed) were classified as unprocessed or minimally processed foods (MPF) or drinks (MPD) such as plain yoghurt, rice, coffee and tea. Vegetable oils, butter and other animal fats, and sugar were categorized as processed culinary ingredients. Fresh or slightly altered foods combined with processed culinary ingredients were classified as processed foods or drinks (e.g. tuna in oil, salted nuts). Foods and drinks that were either ready-to-eat, industrially prepared, contained many additives, emulsifiers and/or other comparable formulations/ingredients were classified as ultra-processed (e.g. fruity dairy drinks, confectionery, margarine). All bread was classified as ultra-processed since most bread is industrially prepared and contains food additives. Alcoholic drinks are not classified according to the NOVA classification. In the current study, wine, cider and beer were classified as processed as they are produced by fermentation of unprocessed foods. Other spirits and liquors (e.g. gin or whisky) were classified as ultra-processed. A research dietician cross-checked the classification and provided expert judgement.

Nutritional quality

Foods and drinks from the DNFCS 2012–2016 were linked to food composition data of the Dutch Food Composition Database (NEVO online version 2016/5.0) in order to estimate daily intake of energy, SFA, sodium, mono and disaccharides (sugars), fibre and protein [18]. In addition to often assessed nutrients (e.g. energy, SFA, sodium, sugar and fibre) that associate with UPFD consumption, protein is of importance since proteins plays an important role in the transition towards a sustainable diet. Mono and disaccharides were assessed since free or added sugar are not included in the Dutch food composition table (NEVO-online version 2016/5.0).

Environmental impact

The environmental impacts of foods were evaluated for Greenhouse gas (GHG) emissions (in kg CO_2-eq) and blue water use (in m^3). Blue water use is also referred to as irrigation water. Data on environmental impact were derived from the Dutch Life Cycle Assessment (LCA) food database [19]. In a previous study in which we applied the LCA Food database we showed that the correlation between GHG emissions and other environmental indicators is generally high, except for blue water use [20]. Therefore, this study examines, besides GHG emission, blue water use since this indicator focusses on other important foods which are ignored when solely focussing on GHG emissions. In short, environmental impacts were based on LCA methodology, which quantified the environmental impact through the foods' entire life cycle. LCAs had an attributional approach and hierarchical perspective and were performed following the ISO 14040 and 14,044 guidelines. A time horizon of 100 years was used, and GHG emissions were recalculated following Intergovernmental Panel on Climate Change (IPCC) guidelines (2006) [21]. Economic allocation was applied when production processes led to more than one food product, except for milk, for which bio-physical allocation was used. The functional unit used was 1 kg of prepared food or drink on the plate, and converted to per 100 g. The LCA food database provided primary data for 265 foods and drinks, which cover 75% of total amount of food intake. These foods were previously selected based on frequency of consumption in the DNFCS and variation in types of food. The environmental impact of foods and beverages for which primary data were not available but that were consumed in the DNFCS 2012–2016 were matched with similar foods. The same methodology was applied in a previous study [20]. In short, foods were matched by expert judgement of a panel of scientists and were based on similarities in types of food, production systems and ingredient composition. For composite dishes, standardized recipes from the Dutch Food composition table (NEVO-online version 2016/5.0) were used where available and if not available, recipes were based on label information. More detailed information on the use of the database can be found elsewhere [19, 20].

Food costs

The Dutch food cost database was used to estimate food costs. A detailed description of the database can be found elsewhere [22]. Briefly, retail food prices (n = 902) of the lowest, non-promotional price were collected from a high segment supermarket (Albert Heijn) and a discount supermarket (Lidl) during July and August 2017 in Amsterdam, the Netherlands. Prices were adjusted for the weight of packaging, preparation (shrinkage/gain) and waste and expressed in € per 100 g edible portion. Eight hundred thirty-nine food prices were directly linked to food composition data of the Dutch Food Composition Database (NEVO-online version 2016/5.0) and covered 62% of the total amount of food intake [18]. Remaining foods were matched to similar foods based on similarities in product, brand, (relative) price and ingredient composition. For composite dishes, standardized recipes from the Dutch food composition table (NEVO-online version 2016/5.0) were used.

Data analysis

Descriptive statistics were applied to characterize the nutritional and environmental indicators and costs for foods and drinks (per 100 g) reported by DNFCS 2012–2016, according to the degree of processing. Primary data was used to characterize environmental impact and costs according to the degree of processing. Notable differences in characteristics between foods and drinks per 100 g according to their degree of processing were reported based on mean and 95%CI. Daily average consumption of UPFD, UPF and UPD was calculated over two consumption days and expressed in weight (g) per 2000 kcal. The outcomes were standardized in order to assess the relative contribution of food intake according to degree of processing towards the total dietary intake. Mann–Whitney U test or Kruskal–Wallis test for non-normally distributed data and ANOVA for normal distributed data were applied to examine differences in UPFD consumption across population subgroups. Nutritional quality (energy, SFA, sodium, sugar, fibre and protein), environmental impact (GHG emissions and blue water use) and food costs for total diet and according to degree of processing were calculated over two consumption days and standardized to 2000 kcal per day and were reported for total diet and according to degree of processing. Wilcoxon signed rank test for non-normally distributed data and paired t-test for normal distributed data were used to assess whether the nutritional quality, environmental impacts and food costs of the consumption of culinary processed ingredients, processed foods and drinks, and UPF and UPD differs from those of unprocessed or minimally processed foods and drinks. Descriptive statistics were reported as mean, 95% confidence interval (95%CI), 25th percentile, 50th percentile and 75th percentile (P25, P50, P75). Reported values were weighted for demographic properties, season, and combination of both consumption days (week or weekend). A sensitivity analysis was performed with alternations made in the food classification for bread (processed instead of ultra-processed). The statistical analysis was performed using SAS software, version 9.4 (SAS Institute Inc., Cary, NC, USA). A two-sided p-value of < 0.05 was considered statistically significant.

Results

Foods and drinks classified according to NOVA

Around half to two-thirds of the foods (54%) and drinks (62%) identified in DNFCS 2012–2016 were categorized as ultra-processed foods (UPF) or drinks (UPD) (Fig. 1). Approximately a quarter of foods (25%) and one-third of drinks (31%) were classified as unprocessed or minimally processed foods (MPF) or drinks (MPD). In the food groups ‘Sugar, sweets and (savoury) snacks' (98%), 'Soft drinks' (93%) 'Grains and breads' (76%), and 'Fats and oils' (71%), the majority of foods were classified as UPF or UPD. The food groups 'Eggs' (0%), 'Legumes' (0%), 'Vegetables' (1%), 'Fish' (8%), 'Fruits' (13%), 'Tap water' (0%) and 'Fruit and vegetable juice' (0%) contained a low or no share of UPF or UPD.

Characteristics of ultra-processed foods and drinks

UPF contained around double the amount of energy (313 vs 150 kcal/100 g (+ 109%)), triple the mono and disaccharides (16.1 vs 4.9 g/100 g (+ 229%)) and SFA (5.4 vs 1.9 g/100 g (+ 184%)), and four times the sodium (478 vs 126 mg/100 g (+ 279%)) compared with MPF (Table 1). UPF contained reasonably similar amounts of protein (7.1 vs 8.9 g/100 g) and fibre (2.3 vs 2.7 g/100 g) compared with MPF. UPD had a similar energy (67 vs 75 kcal/100 g) and mono- and disaccharides (8.7 vs 7.3 g/100 g) content compared with MPD.

UPF were associated with slightly higher GHG emissions (0.62 vs 0.55 kg CO_2-eq/100 g (+ 12%)) but less usage of blue water (0.008 vs 0.033 m^3/100 g (-97%)) compared with MPF. Underlaying food groups showed a large variation in average environmental impact, e.g. GHG emissions were on average 0.19 kg CO_2-eq/100 g for unprocessed or minimally processed vegetables while 2.75 kg CO_2-eq/100 g for unprocessed or minimally processed meat. UPD were associated with similar GHG emissions (0.11 vs 0.10 kg CO_2-eq/100 g) but less blue water use (0.002 vs 0.008 m^3/100 g (-75%)) than MPD. UPF were almost half as expensive as MPF (€0.55 vs €0.97/100 g (-43%)). UPD cost two times more (€0.37 vs €0.15/100 g (+ 147%)) compared with MPD.

Ultra-processed foods and drinks in daily diets

The Dutch population consumed a daily absolute average of 3053 g (2126 kcal) of foods and drinks, of which 925 g UPFD (478 g UPF and 477 g UPD). The absolute daily average UPFD consumption was 743 g for 1–3-year-olds, 1014 g for 4–8-year-olds, 1230 g for 9–13-year-olds, 1259 g for 14–18-year-olds, 1091 g for 19–30-year-olds, 959 g for 31–50-year-olds, 737 g for 51–70-year-olds and 617 g for 71–79-year-olds. Figure 2shows the daily consumption of UPF and UPD by age, in grams per 2000 kcal. Per 2000 kcal, the daily average UPFD consumption was 893 g (456 g UPF and 437 g UPD) and did not differ between men (889 g/2000 kcal) and women (898 g/2000 kcal) ($p > 0.05$) (Table 2). Daily UPFD consumption differs significantly between age groups ($p < 0.001$). Children and teenagers up to 18 years consumed, almost twice as much UPFD (approximately 1200 g/2000 kcal) compared with adults and older adults aged 51 to 79 years (ranging between 632 g/2000 kcal to 700 g/2000 kcal). Adults aged 19 to 30 years and 31 to 50 years consumed 962 g and 874 g UPFD per 2000 kcal, respectively. Consumption of UPF ranged from 438 to 485 g/2000 kcal for all age groups. Children and teenagers consumed more UPD (approximately 700 g/2000 kcal) than adults aged 19 to 50 years old (415 to

525 g/2000 kcal) and adults aged 51 to 79 years old (ranging between 180 to 247 g/2000 kcal).

There were significant differences overall by subgroups of education level and degree of urbanization (Table 2), ranging around 4–9% between the subgroups. Participants with a moderate education level (939 (95%CI 916, 962) g/2000 kcal) consumed 89 g more UPFD compared with higher educated participants (850 (95%CI 830, 871) g/2000 kcal) and 68 g more compared with lower educated participants (871 (95%CI 838,903) g/2000 kcal) ($p < 0.001$). Participants living in low urbanized areas consumed 916 (95%CI 891, 942) g/2000 kcal UPFD, and consumed 40 or 20 g UPFD more than those living in highly or moderately urbanized areas, 876 (95%CI 856, 896) g/ 2000 kcal and 898 (95%CI 868, 928) g/ 2000 kcal respectively ($p < 0.01$).

Nutritional quality, environmental impact and food costs

Although there was a statistically significant difference observed between UPF and MPF consumption, their consumption was more or less similar with 442 g/2000 kcal and 456 g/2000 kcal, respectively for UPF and MPF. Energy intake from UPF was almost three times higher at 1107 kcal (55%)compared with 372 kcal (19%) from MPF ($p < 0.001$). Per 2000 kcal, UPF consumption contributed most towards daily intake of sodium (1596 mg, 70%), fibre (11.1 g, 58%), SFA (15.3 g, 54%), protein (33 g, 44%) and mono and disaccharides (42 g, 40%) (Table 3). MPF consumption contributed less to daily nutrient intake, ranging between 7% (for sodium) and 37% (for fibre). The consumption of UPD (437 g/2000 kcal) was around three times lower than the consumption of MPD (1510 g/2000 kcal) ($p < 0.001$), contributed 6% to daily energy intake and determined 25 g (24%) of daily sugar intake.

Compared with MPF, consumption of UPF contributes more to GHG emissions (36% vs 30%) ($p < 0.001$) but less to blue water use (19% vs 35%) ($p < 0.001$) per 2000 kcal. UPD determined approximately twice less GHG emissions (7% vs 12%) ($p < 0.001$) and seven times less blue water use (4% vs 27%) ($p < 0.001$) compared with MPD.

Dietary costs for UPF (€1.24/2000 kcal) and UPD (€0.42/2000 kcal) consumption were lower compared with costs of MPF (€1.32/2000 kcal) ($p < 0.001$) and MPD (€0.63/2000 kcal) ($p < 0.001$) consumption.

Sensitivity analysis

In a sensitivity analysis, all bread was classified as processed instead of ultra-processed. The percentage UPF in ‘Grains and breads’ decreased from 76 to 35%. As a result, the average fibre content of UPF decreased with 0.2 g fibre per 100 g (2.1 g fibre per 100 g). Daily average UPF consumption decreased from 456 g per 2000 kcal to 336 g per 2000 kcal, resulting in an difference of 120 g (309 kcal). Obviously, UPF contributed less to daily intake of fibre (-6.3 g, -57%), protein (-12.6 g, -38%), sodium (-523 mg, -33%) and determined less GHG emissions (-0.14 kg CO_2-eq, -8%), blue water use (-0.003 m^3, -12%) and food costs (-€0.23, -19%).

Discussion

This study investigated nutritional quality, environmental impact and costs of foods, drinks and daily diets according to the degree of processing across the Dutch population. Per 100 g, ultra-processed foods were on average energy-denser, less healthy, and associated with higher GHG emissions but lower blue water use and were cheaper than unprocessed or minimally processed foods. Per 100 g, ultra-processed drinks had on average a similar energy and sugar content, similar GHG emissions but lower blue water use and were more expensive compared with unprocessed or minimally processed drinks. In the current Dutch dietary pattern, UPFD consumption accounted for 29% of daily food consumption in weight per 2000 kcal and determined 61% of daily energy intake. Children consumed more UPFD per 2000 kcal, and especially UPD, compared with adults and older adults. The consumption of UPFD was found to be unhealthy given its significant contribution to the intake of nutrients such as sodium (72%), sugar (64%) and SFA (54%). The high UPFD consumption determined 45% of GHG emissions and 23% of blue water use. Furthermore, food costs related to UPFD consumption were lower since UPFD determined a smaller proportion of daily food costs compared with those unprocessed or minimally processed foods.

The UPFD consumption in the Netherlands is comparable to studies from the USA (58%) [23] and the UK (57%) [24] but higher compared with studies from Brazil [25], Chile [26] or Canada [27], ranging between 22 to 48% of daily energy intake. Differences might be explained by the NOVA classification of bread. Firstly, all bread in our study was classified as UPF since most bread is mass-produced nowadays and contains additives. Secondly, the Dutch consume large quantities of bread: on average 120 g or 309 kcal on a daily basis. Other studies sometimes categorized bread as unprocessed or minimally processed [28], processed [29] or ultra-processed [30]. The difficulty of classifying bread according to NOVA has been addressed previously as terminology such as artisanal bread, sliced or unsliced, mass-produced is used, but their exact interpretation is not self-evident [31, 32]. The classification of bread has direct implications for protein and fibre since we identified high – or similar compared to unprocessed or minimally processed foods – levels in UPF. In a sensitivity analysis we demonstrated that if 120 g or 309 kcal of UPF shifted to processed foods, consequently a lower contribution from UPF to daily protein and fibre intake was observed. This underlines a certain level of arbitrariness in food classification since results would be significantly different if bread was not classified as UPF. In accordance with previous studies, our overall results show that ultra-processed foods and drinks are unhealthy as they are on average more energy dense, contain high levels of SFA, sodium and sugar [33] and contribute significantly to daily energy, SFA, sodium and sugar intake [4].

We found that children and teenagers from 1 to 18 years consumed more UPFD than adults and older adults. This finding is in line with studies from Belgium [30], the USA [34], Canada [27] and Chile [26]. UPFD consumption appears to be inversely associated with age, as demonstrated in various studies [27, 29, 34, 35]. Our results indicated that the lower UPFD consumption with increasing age was mainly due to lower consumption of UPD. The older population consumed more unprocessed or minimally processed drinks such as coffee, tea and water, which raises the question of whether the observed UPD consumption in the younger age groups is a temporary effect or whether it is a birth-cohort effect that will remain when this groups reaches adult and older ages. Furthermore, although children do not consume 2000 kcal daily, the relative observed dietary share of UPFD for children and teenagers (1 to 18 years) in our study (75% of daily energy intake (not standardized)) was higher than reported values from UK (65%) [36] or Belgium (33%) [30]. The high consumption of UPFD among Dutch children is of concern, given its association with poor diet quality, weight gain, obesity and other adverse health outcomes [37]. Convenience, attractiveness and aggressive marketing campaigns targeting children can increase UPF consumption in children and is suggested as an important reason why energy intake from UPF is high in high-income countries [3].

The environmental impact per kg foods or diets according to the degree of processing (NOVA) has not been determined in detail in previous research. Fardet and Rock (2020) demonstrated based on GHG emissions of dietary patterns, that UPF-like discretionary foods do not necessarily produce the highest GHG emissions (per 100 g) [5]. In our study, UPF, per 100 g, were associated with on average a higher GHG emission, but lower blue water use compared with MPF. Per 100 g, the environmental impact for UPD was on average similar for GHG emissions but lower for blue water use compared with MPD such as water, coffee, tea and fruit- and vegetable juices. Those results are divergent and do not convincingly reflect a lower environmental impact for MPFD, compared with UPFD. Moreover, our study showed that UPF and UPD consumption contributed, respectively, 36% and 7% of GHG emissions and 19% and 4% of blue water use. An Australian study estimated the environmental impact of discretionary food consumption and reported at 33% and 35% for associated GHG emission, and water footprint, respectively [38]. The environmental impact associated with UPFD consumption is significant and should therefore not be neglected [39].

Food costs according to NOVA were not in line with outcomes for nutritional quality, as healthier foods (MPF) were more expensive than UPF, while UPD were twice as expensive as MPD. Previous studies did not assess food costs separately for drinks and foods, but did report that UPFD were less expensive than MPFD, for instance, in Belgium (€0.55/100 kcal for UPF and €1.29/100 kcal for unprocessed or minimally processed food) [40], although there are exceptions [41]. Moreover, food costs associated with MPFD consumption were more expensive than costs associated with consumption of UPFD. In Belgium, MPFD contributed most to daily dietary costs (30–42%) compared with UPFD (22–30%) [40]. Higher food costs for unprocessed, healthier foods and diets, might have implications for population health, especially among the lower educated individuals [8, 9].

The applicability of categorizing foods for health-related outcomes according to NOVA is frequently addressed. In addition, the concept of NOVA is more often used in food education. Given current diet-related NCDs and progressive climate change, but also growing gaps in health inequalities and economic status, integrated measures not focussing on one single problem, such as dietary health via NOVA, are preferred. Furthermore, a clear diet advice requires that outcomes for nutritional quality, environmental impact and diet cost are ideally in accordance with each other, for foods as well as for drinks, to facilitate a transition. The NOVA classification could potentially be used to distinguish nutritional quality, environmental impact and cost of diets. NOVA seems suited to identify unhealthy foods, but there are some exceptions: the UPF category in NOVA covers a broad range of unhealthy but also nutritious foods (e.g. wholegrain bread). Although, NOVA was developed to identify degree of food processing, the concept appears not to be of added value for classification for environmental impact and costs evaluations. Our results show no convincing and rather divergent results based on the NOVA concept in assessing—besides nutritional quality—the environmental impact and food costs for UPFD compared with MPFD. Therefore, we question whether food classification according to the degree of processing (NOVA) is needed and a suited methodology to implement for environmental impact as well as for diet cost evaluations or to use as a starting point for food policy.

However, action is needed since current food consumption patterns include many UPFD and a large number of foods that are unhealthy and not recommended for a healthy diet. Interventions focussing on the replacement of UPFD with MPFD will benefit human health but may not automatically lead to a lower environmental impact or reduced food costs. However, for example, replacing sugar-sweetened beverages with tap water is less expensive and benefits both human and planetary health [42]. For population groups with a general overconsumption, reducing UPF consumption without substituting recommended healthy foods remains an interesting lever for achieving a healthier and sustainable diet without adverse health effects [5]. It should be noted that it can be difficult to reduce UPFD consumption, as they are integrated into the diets of many consumers and should be part of an sustainable food system [5, 6]. Therefore, if we continue to consume UPF, it is worthwhile to explore the possibilities to reformulate UPF and UPD in such a way that at least their nutritional composition benefits human health by a lower SFA or sugar content while reducing environmental impact.

Strengths and limitations

This is the first study to explore nutritional quality, environmental impacts and costs of foods and drinks and their consumption, according to the NOVA classification. A significant strength of this study is the quantification of the environmental impact in terms of GHG emissions and blue water use of UPFD and their consumption, using a comprehensive set of environmental indicators. The Dutch LCA Food database provides data on the most frequently consumed Dutch foods and covers 75% of the Dutch diet in weight. GHG emissions were used as a proxy for some other indicators available in the LCA Food database, however, we did not include other sustainability aspects such as animal welfare or pesticide use. The current study has several noteworthy limitations. Firstly, we used memory-based food consumption data, which is associated with misreporting, underreporting or overreporting of dietary intake [43]. Therefore, the reported food consumption by the degree of processing might over or underestimate the true levels. Secondly, UPFD were determined using the NOVA classification. NOVA is the most used system to classify foods by level of processing and is widely recognized as a tool for research into nutrition and public health. However, it should be noted that classification systems such as NOVA conceptually differ from processing level concepts in food science technology [44]. The use of NOVA enables comparison with other studies. Nevertheless, different definitions of UPFD and insufficient standardization make food classification with NOVA difficult [45] and can lead to confusion and subjective recoding of national food consumption databases [32]. Although we had to make assumptions as well, food consumption data in our study was collected with a great level of detail and systematically stored [16]. We were, therefore, able to systematically categorize foods according to NOVA with little inconsistencies or subjective classifications. Thirdly, when interpreting the results and comparing them with other studies, it is important to consider the expression of UPFD consumption. We expressed UPFD consumption as g per kcal to account for total energy intake. Moreover, as light beverages do not contain energy, actual UPD consumption is likely to be underestimated when exclusively using percentage of energy intake. Nonetheless, sensitivity analyses using the energy percentage of UPFD were carried out and did not alter our conclusions. Finally, estimated diet cost might be underestimated because only the lowest prices were included in the Dutch food price database. The food price data used was collected in the past (2017) to reflect prices from when dietary data was collected (2012–2016) and may differ from prices today due to inflation or VAT increasing from 6 to 9% for foods and beverages in the Netherlands.

Although absolute food costs may differ, this method is suitable for the purpose of ranking foods based on total dietary cost.

Conclusion

With this study we provide insight into the associated nutritional quality, environmental impact and costs of foods, drinks and daily diets according to the degree of processing across the Dutch population. Compared with unprocessed or minimally processed foods and drinks, UPF and UPD were found to be less healthy considering their high energy, SFA, sugar and sodium content. However, UPF were associated higher GHG emissions and with less blue water use and food costs. Therefore daily blue water use and food costs might increase if UPF are replaced by those unprocessed or minimally processed. As nutritional quality, environmental impacts and food costs relate differently to the NOVA classification, the classification is not directly applicable to identify win–win-wins of nutritional quality, environmental impacts and food costs. However, given the current high consumption of UPFD, especially in children, a lower consumption would reduce unhealthy intakes of energy, SFA, sugar and sodium, as well as avoid unnecessary GHG emissions.

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Tables and figures

Table 1. The average nutritional quality, environmental impact and costs aspects per 100 g foods and drinks in the DNFCS 2012-2016 by degree of processing.

	Energy(kcal)/100g							**Mono and disaccharides(g)/100g**						
	N	**Mean**	**(95%CI)**		**P25, P50, P75**			**N**	**Mean**	**(95%CI)**		**P25, P50, P75**		
All	2159	243	(235,	251)	71	211	368	2159	10.7	(10.0,	11.5)	0.4	3.1	11.9
Foods														
Unprocessed or minimally processed (MPF)	481	150	(136,	164)	36	105	189	481	4.9	(4.0,	5.9)	0.0	1.6	4.5
Processed culinary ingredients	37	664	(575,	752)	396	737	899	37	23.8	(10.2,	37.4)	0.0	0.2	28.2
Processed	358	249	(228,	271)	83	194	355	358	3.7	(2.8,	4.5)	0.0	0.6	4.0
Ultra-processed (UPF)	1022	313	(303,	323)	194	302	413	1022	16.1	(14.9,	17.4)	1.3	5.3	25.3
Drinks														
Un-or minimally processed(MPD)	82	75	(50,	99)	35	47	68	82	7.3	(5.3.	9.4)	2.1	5.1	9.7
Processed	18	83	(59,	107)	47	66	111	18	4.9	(2.4,	7.5)	0.9	3.1	6.0
Ultra-processed (UPD)	161	67	(54,	80)	24	40	66	161	8.7	(7.2,	10.3)	3.9	7.4	10.8
	Sodium(mg)/100g							**Saturated fatty acids(g)/100g**						
	N	**Mean**	**(95%CI)**		**P25, P50, P75**			**N**	**Mean**	**(95%CI)**		**P25, P50, P75**		
All	2159	325	(284,	365)	10	74	400	2159	4.4	(4.1,	4.8)	0.1	1.2	6.2
Foods														
Unprocessed or minimally processed (MPF)	481	126	(91,	160)	5	25	75	481	1.9	(1.5,	2.3)	0.0	0.2	2.0
Processed culinary ingredients	37	62	(19,	105)	0	0	10	37	19.2	(12.5,	25.9)	1.3	14.3	27.2
Processed	358	398	(334,	463)	26	232	600	358	6.5	(5.5,	7.5)	0.1	2.6	9.7
Ultra-processed (UPF)	1022	478	(398,	558)	50	240	524	1022	5.4	(4.9,	5.8)	0.6	2.6	8.3
Drinks														

Un-or minimally processed(MPD)	82	51	(29,	72)	2	22	39	82	0.9	(0.4,	1.5)	0.0	0.0	1.0
Processed	18	6	(2,	10)	2	3	4	18	0.0	(0.0,	0.0)	0.0	0.0	0.0
Ultra-processed (UPD)	161	19	(14,	23)	1	5	40	161	0.3	(0.1,	0.6)	0.0	0.0	0.0
	Fibre(g)/100g							**Protein(g)/100g**						
	N	**Mean**	**(95%CI)**		**P25, P50, P75**			**N**	**Mean**	**(95%CI)**		**P25, P50, P75**		
All	2159	2	(1.8,	2.1)	0	0.7	2.5	2159	7.1	(6.7,	7.4)	0.8	3.8	10.8
Foods														
Unprocessed or minimally processed (MPF)	481	2.7	(2.3,	3.1)	0.0	1.6	3.0	481	8.9	(8.1,	9.7)	1.1	3.9	18.3
Processed culinary ingredients	37	0.2	(0.1,	0.5)	0.0	0.0	0.0	37	0.3	(0.1,	0.6)	0.0	0.0	0.3
Processed	358	1.2	(1.0,	1.5)	0.0	0.1	1.7	358	9.5	(8.3,	10.6)	0.7	2.8	19.5
Ultra-processed (UPF)	1022	2.3	(2.1,	2.5)	0.2	1.3	3.4	1022	7.1	(6.7,	7.5)	2.1	5.8	10.0
Drinks														
Un-or minimally processed(MPD)	82	0.4	(0.2,	0.5)	0.0	0.2	0.4	82	2.5	(1.3,	3.6)	0.4	1.0	2.2
Processed	18	0.1	(0.0,	0.2)	0.0	0.0	0.3	18	0.2	(0.1,	0.3)	0.0	0.2	0.4
Ultra-processed (UPD)	161	0.4	(0.1,	0.6)	0.0	0.0	0.2	161	1.0	(0.6,	1.4)	0.0	0.1	1.3
	GHGe(kgCO$_2$-eq)/100g							**Blue water use(m^3)/100g**						
	N	**Mean**	**(95%CI)**		**P25, P50, P75**			**N**	**Mean**	**(95%CI)**		**P25, P50, P75**		
All	265	0.54	(0.44,	0.64)	0.14	0.25	0.62	265	0.021	(0.013,	0.029)	0.002	0.006	0.012
Foods														
Unprocessed or minimally processed (MPF)	106	0.55	(0.35,	0.74)	0.12	0.21	0.52	106	0.033	(0.017,	0.049)	0.004	0.007	0.017
Processed culinary ingredients	7	0.57	(0.10,	1.04)	0.11	0.50	1.22	7	0.060	(0.070,	0.191)	0.001	0.010	0.018
Processed	20	0.84	(0.52,	1.16)	0.27	0.85	1.10	20	0.036	(0.010,	0.082)	0.005	0.010	0.012
Ultra-processed (UPF)	98	0.62	(0.49,	0.75)	0.22	0.42	0.64	98	0.008	(0.007,	0.010)	0.004	0.006	0.011

Drinks													
Un-or minimally processed(MPD)	13	0.11	(0.06,	0.15)	0.04	0.14	0.15	13	0.008	(0.002,	0.019)	0.001	0.002	0.004
Processed	4	0.18	(0.06,	0.30)	0.14	0.21	0.22	4	0.007	(0.001,	0.013)	0.005	0.009	0.009
Ultra-processed (UPD)	17	0.10	(0.05,	0.14)	0.05	0.06	0.07	17	0.002	(0.001,	0.002)	0.001	0.001	0.002

	Food costs €/100 g						
	N	**Mean**	**(95%CI)**		**P25, P50, P75**		
All	993	0.65	(0.57,	0.74)	0.19	0.37	0.80
Foods							
Unprocessed or minimally processed (MPF)	256	0.97	(0.66,	1.29)	0.20	0.48	1.09
Processed culinary ingredients	12	0.26	(0.14,	0.38)	0.12	0.20	0.38
Processed	163	0.70	(0.60,	0.79)	0.23	0.54	0.98
Ultra-processed (UPF)	458	0.55	(0.51,	0.59)	0.24	0.40	0.72
Drinks							
Un-or minimally processed(MPD)	31	0.15	(0.07,	0.24)	0.08	0.11	0.13
Processed	9	0.33	(0.25,	0.41)	0.25	0.36	0.40
Ultra-processed (UPD)	64	0.37	(0.23,	0.52)	0.09	0.13	0.36

Table 2. The average and distribution of the consumption of ultra-processed foods and drinks in grams per 2000 kilocalories for total Dutch population and subgroups of the population.

	N	Total UPFD (g)/ 2000 kcal [1]						Ultra-processed foods (UPF) (g)/ 2000 kcal						Ultra-processed drinks (UPD) (g)/ 2000 kcal					
	%	Mean	(95%CI)	P25, P50, P75			p-value	Mean	(95%CI)	P25, P50, P75			p-value	Mean	(95%CI)	P25, P50, P75			p-value
All	100	893	(879, 907)	547	790	1156		456	(452, 461)	353	439	533		437	(423, 450)	93	314	669	
Gender																			
Male	50	889	(870, 907)	551	788	1143		444	(439, 450)	353	434	516		444	(426, 462)	103	332	664	
Female	50	898	(877, 918)	544	794	1172		469	(461, 476)	354	446	554		429	(410, 449)	75	286	672	
Age(y)							***						***						***
1-3	16	1202	(1159, 1246)	799	1145	1494		466	(453, 478)	364	440	536		737	(695, 778)	361	650	1007	
4-8	12	1252	(1217, 1288)	953	1233	1477		471	(460, 482)	388	459	535		781	(746, 817)	483	760	1025	
9-13	12	1209	(1175, 1243)	936	1193	1460		485	(474, 495)	404	468	547		725	(691, 758)	465	699	981	
14-18	12	1165	(1124, 1206)	817	1097	1455		469	(459, 479)	391	461	538		696	(656, 737)	350	615	990	
19-30	12	962	(921, 1003)	622	853	1209		438	(425, 450)	350	419	503		524	(483, 565)	173	406	755	
31-50	12	874	(834, 914)	544	768	1106		459	(446, 472)	350	445	541		415	(377, 453)	97	292	617	
51-70	12	700	(669, 730)	449	628	857		453	(437, 468)	335	429	541		247	(220, 274)	0	137	342	
71-79	12	632	(607, 656)	436	570	757		451	(438, 465)	345	438	533		180	(161, 200)	0	113	276	
BMI [2]							***						**						***
Underweight	5	1104	(1044, 1165)	794	1091	1375		477	(458, 495)	373	470	576		627	(566, 688)	273	568	940	
Normal weight	56	924	(905, 942)	571	833	1206		450	(444, 456)	351	432	524		473	(456, 491)	128	371	712	
Overweight	18	878	(846, 910)	558	768	1113		462	(451, 473)	358	442	543		416	(385, 446)	89	302	658	
Obese	8	907	(852, 962)	542	770	1161		462	(444, 480)	349	441	545		445	(393, 497)	74	274	649	
Education level							***						**						***
Low	19	871	(838, 903)	541	733	1144		457	(446, 468)	350	440	534		414	(382, 445)	60	273	638	
Moderate	37	939	(916, 962)	585	839	1206		458	(451, 466)	355	436	533		481	(458, 503)	128	360	751	

High	44	850	(830,	871)	518	754	1096		454	(447, 461)	356	443	533		397	(378,	416)	82	270	610
Degree of urbanization								**						**						
Low	34	876	(856,	896)	544	777	1117		443	(436, 450)	345	428	522		432	(413,	451)	102	312	664
Moderate	20	898	(868,	928)	552	801	1162		465	(455, 476)	368	445	532		432	(404,	461)	85	315	655
High	46	916	(891,	942)	547	814	1202		470	(462, 479)	363	448	547		446	(422,	470)	88	314	693

[1] Uncorrected energy intake was 1236 kcal for 1-3 year old, 1644 kcal for 4-8 years old, 2052 kcal for 9 to 13 years old, 2207 kcal for 14 to 18 years old, 2317 kcal for 19 to 30 years old, 2250 kcal for 31 to 50 years old, 2139 kcal for 51 to 70 years old and 1966 kcal for 71 to 79 years old.

[2] 12 % missings;

* <0.05, ** <0.01 *** <0.001

Table 3. The average consumption, nutritional quality, environmental impact and food costs aspects per 2000 kilocalories consumed foods and drinks by degree of processing for the Dutch population.

	Weight (g)							**Energy (kcal)**						
	Mean	**(95%CI)**		**P25, P50, P75**			**p-value[1]**	**Mean**	**(95%CI)**		**P25, P50, P75**			**p-value**
All	3039	(3006,	3073)	2258	2801	3499		2000	(2000,	2000)	2000	2000	2000	
Foods														
Unprocessed or minimally processed (MPF)	442	(434,	450)	243	396	576		372	(366,	379)	215	346	489	
Processed culinary ingredients	11	(10,	11)	1	6	16	***	63	(61,	65)	7	40	93	***
Processed	78	(76,	80)	34	65	108	***	177	(173,	181)	83	155	246	***
Ultra-processed (UPF)	456	(452,	461)	353	439	533	***	1107	(1099,	1115)	928	1117	1292	***
Drinks														
Unprocessed or minimally processed (MPF)	1510	(1477,	1542)	770	1304	1993		96	(93,	99)	11	71	144	
Processed	106	(100,	113)	0	0	130	***	62	(59,	66)	0	0	84	***
Ultra-processed (UPD)	437	(423,	450)	93	314	669	***	122	(118,	127)	7	76	186	***
	Mono and disaccharides (g)							**Sodium (mg)**						
	Mean	**(95%CI)**		**P25, P50, P75**			**p-value**	**Mean**	**(95%CI)**		**P25, P50, P75**			**p-value**
All	105	(104,	107)	77	102	130		2295	(2275,	2315)	1850	2189	2648	
Foods														
Unprocessed or minimally processed (MPF)	19	(19,	20)	6	15	28		169	(164,	175)	57	114	207	
Processed culinary ingredients	5	(4,	5)	0	0	5	***	3	(2,	3)	0	0	0	***
Processed	2	(1,	2)	0	0	2	***	389	(379,	398)	156	320	538	***
Ultra-processed (UPF)	42	(41,	42)	26	39	54	***	1596	(1578,	1614)	1198	1521	1922	***
Drinks														

Unprocessed or minimally processed (MPF)	12	(12,	12)	1	9	18		89	(86,	92)	24	62	125	
Processed	1	(1,	1)	0	0	0	***	4	(4,	5)	0	0	6	***
Ultra-processed (UPD)	25	(24,	26)	0	14	37	***	45	(43,	47)	1	17	61	***
	SFA (g)							**Fibre (g)**						
	Mean	**(95%CI)**		**P25, P50, P75**			**p-value**	**Mean**	**(95%CI)**		**P25, P50, P75**			**p-value**
All	28.2	(28.0,	28.4)	23.3	28.0	32.4		19.0	(18.9,	19.2)	15.0	18.4	22.4	
Foods														
Unprocessed or minimally processed (MPF)	3.1	(3.0,	3.2)	0.9	2.1	4.2		6.4	(6.2,	6.5)	3	5.5	8.5	
Processed culinary ingredients	1.6	(1.5,	1.7)	0.0	0.4	1.6	***	0.0	(0.0,	0.0)	0.0	0.0	0.0	***
Processed	6.4	(6.2,	6.6)	2.4	5.3	9.2	***	0.8	(0.8,	0.9)	0.0	0.1	1.0	***
Ultra-processed (UPF)	15.3	(15.1,	15.5)	11.3	15.1	18.8	***	11.1	(11.0,	11.2)	8.5	10.9	13.4	***
Drinks														
Unprocessed or minimally processed (MPF)	1.4	(1.4,	1.5)	0.0	0.5	2.2		0.2	(0.2,	0.2)	0.0	0.0	0.3	
Processed	0.0	(0.0,	0.0)	0.0	0.0	0.0	***	0.2	(0.2,	0.2)	0.0	0.0	0.0	***
Ultra-processed (UPD)	0.4	(0.4,	0.4)	0.0	0.0	0.1	***	0.3	(0.3,	0.3)	0.0	0.0	0.2	***
	Protein (g)							**GHGe (kg CO_2-eq)**						
	Mean	**(95%CI)**		**P25, P50, P75**			**p-value**	**Mean**	**(95%CI)**		**P25, P50, P75**			**p-value**
All	75.3	(74.8,	75.9)	63.1	72.6	85.2		4.72	(4.69,	4.77)	3.80	4.50	5.41	
Foods														
Unprocessed or minimally processed (MPF)	23.2	(22.7,	23.7)	10.4	20	32.1		1.40	(1.36,	1.43)	0.59	1.09	1.85	
Processed culinary ingredients	0.0	(0.0,	0.0)	0.0	0.0	0.0	***	0.05	(0.05,	0.05)	0.00	0.02	0.06	***
Processed	11.1	(10.8,	11.4)	4.5	9.3	15.6	***	0.59	(0.57,	0.60)	0.26	0.5	0.82	***
Ultra-processed (UPF)	33.1	(32.8,	33.4)	25.4	32.1	39.5	***	1.70	(1.68,	1.73)	1.08	1.53	2.14	***

Drinks														
Unprocessed or minimally processed (MPF)	6.0	(5.8,	6.1)	1.1	3.8	9.2		0.55	(0.53,	0.56)	0.24	0.46	0.77	
Processed	0.3	(0.3,	0.3)	0.0	0.0	0.1	***	0.13	(0.12,	0.13)	0.00	0.00	0.17	***
Ultra-processed (UPD)	1.7	(1.6,	1.8)	0.0	0.1	2.0	***	0.32	(0.31,	0.33)	0.05	0.21	0.46	***

	Blue water use (m³)							**Food costs (€)**						
	Mean	**(95%CI)**		**P25, P50, P75**			**p-value**	**Mean**	**(95%CI)**		**P25, P50, P75**			**p-value**
All	0.139	(0.137,	0.141)	0.084	0.12	0.171		4.32	(4.27,	4.36)	3.31	4.09	4.98	
Foods														
Unprocessed or minimally processed (MPF)	0.048	(0.046,	0.049)	0.018	0.035	0.061		1.32	(1.29,	1.35)	0.60	1.09	1.75	
Processed culinary ingredients	0.007	(0.006,	0.007)	0.000	0.001	0.005	***	0.02	(0.02,	0.03)	0.00	0.01	0.03	***
Processed	0.009	(0.008,	0.009)	0.003	0.006	0.009	***	0.44	(0.43,	0.46)	0.18	0.34	0.60	***
Ultra-processed (UPF)	0.026	(0.025,	0.026)	0.017	0.024	0.031	***	1.24	(1.22,	1.25)	0.90	1.19	1.51	***
Drinks														
Unprocessed or minimally processed (MPF)	0.038	(0.037,	0.040)	0.009	0.02	0.053		0.63	(0.62,	0.65)	0.28	0.53	0.85	
Processed	0.004	(0.004,	0.004)	0.000	0.000	0.004	***	0.23	(0.22,	0.25)	0.00	0.00	0.33	***
Ultra-processed (UPD)	0.006	(0.006,	0.007)	0.001	0.003	0.008	***	0.42	(0.41,	0.44)	0.07	0.27	0.60	***

[1] Assesses the difference with the reference unprocessed or minimally processed food or drinks;

* <0.05, ** <0.01 *** <0.001

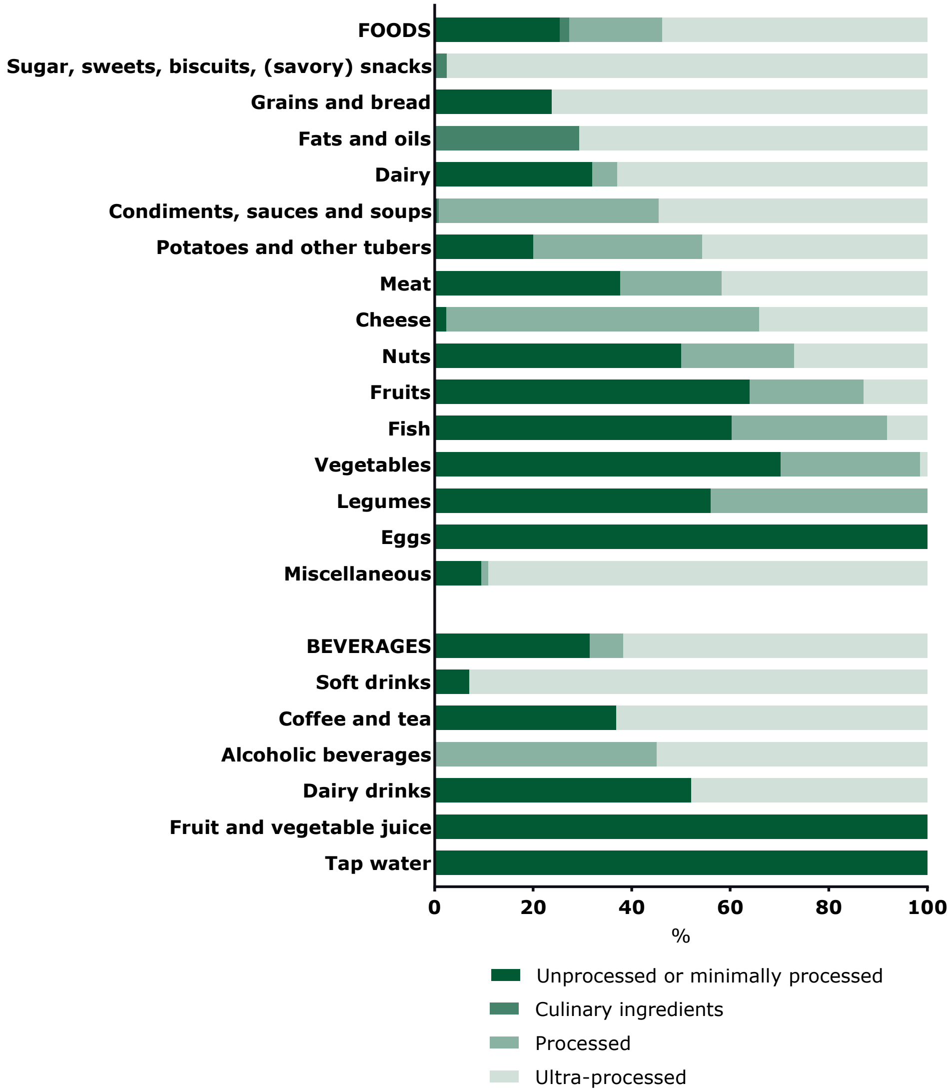

Figure 1. Percentage of foods in the different NOVA-categories for foods and drinks consumed in DNFCS 2012-2016 by food groups.

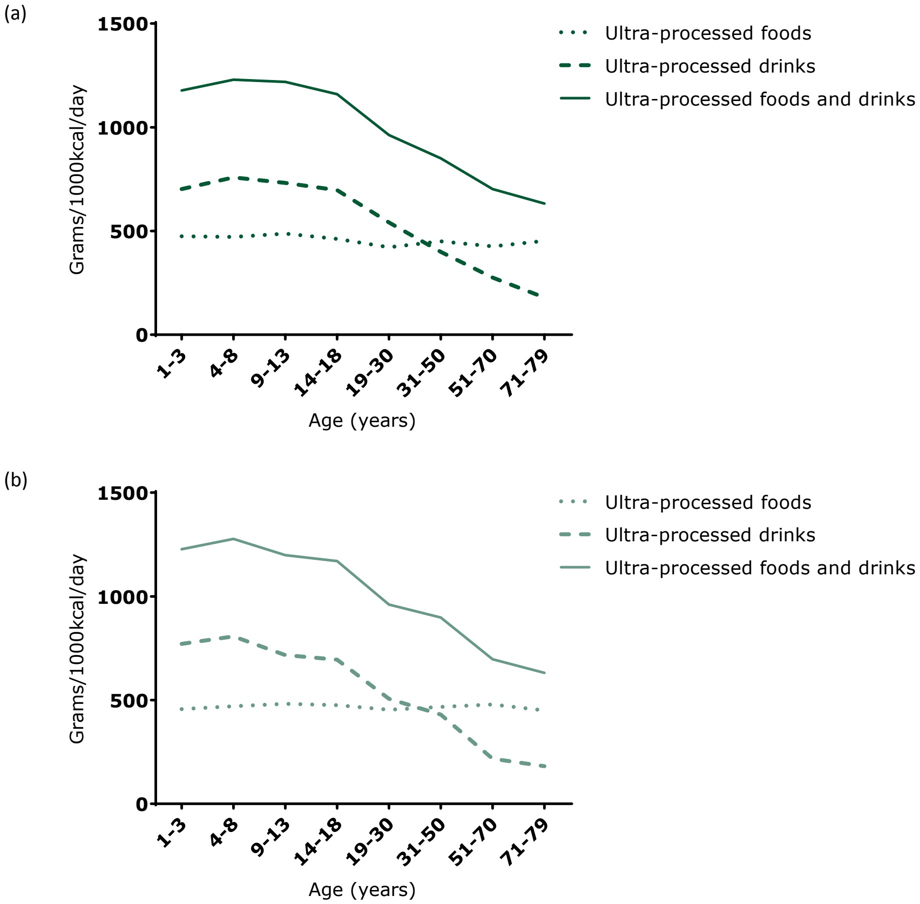

Figure 2. The daily average ultra-processed foods and drink consumption in grams per 2000 kilocalories for Dutch men (a) and women (b) aged 1 to 79 years according to different age groups.

Supplemental files

Supplemental table 1. Food group category rules for assessment of degree of processing.

Food group	Unprocessed or minimally processed foods and drinks	Processed culinary ingredients	Processed foods and drinks	Ultra-processed foods and drinks
Potatoes and other tubers	Conservation method is fresh, vacuum, frozen, dried, home-made, unknown		Potato product frozen or vacuum with added fat, salt or marinated	Manually, based on Dutch food names: Ready-to-eat potato products such as potato croquette, pommes duchesse
Vegetables	Conservation method is unknown, frozen, dried, fresh, vacuum, canned or jarred.		Conservation method is marinated, canned or jarred with added sugar, salt or fat, or unknown	Manually ‘onions, deep fried, dried’, ⍰atjar tjampoer⍰ and frozen vegetables ready-to-eat and include industrial formulations (spinach a la crème etc)
Legumes	Conservation method is unknown, frozen, dried, fresh, vacuum, canned or jarred.		Conservation method is marinated, canned or jarred with added sugar, salt or fat, or unknown	
Fruits and olives, fruit compote	Conservation method is not known, frozen, dried, fresh, heat treated, canned, jarred or medium is in water.		Conservation method is marinated, confit, jarred or canned with added sugar, salt or fat, and medium is in syrup, juice or unknown	Industrially prepared
Nuts, seeds and nut spread	Unsalted or if salt content is not specified		Salted, sugared	If peanut spread and include industrial formulations
Dairy	Not sweetened, not specified if sweetened.		If added sugar, salt or fat.	If sweetened, additives, colours, emulsifiers added
Cheeses			If not spreadable	If spreadable
Cream desserts, puddings (milk based) and Ice cream and substitutes, sorbet and water ice				All foods are categorized as UPF
Dairy and non-dairy creams, creamers	If not sweetened		If sweetened for dairy creams and creamers	If sweetened for non-diary creams and creamers

Food group	Unprocessed or minimally processed foods and drinks	Processed culinary ingredients	Processed foods and drinks	Ultra-processed foods and drinks
Flours, starches, flakes, semolina	All un-or minimally processed			
Pasta, rice, other grain	If conservation method is fresh, not known, dried, vacuum. If pasta is unfilled.			If conservation method is canned or precooked/ frozen and include industrial formulations. If filled pasta. Instant noodles are categorized manually.
Bread, cripsbread, rusks, cough and pastry (plain puff, short-crust)				All foods are categorized as UPF
Breakfast cereals	If sweetened is not specified			If sweetened or it was specified as unknown if sweetened (default is sweetened) or include industrial formulations.
Meat, meat products and substitutes	If conservation method is fresh, not specified, frozen or vacuum.		If conservation method is canned or jarred, dried, salted, smoked, marinated	Meat including industrial formulations
Processed meat			Manually: Processed foods may contain additives used to preserve their original properties or to resist microbial contamination, such as ham, bacon, pastrami and similar.	Manually: meats for which processes include hydrogenation, hydrolysis, extruding, moulding, reshaping, pre-processing by frying, baking; meat containing additives not used to preserve or to resist microbial contamination; pre-prepared meat and other reconstituted meat, such as nuggets en sticks, sausages, burgers, hot dogs, cordon blue.
Meat substitutes				All foods are categorized as UPF
Fish, crustaceans, mollusc, amphibians and reptiles	If conservation method is fresh or frozen or unspecified, vacuum, canned/ jarred, in water (medium).		If conservation method is canned or jarred and medium is not known or in oil; Marinated, smoked/salted fish	

Food group	**Unprocessed or minimally processed foods and drinks**	**Processed culinary ingredients**	**Processed foods and drinks**	**Ultra-processed foods and drinks**
Fish in crumbs				All foods are categorized as UPF
Eggs and egg products	All foods are categorized as un- or minimally processed			
Fats and oils		Vegetable oils, butter, animal fats		Margarines and cooking fats (mixed)
Sugar, honey, jam, syrup, sweet sauce		Sugar, honey		All foods are categorized as UPF, except for the processed culinary ingredients.
Cakes and sweet biscuits				All foods are categorized as UPF
Fruit and vegetable juices	If unsweetened		If sweetened	
Carbonated/soft/isotonic drinks, diluted				All foods are categorized as UPF
Coffee, tea and herbal teas	If tea unsweetened, coffee unsweetened, with milk			If iced coffee sweetened, powdered or instant coffee tea, powdered(instant) or iced coffee ready to eat or and include industrial formulations.
Waters	Plain waters			If additives added /sugared or and include industrial formulations.
Alcoholic beverages			Wine, ciders, fruit wines, sherry, porto, vermouth, beer	Spirits, brandy, Aniseed drinks (pastis) , Liqueurs, mixed punches, cocktails
Condiments, spices, sauces and yeast	Fresh	Vinegars	If 'home-made' sauces without ingredients being disaggregated	If consistence is powder or concentrate. Industrial prepared sauces or sauces with unknown preparation method.
Soups and stocks				All foods are categorized as UPF
Vegetarian products				If industrial prepared
Dietetic products				Artificial sweeteners, meal replacers (shakes, bars, powders): all categorized as UPF

Food group	**Unprocessed or minimally processed foods and drinks**	**Processed culinary ingredients**	**Processed foods and drinks**	**Ultra-processed foods and drinks**
Insects	All foods are categorized as un- or minimally processed			
Savory snacks				All foods are categorized as UPF

Chapter 5

Different levels of ultraprocessed food and beverage consumption and associations with environmental sustainability and all-cause mortality in EPIC-NL

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Abstract

The adverse health effects of high ultraprocessed food and drink (UPFD) consumption are well documented. However, the environmental impact remains unclear, and the separate effects of ultraprocessed foods (UPFs) and drinks (UPDs) on all-cause mortality have not been studied previously. Objectives: To assess the association between levels of UPFD, UPF, and UPD consumption and diet-related environmental impacts and all-cause mortality in Dutch adults. Habitual diets were assessed by a Food Frequency Questionnaire (FFQ) from 1993–1997 in 38,261 participants of the Dutch European Prospective Investigation into Cancer and Nutrition cohort. The mean follow-up time was 18.2 y (SD = 4.1); 4,697 deaths occurred. FFQ items were categorized according to the NOVA classification. Associations between quartiles of UPFD, UPF, and UPD consumption and environmental impact indicators were analyzed using general linear models and all-cause mortality by Cox proportional hazard models. The lowest UPFD, UPF, and UPD consumption quartiles were used as comparator. The average UPFD consumption was 181 (SD = 88) g/1000 kcal. High UPF consumption was statistically significantly inversely associated with all environmental impact indicators (Q4vsQ1: −13.6% to −3.0%), whereas high UPD consumption was, except for land use, statistically significant positively associated with all environmental impact indicators (Q4vsQ1: 1.2% to 5.9%). High UPFD consumption was heterogeneously associated with environmental impacts (Q4vsQ1: −4.0% to 2.6%). After multivariable adjustment, the highest quartiles of UPFD and UPD consumption were significantly associated with all-cause mortality (HRQ4vsQ1: 1.17, 95%CI: 1.08, 1.28 and HRQ4vsQ1: 1.16, 95%CI: 1.07, 1.26, respectively). UPF consumption of Q2 and Q3 were associated with a borderline significant lower risk of all-cause mortality (HRQ2vsQ1: 0.93, 95% CI: 0.85, 1.00; HRQ3vsQ1: 0.91, 95% CI: 0.84, 0.99) whereas Q4 was not statistically significant (HRQ4vsQ1: 1.06, 95% CI: 0.97, 1.15). Reducing UPD consumption may lower environmental impact and all-cause mortality risk; however, this is not shown for UPFs. When categorizing food consumption by their degree of processing, trade-offs are observed for human and planetary health aspects.

Keywords: ultraprocessed foods, ultraprocessed drinks, NOVA classification, all-cause mortality, environmental impact, planetary health, EPIC-NL

Introduction

Industrial processing of foods has increased the shelf life and availability of foods and beverages, resulting in a worldwide decrease of hunger and undernutrition [1]. However, industrial processing has also led to the exhaustion of natural resources and an increase in the production and consumption of ultraprocessed foods and drinks (UPFDs) [1, 2]. UPFDs are mostly or entirely created from substances extracted from foods or derived from food constituents and are often transformed into unrecognizable, ready-to-eat foods that contain cosmetic additives and high amounts of energy, sugar, fat, and salt [3]. UPFDs are generally energy dense and have rapidly replaced unprocessed or minimally processed foods and beverages [4].

In the Netherlands, the consumption of UPFDs has increased in recent decades and now accounts for more than half of the energy intake [5] and in high income countries in general ranges from 24% to 60% of energy intake [6, 7, 8]. High consumption of UPFDs is associated with an increased risk of overweight, obesity, cardiovascular diseases, cancer, and all-cause mortality [2, 9, 10]. Furthermore, it is widely acknowledged that food consumption does not only affect human health [11]. Production and consumption of foods determines 26% of total greenhouse gas (GHG) emissions, 70% of freshwater withdrawals, and 78% of marine and freshwater eutrophication. Additionally, agriculture leads to soil and surface water acidification, loss of biodiversity, and air pollution [11].

Although limited research has been conducted to quantify the environmental impact of UPFDs [5, 12, 13, 14, 15, 16, 17], studies have found that the environmental impact of UPFDs varies depending on the food type, food group, and environmental impact indicators [5, 15]. One study found that, per kg, ultraprocessed foods (UPFs) emit similar or higher GHG emissions, whereas ultraprocessed drinks (UPDs) emit lower GHG emissions compared with unprocessed or minimally processed foods [5]. Generally, UPFDs require more packaging, transportation, and processing, which contribute significantly to environmental impacts [18]. To illustrate, UPFDs are typically packaged in single-use plastics, transported over long distances, and require refrigeration. The production of UPFDs also requires large amounts of energy, water, chemicals, and additives that have negative environmental impacts.

In Brazil, France, and the Netherlands, purchasing or consuming UPFDs accounted for 20%, 24%, and 43% of diet-related GHG emissions and 22%, 23%, and 23% of diet-related water use, respectively [5, 14, 16]. Furthermore, in Brazil and France, UPFD consumption was positively associated with environmental impacts due to higher caloric intake. However, the association disappeared or became negative after energy adjustments [16, 17].

As a previous study suggested that the association between UPF and UPD production and consumption and environmental impact indicators differs, this has raised the question whether this also applies to UPF and UPD consumption in relation to all-cause mortality. Although previous studies have explored the relationship between UPFDs and all-cause mortality [6, 7, 19, 20, 21, 22], no study has assessed the separate effects of UPF and UPD consumption on all-cause mortality. Therefore, the aim of this study was to explore the joint and separate association between UPF and UPD consumption and diet-related GHG emissions, blue water, land use, acidification, fresh- and marine water eutrophication, and all-cause mortality.

Methods

Study population

Participants were selected from the population-based Dutch European Prospective Investigation into Cancer and Nutrition (EPIC-NL) cohort [23]. EPIC-NL consists of 2 cohorts, which are Prospect and the Monitoring Project on Risk Factors for Chronic Diseases (MORGEN). Both cohorts started between 1993 and 1997. At baseline, EPIC-NL consisted of 40,011 participants between the ages of 20 and 70 y, of which 17,357 were females aged 50 to 70 y from Prospect and 22,654 were females and males aged 20 to 59 y from MORGEN. Details are available in the cohort profile [23]. After progressive exclusion of those who withdrew informed consent during follow-up (n = 1), with missing data on dietary intake (n = 218), BMI (n = 21), educational level (n = 264), or smoking status (n = 39), and those with implausible energy intake (<500 or >3500 kcal) (n = 1207), 38,261 participants were included in the analysis (Supplementary Figure 1).

At baseline, general information on age, sex, educational level, physical activity, and smoking status was obtained using a self-reported questionnaire. Height and weight were measured by trained staff according to standardized procedures. BMI was calculated as weight/height2. For BMI, the following categories were used: <18.5 kg/m^2 (underweight), 18.5 to 24.9 kg/m^2 (normal weight), 25 to 29.9 kg/m^2 (overweight), and ≥30 kg/m^2 (obesity). Educational level was defined as the highest attained educational level and was categorized as low (lower vocational education or less), moderate (advanced elementary education until higher general secondary education), and high (at least higher vocational education). Physical activity was assessed with the validated Cambridge Physical Activity Index (CPAI) and categorized into inactive, moderately inactive, moderately active, or active [24]. Smoking status was categorized as never smoked, past smoker, or current smoker.

Dietary assessment

A self-administered validated 178-item FFQ, of which 30 items were beverage-specific, was completed by the participants at baseline (1993–1997) [25]. The FFQ was validated against 12 24-h recalls and biomarkers in 24-h urine and blood [25, 26]. Spearman rank correlation coefficients based on estimates of the FFQ and 24-h recalls were 0.58 for potatoes, 0.38 for vegetables, 0.68 for fruits, 0.47 for meat, 0.32 for fish, 0.64 for cheese, 0.71 for dairy, 0.78 for sweet products, 0.56 for biscuits and pastry, 0.65 for nuts and seeds, 0.67 for nonalcoholic beverages, and 0.74 for alcoholic beverages. The FFQ covered questions on the habitual consumption frequency and portion sizes of food items in the year preceding enrollment. Energy and sodium intake and macronutrients were estimated using the 1996 Dutch Food Composition Table [27].

Classification of dietary intake according to the degree of processing

The NOVA classification was applied to define the degree of processing of foods and beverages [3]. The classification contains 4 categories: unprocessed or minimally processed foods, processed culinary ingredients, processed foods, and UPFs. Unprocessed or minimally processed foods and drinks are foods or drinks that are unaltered or only slightly altered by industrial processes such as removal of inedible or unwanted parts, drying, crushing, grinding, fractioning, roasting, boiling, pasteurization, refrigeration, freezing, placing in containers, vacuum packaging, or nonalcoholic fermentation. Examples are vegetables, plain yogurt, and muscle meat. Processed culinary ingredients are substances obtained from unprocessed foods or from nature and created by industrial processes such as pressing, centrifuging, refining, extracting, or mining, for example, salt, sugar, and oils. Processed foods are industrial products made by adding ingredients such as salt, sugar, oils, or fats to unprocessed or minimally processed foods, resulting in canned fruits and vegetables, cheeses, and smoked or salted meat. UPFDs are formulations of ingredients mostly of exclusive industrial use that result from a series of industrial processes like hydrogenation, hydrolysis, chemical modifications, extrusion, molding, and prefrying, which often contain cosmetic additives (such as colors, flavors, emulsifiers) to make them palatable, for example, sausages, cookies, and sugar-sweetened beverages. Prior to analysis, FFQ items were classified according to corresponding NOVA categories, which is described elsewhere [28]. Briefly, since dietary assessment was conducted in the nineties, the food items were classified into 3 scenarios (lower, middle, and upper bound), which reflected how strictly the food items were classified based on NOVA. The 3 scenarios were designed to capture the potential variation in the degree of food processing. The lower bound scenario included food items that could have been less processed compared to the middle-bound scenario, whereas the upper bound scenario encompassed food items that could have been more processed than the middle-bound scenario. The middle-bound scenario, which represented the most likely scenario, was used for the primary analysis [28]. FFQ items were additionally classified as either foods or drinks, resulting in UPFs and UPDs, respectively. The classification of all FFQ items can be found in Supplementary Table 1.

Environmental impact assessment

The environmental impacts of FFQ items were derived from the Dutch Life Cycle Assessments (LCAs) food database [29]. A detailed description of the LCAs can be found elsewhere [5, 30]. Briefly, the LCAs quantify all inputs and materials used through the entire product life cycle, from the primary mining of raw materials, processing, transport (except between supermarket and consumer), distribution, preparation by the consumer, and the waste of products. The LCAs have an attributional approach and hierarchical perspective and were performed following the ISO 14040 and 14044 guidelines. Economic allocation was applied when production processes led to more than one food product, except for milk, for which biophysical allocation was used. The LCA food database provided primary data for 265 foods and drinks, which cover 75% of the total amount of food intake in the Netherlands [5]. Six environmental impact indicators were linked to the FFQ items. Indicators included were: GHG emissions, (kg CO_2-equivalent [eq]), land use (m^2/year), blue water consumption (m^3), acidification (kg SO_2-eq), freshwater eutrophication (kg P-eq), and marine eutrophication (kg N-eq).

All-cause mortality assessment

The vital status of participants was obtained from the municipal population registries. Participants were followed over time until date of death, emigration, loss to follow-up or were censored (survived), with censoring date 31 December, 2014.

Statistical analysis

Both food and beverage consumption and environmental impacts were standardized to 1000 kcal in order to assess the relative contributions toward the total dietary intake and environmental impacts. Participants were divided into quartiles based on UPFD, UPF, and UPD consumption in g/1000 kcal. Baseline characteristics were summarized for the total population and by quartiles with descriptive statistics in means and SDs or median (25th percentile, 75th percentile) for continuous variables and percentages for categorical variables.

In order to investigate associations between quartiles of UPFD consumption and the environmental impact indicators, general linear models were applied to estimate the mean differences in environmental impact with 95% CIs. The first quartile, representing lowest UPFD consumption, was used as a reference in the analyses. Analyses were adjusted for sex, age at baseline, and total energy intake based on the literature [30, 31]. The variables sex, age, and total energy intake were added as covariates to the model. Means and 95% CIs are expressed in percentage difference compared to the reference.

Cox proportional hazard models were used to estimate crude and adjusted HRs with 95% CIs for the strength of associations between quartiles of UPFD consumption and all-cause mortality. The first quartile, representing lowest UPFD consumption, was used as reference in the analyses. The proportionality of hazard assumptions was assessed using log minus log plots. The Cox proportional hazard models were all Cox-stratified for age because the covariate age failed to meet the proportional hazard assumption. Models were adjusted for potential confounders, which were identified in advance based on the literature rather than statistics [32]. Three successive models were built. Model 1 was Cox stratified for age and adjusted for sex. Model 2 was additionally adjusted for educational level (low, moderate, high), smoking status (never, former, current), physical activity level (inactive, moderately inactive, moderately active, active), and total energy intake (continuous, kcal/d). Model 3 consisted of model 2 with adjustments for BMI (continuous, kg/m^2). All models were repeated for UPFs and UPDs separately. The statistical analysis was performed using SAS software, version 9.4 (SAS Institute Inc).

Results

Of the participants, 76% were female, with a mean age of 50 (SD = 12) y (Table 1). The average UPFD consumption was 181 (SD = 88) g/1000 kcal of which 91 (SD = 29) g were UPFs and 90 (SD = 86) g were UPDs. Cookies/biscuits, salty snacks, and chocolate bars/candy bars contributed the most to daily energy intake from UPFs (Table 2). Chocolate milk, liquors, sweetened soft drinks, and specifically cola, contributed most to daily energy intake from UPDs.

Participants in the highest quartile of UPFD consumption (Q4) consumed approximately 3 times as much UPFD per day (297 g/1000 kcal) compared to participants in the lowest quartile (Q1) (97 g/1000 kcal) (Table 1). Participants with a higher UPFD consumption were more likely to be male, younger, current smokers with higher BMIs and a lower educational level than those with a lower UPFD consumption. Population characteristics according to quartiles of UPFs and UPDs can be found in Table 3 and 4.

Higher UPFD consumption (Q4vsQ1) was significantly associated with slightly higher eutrophication of fresh water (2.6%; 95% CI: 2.1, 3.0%) and GHG emissions (1.9%; 95% CI: 1.3, 2.4%) compared to low UPFD consumption. On the contrary, blue water consumption (−4.0%; 95% CI: −4.9, −3.0%), eutrophication of marine water (−1.5%; 95% CI: −2.2, −0.8), land use (−0.9%; 95% CI: −1.4, −0.5%), and terrestrial acidification (−0.9%; 95%CI: −1.6, −0.1%) were lower for those with higher UPFD consumption compared with those with lower UPFD consumption (Q4vsQ1) (Table 5). Except for GHG emissions, the estimates for the second and third quartiles compared with the lowest quartile were generally in the same direction as estimates for the highest quartile, but with a lower magnitude.

More pronounced differences in environmental impact were observed between the highest and lowest quartiles of UPF and UPD consumption when analyzed separately. Compared to low UPF consumption, higher UPF consumption (Q4vsQ1) was statistically significantly inversely associated with blue water (−13.6%; 95% CI: −14.4, −12.7%), GHG emissions (−7.7%; 95% CI: −8.2, −7.2%), acidification (−7.2%; 95% CI: −7.9, −6.4%), marine water eutrophication (−5.4%; 95% CI: −6.1, −4.7%), freshwater eutrophication (−5.3%; 95% CI: −5.8, −4.9%), and land use (−3.0%; 95% CI: −3.5, −2.6%). Contrarily, higher UPD consumption (Q4vsQ1) was statistically significantly associated with higher GHG emissions (5.9%; 95% CI: 5.4, 6.5%), fresh water eutrophication (5.0%; 95% CI: 4.5, 5.5%), blue water (3.2%; 95% CI: 2.2, 4.1%), acidification (2.9%; 95% CI: 2.1, 3.7%), marine water eutrophication (1.2%; 95% CI: 0.5, 2.0%), and similar land use (0.4%; 95% CI: −0.1, 0.9%) when compared with low UPD consumption.

For both UPF and UPD, estimates for the second and third quartile compared with the lowest quartile were in the same direction as estimates for the highest quartile, but with a lower magnitude.

After a mean follow-up of 18.2 y (SD = 4.1), 4,697 deaths occurred. Higher UPFD consumption was significantly positively associated with all-cause mortality risk (HRQ4vsQ1: 1.18, 95% CI: 1.09, 1.28) in model 1 (Table 6) compared to lower UPFD consumption. In the fully adjusted model 3, including adjustments for educational level, smoking status, physical activity, BMI, and total energy intake, the HR was essentially similar (HRQ4vsQ1: 1.17, 95% CI: 1.08, 1.28). Compared to the lowest UPFD quartile, no associations between UPFD consumption and all-cause mortality were observed for the second and third UPFD quartiles.

The association between UPF and UPD consumption with all-cause mortality was separately assessed. Compared with a lower UPF consumption, higher UPF consumption across all quartiles was significantly associated with a lower mortality risk (HRQ2vsQ1: 0.83, 95% CI: 0.76, 0.89; HRQ3vsQ1: 0.78, 95%CI: 0.72, 0.84; and HRQ4vsQ1: 0.87, 95% CI 0.80, 0.94) in model 1 (Table 6). In the fully adjusted model, UPF consumption was associated with a borderline significant lower risk of all-cause mortality (HRQ2vsQ1: 0.93, 95% CI: 0.85, 1.00; HRQ3vsQ1: 0.91, 95% CI: 0.84, 0.99). Additionally, the association reversed for the highest UPF quartile (HRQ4vsQ1: 1.06, 95% CI: 0.97, 1.15). In the fully adjusted model, higher UPD consumption was significantly associated with a higher risk of all-cause mortality (HRQ4vsQ1: 1.16, 95% CI: 1.07, 1.26) compared with lower UPD consumption. No associations between UPD consumption with all-cause mortality in the second and third quartile, compared with the lowest quartile, were observed.

Discussion

In this prospective study among 38,261 Dutch adults aged 20 to 70 y, the joint and separate association of UPFD consumption with diet-related GHG emissions, blue water, land use, acidification, fresh- and marine water eutrophication, and all-cause mortality was investigated.

One of the primary aims of this study was to investigate the joint and separate effect of UPFs and UPDs on the environment. The limited number of previous studies showed heterogeneous results for UPF and UPD separately [5], and no or inverse associations for UPFD, after energy adjustments [16, 17]. The differences in environmental impact indicators for diets low versus high in UPFs or UPDs in this study were statistically significant (except for the null association between UPD and land use) but relatively small. Our results showed that, compared with lower consumption, higher UPF consumption was associated with lower diet-related environmental impacts (Q4vsQ1: −13.6% to −3.0%), whereas higher UPD consumption was associated with higher diet-related environmental impacts (Q4vsQ1: 1.2% to 5.9%), except for land use. Subsequently, the net diet effect on the environment of higher UPFD consumption compared to lower intakes was more neutral. The amounts consumed according to degree of processing and their associated environmental impact varied across the quartiles. Participants with diets high in UPF consumed less from unprocessed and minimally processed foods and vice versa. Therefore, the amount of unprocessed and minimally processed foods consumed is likely to be a more significant factor in determining the dietary environmental impacts and might determine the total daily dietary environmental impacts to a larger extent than UPFD, as has been shown elsewhere [5, 12, 14]. For UPD, our outcome is mainly attributable to a higher consumption of UPD itself; the consumption of other foods and drinks was approximately similar across the quartiles.

Previous studies showed increased all-cause mortality risks for high versus low UPFD consumption and reported HRs between 1.14 and 1.62 [6, 7, 19-22] and did not focus on the separate effects of UPFs and UPDs. The different settings and applied methods, such as exposure expressed in frequency, grams, or En%, indicate a robust association. Our findings suggest that the obtained association between UPFD consumption and all-cause mortality might be predominantly driven by UPD consumption. In accordance with previous studies, we observed a positive association between UPDs, such as sugar- and artificially sweetened beverages, and all-cause mortality. A meta-analysis demonstrated that a high consumption of sugar- and artificially sweetened beverages are associated with a higher risk of all-cause mortality, with HRs of 1.12 (95% CI: 1.06, 1.19) and 1.12 (95% CI: 1.04, 1.21), respectively [33]. The absence of a significant association between UPF consumption and all-cause mortality observed in our study may be attributed to the comparatively less pronounced contrast between high and low UPF consumption as opposed to the contrast in UPD consumption. This might be explained by the relatively advanced age of the cohort and of the population within this cohort.

To facilitate the transition toward a healthier and more environmentally sustainable diet, recommended foods and beverages are ideally both the healthy and sustainable choice. Our findings underpin the adverse health effects of UPFD, and especially UPD, consumption. From a public and planetary health perspective, a lower consumption of UPDs results in win-wins. However, this is not directly applicable to UPFs, based on our study. Diets with higher shares of UPFs had lower environmental impacts; therefore, even the opposite might occur: by replacing UPFs with less processed alternatives with higher environmental pressure, the burden on the environment might increase while consumption is generally healthier. This is, for instance, the case when processed meat is replaced by unprocessed meat [29]. Further research is needed to quantify the impact on the environment of UPF and UPD consumption and to obtain a deeper understanding of their relationship.

Strengths and limitations

To our knowledge, this is the first study that examined the associations between UPFD, UPF and UPD consumption, environmental impacts, and all-cause mortality. Strengths of our study were its prospective design, relatively large sample size, and long follow-up time, which broadens the generalization of our results. Moreover, the inclusion of 6 environmental impact indicators enabled us to study the environmental effects of UPFD consumption on more than climate change only. Previous studies mainly focused on GHG emission and water use; however, as processing steps add up to, for instance, acidification, it is important to include other indicators, besides GHG emission and water use, for a comprehensive assessment.

This study also has limitations. Dietary data was collected using a FFQ that was not designed to collect data on the degree of food processing. For instance, misclassification could occur because, according to the FFQ, it was not clear if tomato sauce was homemade (unprocessed or minimally processed food) or ready-to-eat (processed food). This complicates the classification of foods according to the degree of processing. In order to account for the variation in the level of strictness and the potential transition of food processing over time we applied a middle-bound scenario, which was developed previously by Cordova et al. [28] for the international EPIC study and most likely reflects the scenario in the nineties. Although the NOVA classification is most used to classify foods according to their degree of processing, insufficient standardization of the application of the methodology makes food classification with NOVA difficult [34] and can lead to confusion and subjective coding of foods and drinks [35]. The classification was cross-checked through the process of triangulation to minimize misclassification. Dietary data was collected between 1993 and 1997 and may not reflect current dietary patterns in the Netherlands. We used a single measurement of dietary intake data. In a comparison study with a second FFQ measurement of the EPIC-NL cohort in 2015, it was concluded that the consumption by food groups has not changed significantly [36]. A previous study has examined the consumption of UPFDs using the second FFQ from 2015 with slightly different application of the NOVA classification method and measured 37% energy intake derived from UPFD [37]. A Dutch food consumption survey (2012–2016), based on a repeated 24-h recall, estimated a share of UPFDs of 62% of energy intake [5]. The influence of differences in dietary assessment method, application of food processing application methods such as NOVA, and time period might have influenced the results and cannot be disentangled. Finally, it is important to note that although our dietary data is from the nineties, our environmental impact data is from 2019. Technological improvements in production over time may mean we are underestimating the absolute environmental impact of the diet in the nineties.

To conclude, reducing UPD consumption could lower environmental impact and all-cause mortality risk; however, this was not shown for UPFs. When categorizing food consumption by their degree of processing, trade-offs are observed for human and planetary health aspects.

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Tables and figures

Table 1. Characteristics of the total population and according to quartiles of ultra-processed food and beverage consumption.

UPFD (g/1000 kcal)	Total		Q1(low) [<124]		Q2 [124-162]		Q3 [162-217]		Q4 (high) [>217]	
n	**38261**		**9565**		**9565**		**9566**		**9565**	
Age at enrolment (y)	50	(12)	53	(10)	51	(11)	49	(12)	46	(13)
BMI (kg/m^2)	25.7	(4.1)	25.5	(4.0)	25.5	(3.9)	25.7	(3.9)	26.2	(4.3)
Sex										
Male	24	%	21	%	22	%	24	%	27	%
Female	76	%	79	%	78	%	76	%	73	%
BMI (kg/m^2)										
<18.5	1	%	1	%	1	%	1	%	1	%
18.5-24.9	48	%	49	%	49	%	48	%	43	%
25-29.9	38	%	37	%	38	%	39	%	39	%
>30	13	%	12	%	12	%	12	%	16	%
Educational level										
Low	17	%	21	%	16	%	14	%	15	%
Moderate	63	%	56	%	61	%	65	%	70	%
High	20	%	23	%	23	%	21	%	16	%
Level of physical activity										
Inactive	8	%	9	%	7	%	7	%	9	%
Moderately inactive	25	%	26	%	25	%	25	%	25	%
Moderately active	26	%	25	%	27	%	27	%	25	%
Active	41	%	40	%	41	%	41	%	41	%
Smoking status										
Never	38	%	38	%	40	%	39	%	37	%
Former	32	%	32	%	33	%	32	%	29	%
Current	30	%	30	%	27	%	29	%	34	%
Food and energy intake										
Quantity (g/1000kcal)	1547	(436)	1592	(447)	1510	(395)	1493	(397)	1593	(490)
Total energy intake (kcal)	1991	(535)	1898	(525)	2006	(510)	2044	(525)	2018	(567)
Unprocessed and minimally processed foods (g/1000kcal)	1215	(451)	1314	(477)	1216	(414)	1166	(410)	1166	(481)
Energy intake from unprocessed and minimally processed foods (En%)	35	(9)	37	(10)	35	(8)	34	(8)	33	(9)
Processed culinary ingredients (g/1000kcal)	11	(10)	13	(11)	11	(9)	11	(9)	10	(9)

Energy intake from processed culinary ingredients (En%)	6	(5)	7	(5)	6	(4)	6	(4)	6	(4)
Processed foods (g/1000kcal)	139	(95)	169	(121)	140	(88)	129	(80)	120	(77)
Energy intake from processed foods (En%)	27	(9)	31	(10)	28	(8)	26	(8)	24	(8)
UPFD (g/1000kcal)	181	(88)	97	(20)	143	(11)	187	(15)	297	(92)
Energy intake from UPFD (En%)	32	(9)	25	(7)	31	(7)	34	(7)	37	(8)
UPF (g/1000kcal)	91	(29)	72	(21)	93	(24)	99	(28)	100	(33)
UPD (g/1000kcal)	90	(86)	25	(18)	50	(25)	88	(32)	198	(100)
Energy intake from UPF (En%)	28	(8)	23	(7)	28	(7)	30	(8)	30	(9)
Energy intake from UPD (En%)	4	(4)	2	(2)	3	(2)	4	(3)	7	(5)
Carbohydrates (En%)	45	(6)	44	(7)	45	(6)	45	(6)	47	(6)
Total fat (En%)	36	(5)	36	(6)	36	(5)	36	(5)	35	(5)
Protein (En%)	16	(2)	16	(3)	16	(2)	15	(2)	15	(2)
Alcohol (En%)	2	(0,5)	2	(0,6)	2	(0,5)	2	(0,5)	2	(0,5)
Fibre (g/1000kcal)	12	(3)	13	(3)	12	(3)	12	(3)	11	(3)
Sodium (mg/1000 kcal)	1174	(235)	1184	(250)	1179	(225)	1174	(224)	1159	(238)
Potatoes (g/1000kcal)	45	(29,67)	47	(28,71)	45	(29,66)	45	(30,65)	45	(29,65)
Cereals (g/1000kcal)	89	(71,110)	93	(74,117)	91	(73,110)	88	(71,108)	83	(66,104)
Vegetables and legumes (g/1000kcal)	67	(49,91)	76	(55,102)	68	(51,90)	64	(48,85)	63	(45,86)
Fruit, nuts and seeds (g/1000kcal)	91	(52,149)	108	(59,175)	97	(56,154)	86	(52,138)	76	(42,130)
Dairy and cheese (g/1000kcal)	200	(117,296)	203	(112,309)	208	(130,299)	202	(124,290)	184	(103,285)
Meat (g/1000kcal)	50	(33,65)	49	(31,66)	49	(33,65)	50	(34,65)	51	(35,67)
Fish (g/1000kcal)	4	(1,8)	4	(1,8)	4	(2,7)	4	(2,7)	4	(1,7)
Eggs (g/1000kcal)	7	(4,11)	7	(4,11)	7	(4,11)	7	(4,11)	7	(4,11)
Sugar and confectionery (g/1000kcal)	14	(7,23)	13	(6,22)	15	(8,24)	15	(8,24)	14	(7,24)
Cake and biscuits (g/1000kcal)	12	(6,21)	11	(5,19)	14	(8,23)	14	(7,22)	11	(5,19)
Fats and oils (g/1000kcal)	13	(9,17)	13	(9,18)	13	(9,18)	13	(9,17)	12	(8,17)
Savory sauces, snacks and bread toppings (g/1000kcal)	12	(7,18)	10	(5,16)	11	(6,17)	13	(7,19)	14	(8,21)

Composite dishes and soups (g/1000kcal)	30	(16,53)	27	(14,53)	30	(16,53)	31	(17,54)	31	(17,53)
Miscellaneous (g/1000kcal)	0	(0,0)	0	(0,0)	0	(0,0)	0	(0,0)	0	(0,0)
Non-alcoholic beverages(g/1000kcal)	693	(521,932)	701	(518,946)	667	(509,880)	667	(508,884)	753	(559,1019)
Alcoholic beverages (g/1000kcal)	28	(4,90)	25	(2,101)	29	(5,82)	31	(5,86)	28	(4,92)

Abbreviations: UPFD, Ultra-processed foods and drinks; BMI, Body Mass Index; En%, energy percentage; UPF, ultra-processed foods: UPD, ultra-processed foods.
Numbers are mean (SD), median (25th percentile, 75th percentile) or percentage (%).

Table 2. Top 5 foods and beverages according to the degree of food processing that contribute the most to daily energy intake.

Foods

	Unprocessed or minimally procecessed	**Processed culinary ingredients**	**Processed**	**Ultra-processed**
1	Potatoes	Sugar	Bread, wholegrain,	Cookies, biscuits
2	Soups	Butter, unsalted	Bread, brown/ wheat	Salty snacks
3	Pasta’s without filling	Oil, soy	Cheese, creamcheese,	Chocolatebars, candybars
4	Apple, pear	Oil, sunflower	Bread, white	Sweet bread toppings
5	Pork meat	Whipping cream	Nuts, groundnuts	Cakes, large cookies

Drinks

	Unprocessed or minimally procecessed	**Processed culinary ingredients**	**Processed**	**Ultra-processed**
1	Milk, semi-skimmed		Beer	Milk, chocolate
2	Buttermilk		Wine, red, rosé	Liquor
3	Orange, grapefruit juice		Wine, white	Sugar sweetened softdrinks
4	Yoghurt drink			Cola
5	Milk, full-fat			Port, sherry, etc.

Table 3. Characteristics of the total population and according to quartiles of ultra-processed food consumption.

UPF (g/1000kcal)	Q1(low) [<72]		Q2 [72-90]		Q3 [90-109]		Q4 (high) [>109]	
n	9565		9565		9566		9565	
Age at enrolment (y)	51	(11)	50	(12)	49	(12)	48	(12)
BMI (kg/m^2)	25.9	(4.2)	25.7	(34.1)	25.6	(3.9)	25.7	(4.1)
Sex								
Male	24	%	24	%	23	%	23	%
Female	76	%	76	%	77	%	77	%
BMI (kg/m^2)								
<18.5	1	%	1	%	1	%	1	%
18.5-24.9	47	%	47	%	48	%	48	%
25-29.9	38	%	39	%	39	%	38	%
>30	15	%	13	%	12	%	13	%
Educational level								
Low	19	%	16	%	15	%	16	%
Moderate	59	%	63	%	64	%	67	%
High	22	%	21	%	21	%	17	%
Level of physical activity								
Inactive	11	%	7	%	7	%	7	%
Moderately inactive	26	%	25	%	25	%	26	%
Moderately active	25	%	25	%	27	%	27	%
Active	39	%	43	%	41	%	41	%
Smoking status								
Never	31	%	37	%	41	%	45	%
Former	31	%	32	%	32	%	31	%
Current	38	%	31	%	27	%	25	%
Food and energy intake								
Quantity (g/1000kcal)	1683	(485)	1564	(418)	1500	(405)	1441	(394)
Total energy intake (kcal)	1862	(530)	2000	(530)	2047	(524)	2057	(535)
Unprocessed and minimally processed foods (g/1000kcal)	1340	(502)	1236	(434)	1177	(421)	1109	(408)
Energy intake from unprocessed and minimally processed foods (En%)	38	(10)	36	(8)	34	(8)	31	(7)
Processed culinary ingredients (g/1000kcal)	13	(12)	12	(9)	11	(8)	10	(8)
Energy intake from processed culinary ingredients (En%)	8	(5)	6	(4)	6	(4)	5	(4)
Processed foods (g/1000kcal)	174	(129)	145	(88)	128	(73)	110	(63)

Energy intake from processed foods (En%)	31	(10)	28	(8)	26	(7)	23	(7)
UPFD (g/1000kcal)	156	(98)	172	(88)	185	(77)	212	(79)
Energy intake from UPFD (En%)	23	(7)	30	(5)	34	(5)	40	(7)
UPF (g/1000kcal)	56	(13)	81	(5)	99	(5)	128	(19)
UPD (g/1000kcal)	100	(98)	91	(88)	86	(76)	83	(78)
Energy intake from UPF (En%)	18	(5)	26	(4)	30	(4)	37	(6)
Energy intake from UPD (En%)	5	(5)	4	(4)	4	(3)	3	(3)
Carbohydrates (En%)	44	(7)	45	(6)	46	(6)	47	(6)
Total fat (En%)	34	(6)	36	(5)	36	(5)	36	(5)
Protein (En%)	16	(3)	16	(2)	15	(2)	15	(2)
Alcohol (En%)	4	(0,9)	2	(0,6)	3	(0,4)	2	(0,3)
Fibre (g/1000kcal)	12	(3)	12	(3)	12	(3)	12	(3)
Sodium (mg/1000 kcal)	1137	(256)	1171	(222)	1181	(217)	1207	(237)
Potatoes (g/1000kcal)	43	(26,68)	46	(30,68)	46	(31,67)	45	(30,65)
Cereals (g/1000kcal)	88	(68,112)	89	(72,110)	89	(72,108)	89	(71,109)
Vegetables and legumes (g/1000kcal)	76	(54,104)	69	(51,92)	65	(48,87)	61	(45,82)
Fruit, nuts and seeds (g/1000kcal)	99	(52,169)	95	(54,157)	90	(53,143)	81	(48,131)
Dairy and cheese (g/1000kcal)	207	(111,328)	209	(121,307)	206	(126,292)	181	(108,262)
Meat (g/1000kcal)	50	(31,67)	50	(34,65)	50	(34,64)	49	(33,66)
Fish (g/1000kcal)	4	(2,8)	4	(2,8)	4	(1,7)	3	(1,7)
Eggs (g/1000kcal)	7	(4,12)	7	(4,11)	7	(4,10)	6	(4,10)
Sugar and confectionery (g/1000kcal)	10	(4,19)	13	(7,22)	16	(9,24)	18	(11,27)
Cake and biscuits (g/1000kcal)	7	(3,12)	12	(6,19)	15	(9,23)	18	(11,28)
Fats and oils (g/1000kcal)	12	(8,16)	13	(9,17)	13	(9,18)	14	(9,18)
Savory sauces, snacks and bread toppings (g/1000kcal)	10	(5,16)	12	(7,18)	13	(7,19)	13	(8,20)
Composite dishes and soups (g/1000kcal)	26	(13,53)	29	(16,52)	31	(17,52)	33	(18,56)
Miscellaneous (g/1000kcal)	0	(0,0)	0	(0,0)	0	(0,0)	0	(0,0)
Non-alcoholic beverages(g/1000kcal)	756	(559,1026)	704	(531,936)	669	(510,895)	656	(497,870)
Alcoholic beverages (g/1000kcal)	54	(6,142)	35	(6,97)	24	(4,72)	15	(2,52)

Abbreviations: UPFD, Ultra-processed foods and drinks; BMI, Body Mass Index; En%, energy percentage; UPF, ultra-processed foods: UPD, ultra-processed foods.
Numbers are mean (SD), median (25th percentile, 75th percentile) or percentage (%).

Table 4. Characteristics of the total population and according to quartiles of ultra-processed drink consumption

	Q1(low)		**Q2**		**Q3**		**Q4 (high)**	
UPD (g/1000kcal)	**[<32]**		**[32-67]**		**[67-121]**		**[>121]**	
n	9565		9565		9566		9565	
Age at enrolment (y)	53	(10)	50	(11)	49	(12)	46	(13)
BMI (kg/m^2)	25.5	(4.0)	25.5	(3.9)	25.6	(3.9)	26.2	(4.3)
Sex								
Male	19	%	24	%	25	%	27	%
Female	81	%	76	%	75	%	73	%
BMI (kg/m^2)								
<18.5	1	%	1	%	1	%	1	%
18.5-24.9	49	%	49	%	49	%	43	%
25-29.9	38	%	37	%	38	%	40	%
>30	12	%	12	%	12	%	17	%
Educational level								
Low	21	%	15	%	15	%	15	%
Moderate	58	%	61	%	64	%	68	%
High	21	%	24	%	21	%	16	%
Level of physical activity								
Inactive	8	%	7	%	7	%	9	%
Moderately inactive	27	%	24	%	25	%	25	%
Moderately active	26	%	26	%	27	%	25	%
Active	39	%	43	%	41	%	41	%
Smoking status								
Never	41	%	40	%	38	%	35	%
Former	32	%	33	%	32	%	29	%
Current	27	%	27	%	31	%	36	%
Food and energy intake								
Quantity (g/1000kcal)	1552	(442)	1494	(390)	1508	(391)	1635	(499)
Total energy intake (kcal)	1912	(516)	2032	(526)	2035	(526)	1987	(563)
Unprocessed and minimally processed foods (g/1000kcal)	1282	(468)	1198	(413)	1177	(410)	1206	(498)
Energy intake from unprocessed and minimally processed foods (En%)	35	(9)	35	(9)	34	(8)	34	(9)
Processed culinary ingredients (g/1000kcal)	12	(10)	11	(10)	11	(9)	11	(9)
Energy intake from processed culinary ingredients (En%)	7	(5)	6	(5)	6	(4)	6	(4)
Processed foods (g/1000kcal)	149	(108)	144	(94)	137	(89)	127	(86)

Energy intake from processed foods (En%)	29	(10)	28	(9)	27	(8)	25	(8)
UPFD (g/1000kcal)	109	(32)	142	(30)	183	(32)	292	(96)
Energy intake from UPFD (En%)	29	(9)	31	(8)	32	(8)	34	(9)
UPF (g/1000kcal)	92	(30)	93	(28)	91	(29)	88	(29)
UPD (g/1000kcal)	17	(9)	49	(10)	91	(15)	204	(94)
Energy intake from UPF (En%)	28	(9)	28	(8)	28	(8)	27	(8)
Energy intake from UPD (En%)	1	(1)	3	(2)	4	(3)	8	(5)
Carbohydrates (En%)	45	(6)	45	(6)	45	(6)	46	(7)
Total fat (En%)	36	(6)	36	(5)	36	(5)	34	(5)
Protein (En%)	16	(2)	16	(2)	15	(2)	15	(2)
Alcohol (En%)	1	(0,4)	2	(0,5)	2	(0,6)	2	(0,6)
Fibre (g/1000kcal)	13	(3)	12	(3)	12	(3)	11	(3)
Sodium (mg/1000 kcal)	1202	(248	1182	(225	1168	(226	1143	(235
Potatoes (g/1000kcal)	48	(30,71)	44	(29,66)	45	(29,65)	45	(29,66)
Cereals (g/1000kcal)	93	(75,115)	91	(74,111)	88	(71,109)	83	(65,103)
Vegetables and legumes (g/1000kcal)	73	(54,98)	67	(49,88)	65	(48,88)	65	(46,88)
Fruit, nuts and seeds (g/1000kcal)	105	(59,168)	93	(54,150)	87	(52,141)	79	(43,135)
Dairy and cheese (g/1000kcal)	196	(111,291)	205	(126,297)	204	(123,300)	192	(107,296)
Meat (g/1000kcal)	49	(31,66)	49	(33,64)	50	(34,64)	51	(35,67)
Fish (g/1000kcal)	4	(1,8)	4	(2,7)	4	(2,7)	4	(1,8)
Eggs (g/1000kcal)	7	(4,11)	7	(4,11)	7	(4,11)	7	(4,11)
Sugar and confectionery (g/1000kcal)	15	(8,24)	15	(8,24)	15	(8,24)	13	(6,22)
Cake and biscuits (g/1000kcal)	15	(7,24)	14	(7,22)	12	(6,20)	10	(5,17)
Fats and oils (g/1000kcal)	14	(9,18)	13	(9,18)	13	(9,17)	12	(8,16)
Savory sauces, snacks and bread toppings (g/1000kcal)	10	(5,16)	12	(7,18)	13	(7,19)	13	(8,20)
Composite dishes and soups (g/1000kcal)	28	(14,53)	30	(16,54)	31	(17,54)	30	(16,52)
Miscellaneous (g/1000kcal)	0	(0,0)	0	(0,0)	0	(0,0)	0	(0,0)
Non-alcoholic beverages(g/1000kcal)	686	(511,928)	656	(497,865)	672	(514,885)	772	(573,1048)
Alcoholic beverages (g/1000kcal)	15	(1,69)	32	(6,83)	34	(6,94)	34	(4,108)

Abbreviations: UPFD, Ultra-processed foods and drinks; BMI, Body Mass Index; En%, energy percentage; UPF, ultra-processed foods: UPD, ultra-processed foods.
Numbers are mean (SD), median (25th percentile, 75th percentile) or percentage (%).

Table 5. Adjusted mean difference (absolute and in %) in environmental impact standardized to 1000 kcal for quartiles of ultra-processed food and drink, ultra-processed food and ultra-processed drink consumption.

UPFD(g/1000 kcal)	**Q1(low) [<124]**	**Q2 [124-162]**			**Q3 [162-217]**			**Q4 (high) [>217]**		
	Mean	Mean^a	95%CI		Mean^a	95%CI		Mean^a	95%CI	
GHG emission (kg CO_2-eq)	2,856	-0,027	(-0,042,	-0,013)	-0,009	(-0,024,	0,005)	0,053	(0,038,	0,068)
%		-1,0%	(-1,5%,	-0,4%)	-0,3%	(-0,8%,	0,2%)	1,9%	(1,3%,	2,4%)
Blue water consumption (m^3)	0,083	-0,002	(-0,003,	-0,002)	-0,003	(-0,004,	-0,002)	-0,003	(-0,004,	-0,003)
%		-2,8%	(-3,7%,	-1,9%)	-3,5%	(-4,4%,	-2,6%)	-4,0%	(-4,9%,	-3,0%)
Land use (m^2/y)	1,625	-0,015	(-0,022,	-0,007)	-0,015	(-0,023,	-0,007)	-0,015	(-0,023,	-0,007)
%		-0,9%	(-1,4%,	-0,4%)	-0,9%	(-1,4%,	-0,4%)	-0,9%	(-1,4%,	-0,5%)
Terrestrial acidification (kg SO_2-eq)	0,030	0,000	(-0,001,	0,000)	0,000	(-0,001,	0,000)	0,000	(0,000,	0,000)
%		-1,3%	(-2,1%,	-0,6%)	-1,2%	(-1,9%,	-0,4%)	-0,9%	(-1,6%,	-0,1%)
Fresh water eutrophication (kg P-eq*10000)	1,968	-0,007	(-0,016,	0,002)	0,009	(0,001,	0,018)	0,051	(0,042,	0,060)
%		-0,4%	(-0,8%,	0,1%)	0,5%	(0,0%,	0,9%)	2,6%	(2,1%,	3,0%)
Marine water eutrophication (kg N-eq*10000)	49,973	-0,645	(-0,999,	-0,291)	-0,709	(-1,065,	-0,353)	-0,757	(-1,118,	-0,396)
%		-1,3%	(-2,0%,	-0,6%)	-1,4%	(-2,1%,	-0,7%)	-1,5%	(-2,2%,	-0,8%)
UPF(g/1000 kcal)	Q1(low) [<72]	Q2 [72-90]			Q3 [90-109]			Q4 (high) [>109]		
	Mean	Mean^a	95%CI		Mean^a	95%CI		Mean^a	95%CI	
GHG emission (kg CO_2-eq)	2,981	-0,097	(-0,111,	-0,082)	-0,157	(-0,172,	-0,143)	-0,229	-(0,244,	-0,215)
%		-3,2%	(-3,7%,	-2,8%)	-5,3%	(-5,8%,	-4,8%)	-7,7%	(-8,2%,	-7,2%)
Blue water consumption (m^3)	0,087	-0,005	(-0,006,	-0,004)	-0,008	(-0,009,	-0,007)	-0,012	(-0,013,	-0,011)
%		-5,8%	(-6,7%,	-5,0%)	-9,3%	(-10,1%,	-8,4%)	-13,6%	(-14,4%,	-12,7%)
Land use (m^2/y)	1,641	-0,022	(-0,029,	-0,014)	-0,036	(-0,044,	-0,028)	-0,050	(-0,058,	-0,042)
%		-1,3%	(-1,8%,	-0,8%)	-2,2%	(-2,7%,	-1,7%)	-3,0%	(-3,5%,	-2,6%)

Terrestrial acidification (kg SO_2-eq)	0,031	-0,001	(-0,001,	-0,001)	-0,001	(-0,002,	-0,001)	-0,002	(-0,002,	-0,002)
%		-2,8%	(-3,5%,	-2,1%)	-4,6%	(-5,3%,	-3,9%)	-7,2%	(-7,9%,	-6,4%)
Fresh water eutrophication (kg P-eq*10000)	2,044	-0,058	(-0,066,	-0,049)	-0,085	(-0,093,	-0,076)	-0,109	(-0,118,	-0,100)
%		-2,8%	(-3,2%,	-2,4%)	-4,1%	(-4,6%,	-3,7%)	-5,3%	(-5,8%,	-4,9%)
Marine water eutrophication (kg N-eq*10000)	50,826	-1,023	(-1,377,	-0,670)	-1,737	(-2,093,	-1,382)	-2,765	(-3,121,	-2,408)
%		-2,0%	(-2,7%,	-1,3%)	-3,4%	(-4,1%,	-2,7%)	-5,4%	(-6,1%,	-4,7%)
UPD(g/1000 kcal)	Q1(low) [<32]	Q2 [32-67]			Q3 [67-121]			Q4 (high) [>121]		
	Mean	Mean[a]	95%CI		Mean[a]	95%CI		Mean[a]	95%CI	
GHG emission (kg CO_2-eq)	2,7850	0,0486	(0,0341,	0,0631)	0,0877	(0,0731,	0,1022)	0,1654	(0,1507,	0,1801)
%		1,7%	(1,2%,	2,3%)	3,1%	(2,6%,	3,7%)	5,9%	(5,4%,	6,5%)
Blue water consumption (m^3)	0,0794	0,0020	(0,0013,	0,0028)	0,0020	(0,0013,	0,0028)	0,0025	(0,0018,	0,0033)
%		2,6%	(1,6%,	3,5%)	2,6%	(1,6%,	3,5%)	3,2%	(2,2%,	4,1%)
Land use (m^2/y)	1,6112	0,0016	(-0,0061,	0,0093)	0,0030	(-0,0048,	0,0107)	0,0067	(-0,0012,	0,0145)
%		0,1%	(-0,4%,	0,6%)	0,2%	(-0,3%,	0,7%)	0,4%	(-0,1%,	0,9%)
Terrestrial acidification (kg SO_2-eq)	0,0294	0,0003	(0,0001,	0,0005)	0,0005	(0,0003,	0,0007)	0,0009	(0,0006,	0,0011)
%		1,0%	(0,2%,	1,7%)	1,7%	(1,0%,	2,5%)	2,9%	(2,1%,	3,7%)
Fresh water eutrophication (kg P-eq*10000)	1,941	0,018	(0,010,	0,027)	0,045	(0,036,	0,054)	0,097	(0,088,	0,106)
%		0,9%	(0,5%,	1,4%)	2,3%	(1,9%,	2,8%)	5,0%	(4,5%,	5,5%)
Marine water eutrophication (kg N-eq*10000)	49,173	0,131	(-0,224,	0,485)	0,343	(-0,013,	0,699)	0,613	(0,252,	0,973)
%		0,3%	(-0,5%,	1,0%)	0,7%	(0,0%,	1,4%)	1,2%	(0,5%,	2,0%)

[a] Represents the mean difference with the first quartile used as the reference category.

UPFD, ultra-processed foods and drinks; UPF, ultra-processed foods; UPD, ultra-processed drinks; GHG, greenhouse gas.

Estimates are adjusted for age, sex and total energy intake.

Table 6. Hazard ratio’s for ultra-processed food and drink, ultra-processed food and ultra-processed drink consumption and all-cause mortality.

	Quartiles according to UPFD consumption in g/1000 kcal			
	Q1(low) [<124]	**Q2 [124-162]**	**Q3 [162-217]**	**Q4 (high) [>217]**
N/ Events	9565/1387	9565/1160	9566/1058	9565/1092
Model 1	Ref	0.91(0.84, 0.99)	0.93(0.86, 1.01)	1.18(1.09, 1.28)
Model 2	Ref	0.95(0.87, 1.02)	0.96(0.88, 1.04)	1.15(1.06, 1.24)
Model 3	Ref	0.97(0.89, 1.05)	0.99(0.91, 1.07)	1.17(1.08, 1.28)
	Quartiles according to UPF consumption in g/1000 kcal			
	Q1(low) [<72]	**Q2 [72-90]**	**Q3 [90-109]**	**Q4 (high) [>109]**
N/ Events	9565/1388	9565/1152	9566/1042	9565/1115
Model 1	Ref	0.83(0.76, 0.89)	0.78(0.72, 0.84)	0.87(0.80, 0.94)
Model 2	Ref	0.89(0.82, 0.97)	0.86(0.79, 0.94)	0.98(0.90, 1.06)
Model 3	Ref	0.93(0.85, 1.00)	0.91(0.84, 0.99)	1.06(0.97, 1.15)
	Quartiles according to UPD consumption in g/1000 kcal			
	Q1(low) [<32]	**Q2 [32-67]**	**Q3 [67-121]**	**Q4 (high) [>121]**
N/ Events	9565/1396	9565/1102	9566/1064	9565/1135
Model 1	Ref	0.94(0.87, 1.02)	0.99(0.91, 1.07)	1.24(1.14, 1.34)
Model 2	Ref	0.97(0.89, 1,05)	0.99(0.99, 1.07)	1.15(1.06, 1.25)
Model 3	Ref	0.98(0.90, 1.06)	1.00(0.92, 1.08)	1.16(1.07, 1.26)

UPFD, ultra-processed foods and drinks; UPF, ultra-processed foods; UPD, ultra-processed drinks.
Model 1 = age stratified and adjusted for sex
Model 2 = Model 1 and adjusted for educational level, smoking status, physical activity and total energy intake.
Model 3 = Model 2 and adjusted for Body Mass Index.

Supplementary files

Supplemental table 1. Classification of foods according to degree of processing (NOVA).

Supplementary figure 1. Flow-chart of participant in present study.

Table 1. Classification of foods according to degree of processing (NOVA).

Classification	
Unprocessed or minimally processed foods	
Coffee creamer, powder	Dairy
Whisk cottage cheese	Dairy
Yogurt, full fat	Dairy
Yogurt, semi skimmed/ full-fat organic	Dairy
Yogurt, skimmed	Dairy
Yogurt, skimmed, pack/bottle	Dairy
Egg chicken- boiled	Eggs
Fish fat >10 g fat raw	Fish
Fish, fat	Fish
Fish, lean	Fish
Fish, lean+fish,	Fish
Shellfish	Fish
Shrimps peeled	Fish
Apple sauce	Fruit
Apple without peel	Fruit
Apple, pear	Fruit
Banana	Fruit
Cherries	Fruit
Citrusfruit	Fruit
Grapes	Fruit
Kiwi	Fruit
Melon	Fruit
Peach	Fruit
Strawberries	Fruit
Brown rice, cookec	Grains
Grains (millet, buckwheat, groats, etc.)	Grains
Macaroni/spaghetti/bami etc.	Grains
Rice, baked	Grains
Rice, brown skin + rice fried	Grains
Rice, white	Grains
Legumes, excluding green beans/slices/green peas	Legumes
Beef, <5 g fat (lean)	Meat
Beef, 5-14 g fat (medium)	Meat
Beef, fat, raw	Meat
Chicken with skin	Meat
Chicken, skinless	Meat
Minced beef, raw	Meat

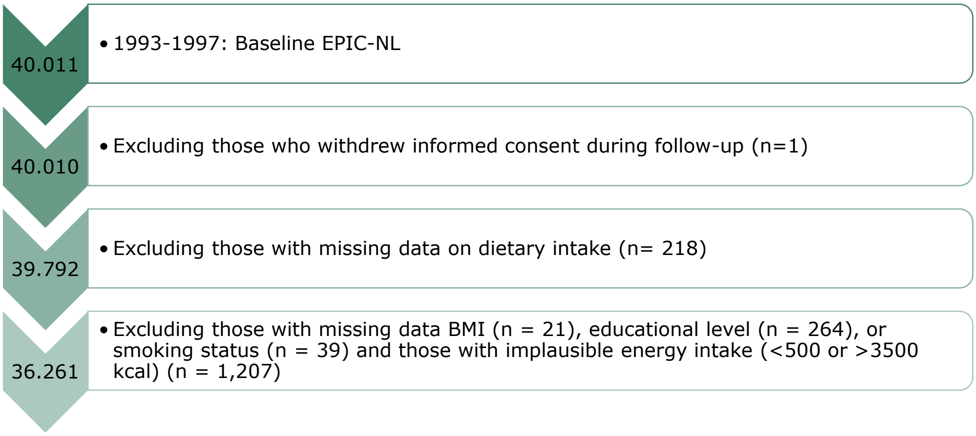
Minced meat, half and half	Meat
Minced pork, raw	Meat
Organ meats	Meat
Other meat, excluding beef/pork/chicken/organ	Meat
Pork, 15-24 g fat (medium)	Meat
Pork, fat	Meat
Pork, lean	Meat
Tea, herbal/caffeine-free	Non-alcoholic beverages
Nuts with a hot meal	Nuts
Potatoes, boiled	Potatoes
Potatoes, baked	Potatoes
Sauce macaroni/spaghetti	Sauce
Soup	Soup
Tempeh / bean curd	Soy product
Beans, green/string	Vegetables
Bell pepper, fried	Vegetables
Bell pepper, green + bell pepper, fried	Vegetables
Bell pepper, raw	Vegetables
Cabbage, cooked	Vegetables
Cabbage, raw	Vegetables
Carrots, cooked	Vegetables
Carrots, raw	Vegetables
Chicory, raw	Vegetables
Cucumber, raw	Vegetables
Endive	Vegetables
Garlic	Vegetables
Leek	Vegetables
Leek cooked with salt	Vegetables
Leek, cooked without salt	Vegetables
leek, onion, cooked	Vegetables
Lettuce	Vegetables
Mushrooms	Vegetables
Mushrooms, cooked without salt	Vegetables
Onion	Vegetables
Onion, cooked with salt	Vegetables
Onion, cooked without salt	Vegetables
Peas	Vegetables
Red beets, cooked without salt	Vegetables
Spinach	Vegetables
Tomato	Vegetables
Tomato, cooked without salt	Vegetables

Tomato, raw	Vegetables
Buttermilk	Dairy
Coffee creamer, diet	Dairy
Coffee creamer, full fat	Dairy
Coffee creamer, semi-skimmed	Dairy
Drink yogurt	Dairy
Milk in coffee, regular	Dairy
Milk, farmers	Dairy
Milk, full fat	Dairy
Milk, raw/farmer	Dairy
Milk, semi-skimmed	Dairy
Milk, skimmed	Dairy
Apple juice	Non-alcoholicbeverages
Coffee	Non-alcoholicbeverages
Coffee, decaf	Non-alcoholicbeverages
Mineral water	Non-alcoholicbeverages
Orange/grapefruit juice	Non-alcoholicbeverages
Tap water	Non-alcoholicbeverages
Tea	Non-alcoholicbeverages
Tea, herbal/decaf	Non-alcoholicbeverages
Vegetable juice	Non-alcoholicbeverages
Processed culinary ingredients	
Cream, whipped	Dairy
Cream, whipped, pack	Dairy
Beef fat, melted	Fats and oils
Butter, herbs	Fats and oils
Butter, unsalted	Fats and oils
Fat fryer- 0-40 g linoleic acid	Fats and oils
Fat frying liquid >40 g linoleic acid	Fats and oils
Frying fat, 0-50mg chol	Fats and oils
Frying fat, 50-300mg chol	Fats and oils
Frying fat, animal + vegetable	Fats and oils
Frying fat, Becel, 40-60 g lin, <50 mg chol	Fats and oils
Oil, corn germ	Fats and oils
Oil, olive	Fats and oils
Oil, palm	Fats and oils
Oil, peanut	Fats and oils
Oil, safflower	Fats and oils
Oil, soybean	Fats and oils
Oil, soybean	Fats and oils
Oil, sunflower	Fats and oils

Oil, corn	Fats and oils
Pork fat, rendered	Fats and oils
Sugar	Sugar
Sugar, granulated	Sugar
Processed foods and beverages	
Bread, brown/wheat	Bread
Bread, other	Bread
Bread, white	Bread
Bread, whole grain	Bread
Cheese on pizza	Cheese
Cheese with a hot meal	Cheese
Cheese, 20+ (spread) cheese	Cheese
Cheese, 40+/48+ cheese spread, 40+	Cheese
Cheese, linoleic acid (eg Trenta)	Cheese
Cheese, piece of	Cheese
Cream cheese, full-fat	Cheese
French cheese	Cheese
Sardines, can	Fish
Olives, can/glass	Fruit
Jam+rose hip+jam, syrup, honey	Confectionery
Syrup apple	Confectionery
Peanut butter, peanuts, etc.	Nuts and peanutbutter
Peanut butter	Nuts and peanutbutter
French fries	Potatoes
French fries, prepared	Potatoes
Onions, silver-sweet and sour glass	Vegetables
Pickles, sweet and sour glass	Vegetables
Puree tomato-concentrated can	Vegetables
Beer, alcoholic,	Alcoholic beverages
Wine, red, rose	Alcoholic beverages
Wine, white	Alcoholic beverages
Ultra-processed foods and beverages	
Bread, currants/raisin	Bread
Bread, luxury	Bread
Bread, luxury sandwiches/croissants	Bread
Bread, rye	Bread
Croissants	Bread
Dough, white bread, pizza	Bread
Rusk, crispbread etc	Bread
Rusk, crispbread, toast, etc.	Bread
Toast	Bread

Pizza	Composite dishes
Russian salad	Composite dishes
Spring roll	Composite dishes
Spring roll	Composite dishes
Candy, excluding chocolate/licorice	Confectionery
Chocolate bars, candy bars	Confectionery
Chocolate flakes milk	Confectionery
Chocolates, bonbons	Confectionery
Liquorice	Confectionery
Sweet in yogurt	Confectionery
Sweet sandwich topping	Confectionery
Custard, porridge	Dairy
Ice in summer and winter	Dairy
Pudding	Dairy
Becel bake and roast plus, tub	Fats and oils
Becel from bottle	Fats and oils
Blue band from bottle	Fats and oils
Butter, olive oil based	Fats and oils
Butter, semi-skimmed	Fats and oils
Croma from bottle	Fats and oils
Elmer half full	Fats and oils
Fat, Blue Band fry and roast, etc	Fats and oils
Fat, Braderije	Fats and oils
Fat, Elmer light	Fats and oils
Fat, fry and fry, 0-50mg chol	Fats and oils
Fat, fry and roast, 50-300 mg chol	Fats and oils
Fat, fry and roast, Reform	Fats and oils
Fat, just Elmer	Fats and oils
French fries sauce	Fats and oils
Gravy, melt	Fats and oils
Halvanaise/yoghonaise	Fats and oils
Liner 3%	Fats and oils
Low-fat margarine, <20g linolz, 25-150mg chol	Fats and oils
Margarine product, <80 g fat Becel	Fats and oils
Margarine product, <80% fat, tub low-fat	Fats and oils
Margarine product, >5-20% fat	Fats and oils
Margarine product, low-fat, <40% fat	Fats and oils
Margarine, 0-20g lin, 0-300mg chol	Fats and oils
Margarine, 0-20g lin, 0-50mg chol	Fats and oils
Margarine, 20-40g lin, 0-50mg chol	Fats and oils
Margarine, diet low-fat, 20-40g lin, 0-25mg chol	Fats and oils

Margarine, diet, 40-60g lin, 0-50mg chol	Fats and oils
Margarine, low-fat, 0-20g lin, 0-25mg chol	Fats and oils
Mayonnaise, 80% oil	Fats and oils
Oil, Becel	Fats and oils
Oriental oil, stir-fry	Fats and oils
Peanut sauce, prepared	Fats and oils
Salad dressing, 25% oil	Fats and oils
Warm sauces, excl. peanut/macaroni sauce	Fats and oils
Fish fingers, unprepared	Fish
Breakfast cereals	Grains
Casserole rib, smoked meat, f.americ, roast beef	Meat
Cervelat / sandwich sausage, bacon	Meat
Cooked ham	Meat
Liver pate, pate, liver sausage	Meat
Piece of sausage	Meat
Pizza, sausage salami	Meat
Smoked sausage	Meat
Apple pie, fruit cake	Pies and cookies
Cake whipped cream, cream pastry	Pies and cookies
Cake, large cakes	Pies and cookies
Cookies, biscuits	Pies and cookies
Gingerbread	Pies and cookies
Croquette	Savory snacks
Meat snacks	Savory snacks
Pretzels	Savory snacks
Vegetarian schnitzel	Soy product
Advocaat	Alcoholic beverages
Beer, low-alcohol/free	Alcoholic beverages
Port, sherry, vermouth, lawyer	Alcoholic beverages
Port+port, sherr, etc	Alcoholic beverages
Strong alcoholic drinks	Alcoholic beverages
Chocolate milk	Dairy
Coke	Non-alcoholic beverages
Fruit juice, excluding orange/grapefr/apple	Non-alcoholic beverages
Roosvicee/karvan cevitam with water	Non-alcoholic beverages
Soft drink diet, without caffeine	Non-alcoholic beverages
Soft drinks with sugar	Non-alcoholic beverages



Supplementary figure 1. Flow-chart of participant in present study.

Chapter 6

Nutritional composition of ultra-processed plant-based foods in the out-of-home environment: a multi-country survey with plant-based burgers

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Abstract

Ultra-processed plant-based foods, such as plant-based burgers have gained in popularity. Particularly in the out-of-home (OOH) environment, evidence regarding their nutritional profile and environmental sustainability is still evolving. Plant-based burgers available at selected OOH sites were randomly sampled in cities of four WHO European Member States; Amsterdam, Copenhagen, Lisbon, and London. Plant-based burgers (patty, bread and condiment) (n=41) were lab-analysed for their energy, macronutrients, amino acids, and minerals content per 100g and serving, and were compared with reference values. For the plant-based burgers, the median values per 100g were: 234 kcal, 20.8g carbohydrates, 3.5g dietary fibre, and 12.0g fat, including 0.08g TFA and 2.2g SFA. Protein content was 8.9g/100g, with low protein quality according to amino acid composition. Median sodium content was 389mg/100g, equivalent to 1g salt. Compared with references, the median serving of plant-based burgers provided 31% of energy intake based on a 2,000 kcal per day, and contributed to carbohydrates (17-28%), dietary fibre (42%), protein(40%), total fat (48%), SFA (26%), and sodium (54%). One serving provided 15-23% of the reference values for calcium, potassium, and magnesium, while higher contributions were found for zinc (30%), manganese (38%), phosphorus (51%), and iron (67%). The ultra-processed plant-based burgers, provide protein, dietary fibre and essential minerals, but also contain relatively high levels of energy, sodium, and total fats. The amino acid composition of the plant-based burgers indicated low protein quality. The multifaceted nutritional profile of plant-based burgers highlights the need for manufacturers to implement improvements to better support healthy dietary habits. These improvements should include reducing energy, sodium and total fats.

Key-words vegan burgers, plant-based foods, ultra-processed foods, out-of-home, food environment

Introduction

Global meat production has more than doubled since 1961 [1], and so have the environmental impacts [2]. The trend to move from an animal-based diet towards a more plant-based diet is a key component of initiatives supporting both healthier eating and environmental sustainability [3, 4]. There is a large body of evidence concluding that limiting the consumption of animal-based foods may to lower environmental pressure [4-6].

A shift towards plant-based diets has the potential to also facilitate a decrease in non-communicable diseases (NCDs). The rise in NCDs is a growing part of the disease burden in Europe and the leading cause of morbidity and mortality in the WHO European Region [7, 8]. Additionally, the growing burden of overweight and obesity in the European Region, itself both an NCD and a risk factor for other NCDs, is a continued public health challenge. In the WHO European Region, overweight and obesity affect almost 60% of adults and nearly one in three children (29% of boys and 27% of girls) in [9].

Research shows that compared to animal-based foods, plant-based foods are lower in total energy and are sources of antioxidants, fibre and other essential nutrients [3]. Studies have found that predominantly vegetarian and vegan populations with no or a low intake of animal-based foods have lower prevalence rates of overweight and obesity [3, 10]. In addition, studies have found that high amounts of red and processed meat consumption, (i.e. ≥ 100–120 g and 50 g per day, respectively), are associated with a 10–20% greater likelihood of developing cancer, type 2 diabetes, stroke, coronary heart disease and heart failure [11, 12].

The transition towards more plant-based diets has stimulated the food industry to develop new plant-based foods and has coincided with expanding markets [13]. While not all, many of the these new industrially developed foods can be classified as ultra-processed foods (UPF)[14]. For instance, approximately 80% of plant-based burger patties evaluated in major Australian supermarkets were categorized as ultra-processed foods (UPF) [15]. With a greater number of plant-based foods being developed and made available, including ultra-processed, quick and affordable foods, there is a need to know how the nutritional profile of these products affect diet quality and subsequently NCDs [13] [16]. A number of studies assessed the nutritional composition of plant-based foods based on nutrition information provided on label [17-19], hence evidence from the out-of-home (OOH) environment is lacking.

In recent years, there has been a rapid increase in the use of digital food environments, the online settings through which flows of services and information that influence people's food and nutrition choices and behaviour are directed [20, 21]. As a result, there has been increased demand for food in the OOH environment, particularly for food ordered through meal delivery apps (MDAs) [20], where ultra-processed convenience foods, including plant-based products, dominate. With a lack of data on the nutritional content of food in the OOH environment due to different regulations regarding nutritional labelling compared to retail products, it is necessary to gather nutrition information on these foods to allow consumers to make healthier and sustainable informed choices [22].

To help build a nutrient profile for the proliferation of ultra-processed plant-based foods in the OOH environment, this study focuses on plant-based burgers as a key example. Laboratory analyses were conducted to gather information on the nutrient content of plant-based burgers in selected cities across the WHO European Region. This multi-country survey provides evidence to initiate the building of an evidence base on which informed policy decisions can be made to improve population health whilst safeguarding the health of the planet.

Methods

Cities in four WHO European Member States were selected for the study in a convenience sample that covers the breadth of the Region: Amsterdam, Copenhagen, Lisbon, and London. As this is a small-scale study to initiate the building of a wider evidence base, only a limited number of cities were identified.

Mapping the sample sites

Representatives from each selected city were asked to determine the location and number of OOH sites that offered plant-based burgers through an online search via Google, TripAdvisor or other related websites. This was done using both English and a local translation of the defined search terms such as "vegan *or plant-based burger + name of the city" and "vegan *or plant-based restaurant + name of the city". Multinational and country-specific food delivery websites including Deliveroo, Uber Eats and Take-away were also used to search for plant-based burgers. The results from this search were cross-checked against the online search engine list. Personal referrals by country representatives were used to complete the list. A final list of locations of the sampling sites for each city was plotted using a Google My Map maps.

City-specific sampling strategies were used to understand the number and density of OOH sites in each city. For Amsterdam, Copenhagen and Lisbon, sites were classified according to neighbourhood, and from each area a sample of ten was drawn (11 for Amsterdam). In London, the city centre (London Underground zone 1) was sampled and was accordingly classified into four areas (North, East, South, West). To achieve the target sample size of ten plant-based burgers per city, the number of burgers purchased within each area was determined by dividing the number of sites in the particular area to the number of total sites in the city, and then multiplying by ten. The OOH plant-based burger sites were then selected by random sampling with an Excel function (=RANDBETWEEN()) for Amsterdam, Copenhagen and Lisbon, and randomizer.org was used for London.

Data collection

A representative from each country visited the identified sites in person and physically purchased the plant-based burger samples. A sample equivalent to one serving 'as sold', was procured from each site identified in the mapping exercise. If a burger could not be purchased, for instance because sites were closed, the list derived from the mapping exercise was consulted, and the next available site was chosen. Samples were collected 'as sold' and included a patty and bun element and may also have included other plant-based components such as plant-based cheese, sauces and condiments, if this was how the product was sold. Samples did not include any side dishes such as fries, chips and crisps and no extra options such as extra plant-based cheese and extra sauce if the consumer had to specifically request these items. If a site had more than one burger option, the best-selling burger was chosen; this was determined by the representative from each country e.g. by asking the server or by checking popularity on food delivery websites/apps. Each sample was labelled with a reference number, the name of the plant-based burger, the name and full address of the sampling site and the date of sampling. The menu item name and ingredient list or description of each sample was recorded on collection In order to minimise bias, the collection of samples at each location was carried out on the same day. If a site was closed on the day of data collection, it was not included in the study and an alternative site was chosen as described above.

All samples were placed in zip lock bags and labelled with a reference number. Samples were stored at -20°C freezer until delivery to the laboratory in Lisbon, Portugal. Delivery was via courier with a certified -20°C cold-chain.

Nutritional Assessment

Laboratory analysis to determine the nutritional composition was performed at Instituto Nacional de Saúde Doutor Ricardo Jorge (INSA), Lisbon, Portugal. Upon arrival in Lisbon, each sample was unpacked, weighed, homogenized, aliquoted and frozen as soon as possible until laboratory analyses could be undertaken. For proximate analysis, samples were analysed for moisture, total protein, fat, carbohydrates including sugars, and total dietary fibre contents. The fatty acid profile, including saturated and trans fatty acids, sodium and minerals, and amino acid composition were also determined. Proximate and mineral analysis were performed according to the methods described by Nascimento et al. (2014) [23]. Moisture and ash contents were determined by gravimetric methods using a dry air oven and a muffle furnace, respectively. Quantification of total fat was performed after an acid hydrolysis method followed by a Soxhlet extraction (Foss Soxtec, Denmark). Quantification of total protein was determined by the Kjeldahl method (Foss Kjeltec, Denmark). The content of total dietary fibre was determined using an enzymatic–gravimetric method, with heat stable α-amylase, protease and amyloglucosidase as enzymes for digestion (Merck, Germany). Minerals were determined after acid digestion with nitric acid, followed by an inductively coupled plasma optical emission spectrometer analysis (ICP-OES Thermo iCAP 6000 series). Fatty acid profile was determined using a gas chromatographer (Agilent 6890N Network GC System, Germany), equipped with a flame ionization detector and according to the ISO 12966 (2015–2017) and the Commission Regulation (EC) No. 796/2002 (2002), with modifications, as described by Albuquerque et al. (2016) [24]. The amino acid profile was analysed using liquid chromatography (Acquity UPLC, Waters, USA), equipped with a photodiode array (PDA) detector after acid hydrolysis and a pre-derivatization as described by Motta et al. (2016) [25].

Data analysis

Descriptive data on the burgers were summarized and presented as median (IQR), 5th and 95th percentile. Outcomes are presented for the entire sample and include energy, macronutrients, and minerals per 100 g and per serving size. Outcomes per serving size were compared with reference values for healthy men and women aged ≥ 18 years (Supplemental Table 1) derived from WHO [26-30] and EFSA [31-38]. The energy intake was set at 2,000 kcal a day. Protein requirement was calculated based on an average bodyweight of 70 kg. The nutrient values for the median serving burger were compared with reference intakes (RI) for macronutrients, and with population reference intakes (PRI) or adequate intakes (AI) if PRI was not available.

Furthermore, descriptive data were used to summarize amino acid composition of the plant-based burgers. Amino acid scores reflects the amount of an amino acid relative to the reference amount of that amino acid per gram of protein. Scores were calculated using the essential amino acids histidine (His), isoleucine (Ile), leucine (Leu), lysine (Lys), sulphur amino acids (SAA) (metheonine (Met) and cysteine (Cys)), aromatic amino acids (AAA) (tyrosine (Tyr) and phenylalanine (Phe)), threonine (Thr), and valine (Val), following the formula (amount of amino acids / 100g) divided by (the total amount of protein), divided by (the reference intake for adults), based on WHO report on protein and amino acid requirements (i.e. mg of amino acids per 1g protein/ mg of amino acids in required pattern) [39]. Furthermore, amino acids per serving in the plant-based burgers were compared with daily references [39]. For each of the essential amino acids, the relative intake per day was estimated based on the amino acid requirements in mg per day for adults > 18 years with a bodyweight of 70 kg.

Results

A total of 171 OOH sites selling plant-based burgers were identified in Amsterdam, 59 in Copenhagen, 70 in London, and 151 in Lisbon in 2022 between March and May. The locations of these sites were listed and mapped (Supplemental figures 1a-1d). Forty-one plant-based burgers were purchased and analysed.

Per 100g the median energy content was 234 kcal (IQR=50) or 978 KJ (IQR=205) (Table 1). The median macronutrient composition per 100g, was 20.8g (IQR=5.7) carbohydrates, 3.5g (IQR=1.8) dietary fibre, and 8.9g (IQR=3.7) protein. Per 100 g, the burgers contained a median total fat content of 12.0g (IQR=4.2), including 0.08g (IQR=0.05) TFA, 2.2g (IQR=2.3) SFA, 5.2g (IQR=3.6) MUFA, and 3.3g (IQR=1.2) PUFA. The median sodium content was 389mg (IQR=113) per 100g, equivalent to 1g salt.

The median serving size of plant-based burgers was 280g (IQR=65), providing 619 kcal (IQR=183) (Table 1). This accounts for 31% of energy intake, based on a 2,000 kcal per day diet (Figure 1). One median serving provided 56.2g (IQR=17.7) carbohydrates, accounting for 17%- 28% of the reference values. One median serving provided 10.6g (IQR=5.9) dietary fibre and 23.2g (IQR=9.1) total protein, corresponding to, respectively, 42% and of 40% of reference values for dietary fibre (25 g) and the protein (58.1 g) (PRI). The median amount of total fat per serving was 31.9g (IQR=13.2), equating to 48% of the maximum level. The fatty acid composition per median serving of plant-based burgers included 0.2g TFA, 5.7g SFA, 13.7g MUFA, and 9.3g PUFA. One median serving accounted for, respectively, 9% and 26% of the daily maximum levels for TFA and SFA. The median sodium content per serving was 1086.6mg (IQR=395.6), equivalent to 2.7 g salt, and 54% of the daily maximum level. One median serving of plant-based burgers provided 15% of the reference value for calcium (AI), and respectively 17% and 23% of the reference values for potassium (PRI) and magnesium (AI). Contributions to the reference values for zinc (30% of PRI), manganese (38% of AI), phosphorus (51% of AI), and iron (67% of PRI) were higher.

Median amino acid scores (AAS) varied between 0 for SAA (Met and Cys) and 43 for His to 110 for Leu and 127 for AAA (Tyr and Phe) (Supplemental Table 2). The amino acid composition of the plant-based burgers indicates low protein quality. The (median) relative contribution towards the daily recommendations for essential amino acids were 0% for SAA, 24% for His, 25% for Lys, 41% for Ile, 41% for Val, 45% for Thr, 58% for Leu, and 65% for AAA (Figure 2).

Discussion

Ultra-processed plant-based foods have gained in popularity as a perceived healthier and more sustainable alternative to animal-based foods, yet the evidence regarding their nutritional profile, environmental sustainability, and impact on NCDs is still evolving [13]. This study aimed to contribute to the understanding of the nutrient profile of ultra-processed plant-based foods in the out-of-home (OOH) environment, by focusing on plant-based burgers. The study provides an overview of the nutritional content and amino acid composition of plant-based burgers available in OOH environments in Amsterdam, Copenhagen, Lisbon, and London. Our results indicate that while plant-based burgers are a source of (low quality) protein, dietary fibre, and essential minerals, they also contain relatively high levels of energy, sodium, total fat and SFA, which are directly linked to NCDs.

Our study findings are consistent with existing literature indicating that ultra-processed plant-based foods such as plant-based burgers can provide dietary fibre, (low quality) plant-based protein and minerals [40-43]. Therefore, their inclusion in the diet may contribute to meeting daily requirements and may have lower environmental impacts than meat-based burgers. Additionally, the intake of plant-based protein, dietary fibre, and minerals, which are abundantly present in plant-based burgers, has been linked to a reduced risk of certain NCDs such as cardiovascular disease [26, 30, 44]. While ultra-processed plant-based foods can serve as a source of certain nutrients, the extent to which these foods contribute to overall nutrient intake is influenced by various factors, including but not limited to an individual's dietary pattern, their nutritional status, and the bioavailability of the nutrients in question. The magnitude of the contribution made by the consumption of the burgers to daily nutrient intake may vary depending on dietary patterns of individuals. This is beyond the scope of the current study. Nevertheless, it has been reported that current intake levels of certain essential nutrients, including dietary fibre [45], and minerals such as iron [46] and potassium [26], are, in general, below the daily recommendations in Europe. Therefore, the consumption of these burgers may contribute to daily requirements, independent of the consumption of other foods.

On the other hand, in agreement with prior research, the plant-based burgers are energy-dense and contain relatively high amounts of added salt and fat which can adversely impact their overall healthfulness [19, 41-43]. In the WHO European Region, energy, sugar, fatty acids, and salt intakes generally exceed the recommended levels and for health reasons their intake should be decreased [30]. For instance, a high intake of sodium has been associated with an increased risk of NCDs such as cardiovascular disease, stroke, and high blood pressure [27, 30]. Similarly, the consumption of excessive sugar and unhealthy fatty acids has been linked to a heightened risk of obesity, type 2 diabetes, and other NCDs [28, 30, 47]. Therefore, besides the beneficial nutritional factors present in ultra-processed plant-based foods, they are also a source of unhealthy compounds. This contradiction raises the question whether the healthier aspects of plant-based burgers outweigh the less healthy aspects, which is contingent on an individual's dietary patterns and nutritional status. Factors such as the frequency and quantity of burger consumption, as well as the overall dietary context in which burgers are consumed, can affect the potential health outcomes of their consumption.

The AAS of the plant-based burgers analyzed in our study ranged from 0 for SAA to 127 for AAA, indicating low protein quality. AAS <100 indicate less than the recommended amino acids per 1g protein, while AAS above 100 indicate sufficient of the recommended amino acids per 1g protein (39). To synthesize a protein from amino acids, a specific quantity of amino acids is required. The amino acid that exists in the lowest quantity becomes the limiting factor, and the protein cannot be constructed beyond this particular amino acid's availability. Although Lys is often the limiting factor, in our study Cys and Met were the limiting amino acids as they were below the limit of detection (25). Sulphur containing amino acids can be destroyed depending on the cooking procedures, especially in foods from vegetable sources. Cooked pulses and meat substitutes are the foods that contribute less to the recommended intake on SAA (Cys and Met) (48). Nevertheless, in order to predict protein quality it is imperative to incorporate digestibility factors. The quality of protein can be predicted by comparing the pattern of digestible amino acid composition with human amino acid requirements: the digestible indispensable amino acid score (DIAAS) [39]. Furthermore, the amino acid bioavailability in plant-based foods may differ from animal-based foods (48). At last, if complementary foods are consumed within 3-4 hours, deficient amino acids can be supplied, enhancing the amino acid content.

Additionally, as for amino acids, it is important to consider the potential impact of factors present in plant-based foods (such as phytates) affecting the bioavailability of the nutrients in the burgers [43]. These factors may, for instance, inhibit the absorption of certain nutrients and therefore influence their ultimate contribution to overall nutritional status [43] [48]. The relatively high iron content of the burgers for instance, may be largely composed of non-heme iron, which is primarily found in plant sources and more variable to absorption compared to heme iron [48-50]. Fortification of the burgers cannot be ruled out as it was not within the scope of current study.

Despite the aforementioned considerations, it is possible to compare the burgers to established guidelines that are commonly used to evaluate the nutritional value of foods. In order to encourage or discourage the consumption of certain foods, the WHO Regional Office for Europe has developed the nutrient profile model in 2015 and updated it in 2023 [51]. This model aims to provide guidance for restricting the marketing of foods to children, and classifies foods according to its nutritional composition as whether or not it is nutritionally suitable to be marketed for consumption by children. According to the nutrient profile model, the product category ’Savory plant-based foods/meat analogues’ in which plant-based burgers are situated, marketing is prohibited of plant-based burgers that contain >17 fat , >1 g TFA or >0.05 g sodium per 100 g. In light of the nutritional content of the sampled burgers, including bread and sauces, 10% of the burgers contained more than the maximum level for total fat, and 20% of the burgers contained more than the maximum level for sodium. Therefore, they exceeded the threshold making them unsuitable to be marketed according to the nutrient profile model [51].

A strength of this multi-country survey lies in its focus on investigating the nutritional content of ultra-processed plant-based foods in various cities across the WHO European Region, which will provide case study evidence to initiate the building of an evidence base on which informed policy decisions can be made to improve population health while safeguarding that of the planet. As there is a rapid increase in the availability of ultra-processed plant-based food in current food environments, this current study highlights the need to critically assess the availability, composition and consumption of those foods in the OOH food environment. Moreover, the nutrient analyses done in this study is a strength since existing studies often used labelling information [17-19]. At last, the consideration of plant-based burgers (i.e. patty, bread and condiment) in current study is a major strength as it reflects the nutrients associated with food intake rather than the patty only. For the interpretation of our results, certain limitations should be noted. This study aimed to initiate the building of a wider evidence base for plant-based burgers, but its generalizability is limited by the sample size and coverage of burgers and locations. The study included 41 plant-based burgers from four cities within the WHO Region Europe (Amsterdam, Copenhagen, Lisbon, and London), but these cities might not be representative of other regions. The results might also differ between and within countries and the samples might not cover all different types of plant-based burgers. However, due to the low sample sizes in each city (n = 10) no comparison can be made. Furthermore, the current study did not measure micronutrients such as vitamin B12 which are mainly present in animal-based foods and important to monitor its adequacy in the transition towards a plant-based diet. Although B12 is not naturally present in plant-based foods, the burgers could potentially be fortified with it.

The current multi-country survey provides a case study on ultra-processed plant-based foods, using plant-based burgers as an example. Plant-based burgers have a multifaceted nutritional profile with aspects that support and go against healthy dietary habits. Most of the plant-based burgers did not exceed the maximum levels for total fat, SFA and sodium levels according to the WHO nutritional profile model to prevent inappropriate marketing to children marketing [51]. In addition, (ultra-processed) plant-based foods often have a ‘health-halo’, being perceived by consumers as healthy [13, 52, 53], which is not the case necessarily. The food environment, among food marketing and the availability of foods, has a large influence on what consumers unconsciously purchase and consume [54]. In general, the marketing of ultra-processed plant-based foods such as plant-based burgers in the OOH environment is strong [55] and, according to our study, they are widely available. Therefore, policy for marketing regulation is needed and, improved awareness of the health and environmental aspects of ultra-processed plant-based foods might be required. Furthermore, the variation in nutrient content between burgers highlights the potential for reformulation of ultra-processed plant-based foods by manufacturers and food handlers, and may contribute to more healthier and sustainable plant-based burgers in the OOH environment. Future scaled-up studies on the nutritional composition of ultra-processed plant-based foods are needed and should also be coupled with life-cycle assessments to understand the relative environmental impacts.

Conclusion

With this study, we provide data to help build an evidence base on which informed policy decisions can be made to improve population health whilst safeguarding the health of the planet. The findings indicate that ultra-processed plant-based foods, such as plant-based burgers, provide protein, dietary fibre and essential minerals, but they also contain relatively high levels of energy, sodium, and total fats. Despite their potential as a source of protein, the amino acid composition of the plant-based burgers indicated low protein quality. Therefore, ultra-processed plant-based foods in the OOH environment have components that contribute to healthier dietary habits, but also some components are relatively high, which may contribute to increased risk of developing NCDs. The multifaceted nutritional profile of plant-based burgers highlights the need for manufacturers to implement improvements to better support healthy dietary habits. These improvements should include reducing energy, sodium and total fats.

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Tables and figures

Table 1. Composition of energy, macronutrients and minerals of plant-based burgers per 100g and per serving.

	Per 100 g			Per serving		
	Median	**IQR**	**[5th-95th percentile]**	**Median**	**IQR**	**[5th-95th percentile]**
Quantity (g)				280,0	65,0	[200,3 - 339,0]
Energy (kcal)	233,8	49,6	[184,5 - 295,8]	618,8	183,3	[469,2 - 945,8]
Energy (kJ)	977,5	204,8	[774,5 - 1231,6]	2585,5	763,7	[1965,4 – 3942,6]
Carbohydrates (g)	20,8	5,7	[17,4 - 27,4]	56,2	17,7	[40,4 – 84,0]
Dietary fibre (g)	3,5	1,8	[2,0 - 6,4]	10,6	5,9	[4,4 – 18,3]
Total fat (g)	12,0	4,2	[6,2 - 19,3]	31,9	13,2	[16,4 – 57,3]
TFA (g)	0,1	0,1	[0,0 - 0,1]	0,2	0,1	[0,1 – 0,5]
% TFA /100g total fat	0,7	0,3	[0,3-1,0]			
SFA (g)	2,2	2,3	[0,9 - 5,7]	5,7	5,6	[2,0 – 19,1]
MUFA (g)	5,2	3,6	[2,1 - 10,3]	13,7	8,3	[5,2 – 33,9]
PUFA (g)	3,3	1,2	[1,3 - 5,9]	9,3	4,6	[4,3 - 33,9]
Protein (g)	8,9	3,7	[5,0 - 11,8]	23,2	9,1	[15,7 – 31,4]
Na (mg)	388,9	112,9	[246,0 - 573,5]	1086,6	395,6	[702,7 – 1661,6]
K (mg)	220,1	85,9	[139,8 - 356,7]	607,6	271,1	[324,9 – 1255,0]
Mg (mg)	24,8	8,2	[14,3 - 44,6]	70,1	33,6	[38,1 – 132,0]
Ca (mg)	46,5	34,8	[33,0 - 103,6]	125,7	82,3	[88,1-337,2]
P (mg)	91,3	35,6	[66,8 - 145,7]	278,9	93,7	[157,8-409,9]
Mn (mg)	0,4	0,1	[0,3 - 0,7]	1,1	0,4	[0,7 - 2,1]
Fe (mg)	1,4	0,5	[1,0 - 2,0]	4,0	1,1	[2,3 – 5,8]
Zn (mg)	0,9	0,4	[0,6 - 1,3]	2,2	1,2	[1,3 – 3,6]
Salt (g)	1,0	0,3	[1,2 - 6,8]	2,7	1,0	[3,4 – 14,4]

TFA, trans fatty acids; SFA, saturated fatty acids; MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids ; Na, sodium; K, potassium; Mg, magnesium; Ca, calcium; P, phosphorus; Mn, manganese; Zn, Zinc; Fe, iron.

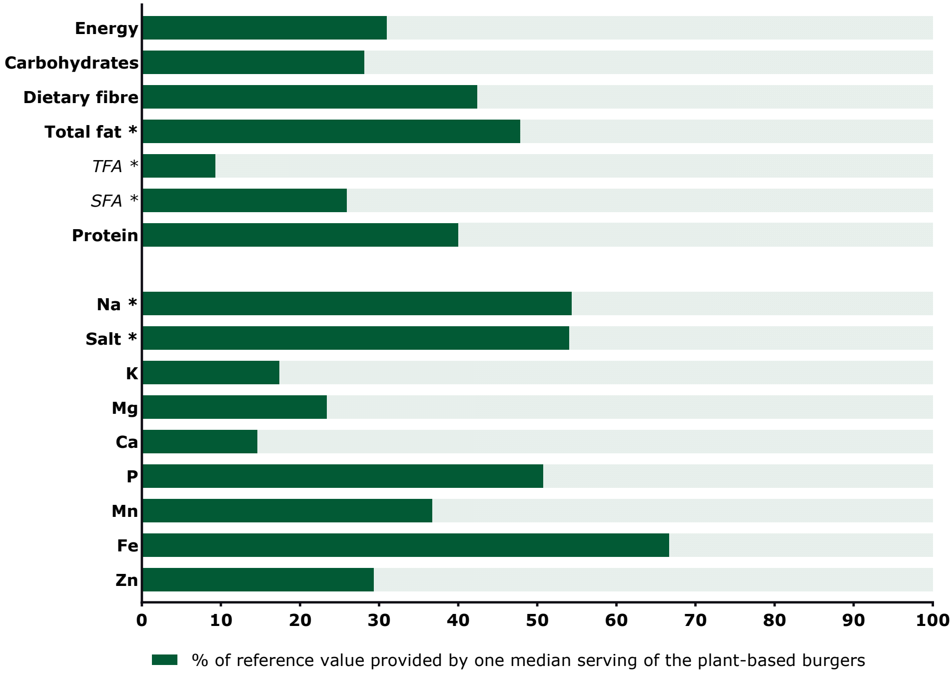

Figure 1. The relative amount of energy, macronutrients and minerals per serving (in %) compared to the daily reference values.

* indicates the contribution towards the maximum recommendations.

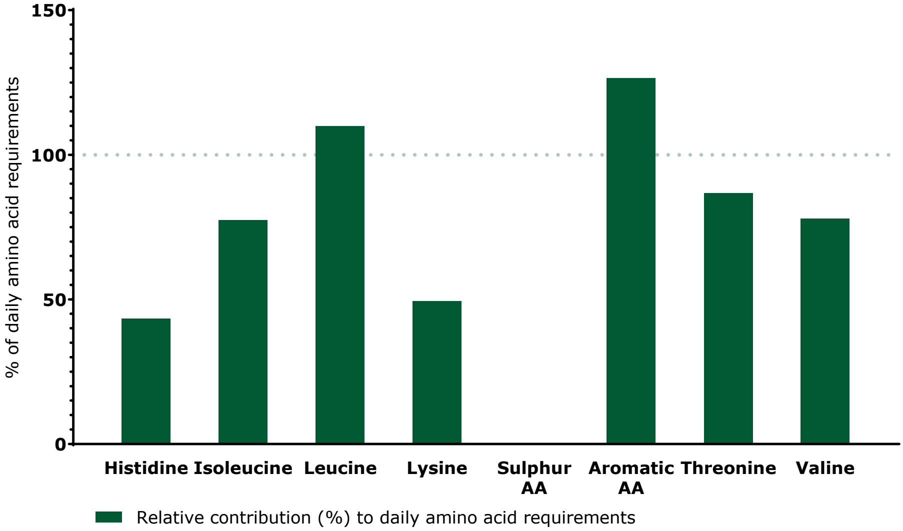

Figure 2. The relative amount of amino acids per serving (in %) compared to the daily reference values. Aromatic amino acids, tyrosine and phenylalanine; sulphur amino acids, meteonine and cysteine

Supplemental files

Supplemental table 1. Reference values

Supplemental table 2. Composition of amino acids of plant-based burgers per 100g and per serving, and comparison with requirements for essential amino acids.

Supplemental figures 1a-d. Distribution of out of home sites selling plant-based burgers for Amsterdam, Copenhagen, Lisbon and London.

Supplemental table 1. Reference values.

	Reference value	Type	Source
Energy (kcal)	The recommended daily energy intake varies based on age, sex, weight, and physical activity level. However, the average recommended daily energy intake for an adult is around 2000-2500 kcal/day. For current study we set energy intake at 2,000 kcal.		WHO [2]
Energy (kJ)	8368 kJ		
Total carbohydrates (g)	45-60 % of total energy	RI	EFSA [3]
Dietary fibre (g)	25 g	AI	EFSA [3]
Total fat (g)	The WHO recommends that total fat intake should not exceed 30% of total energy intake. This means that for an adult consuming 2000 calories per day, the daily fat intake should not exceed 67 grams.	RI	WHO [4]
TFA (g)	The WHO recommends that TFA intake should be limited to less than 1% of total energy intake. This means that for an adult consuming 2000 calories per day, the daily TFA intake should not exceed 2 grams. TFA limit is also 2% per 100 g total fat.	RI	WHO [5]
SFA (g)	The WHO recommends that SFA intake should not exceed 10% of total energy intake. This means that for an adult consuming 2000 calories per day, the daily SFA intake should not exceed 22 grams.	RI	WHO [5]
Protein (g)	0,83 g/kw/bw. Based on 0,83g/kg/bodyweight and 70 kg bodyweight, this results in 58.1 g protein	PRI	EFSA [6]
Na (mg) /Salt (g)	The WHO recommends that adults should consume less than 5 grams of salt (or 2000 mg of sodium) per day.	Safe and adequate intake	WHO [7]
K (mg)	The WHO recommends that adults should consume at least 3.51 grams of potassium per day.	PRI	WHO [8]
Mg (mg)	Male, female 350 mg/day, 300 mg/day*	AI	EFSA [9]
Ca (mg)	1000 mg/day (18-24 y) 950 mg/day (≥ 25 y)	PRI	EFSA [10]
P (mg)	550 mg/day	AI	EFSA [11]
Mn (mg)	3 mg/day	AI	EFSA [12]
Fe (mg)	11 mg/day for males 11 mg/day for females* (premenopausalwomen=16; postmenopausal women=11)	PRI	EFSA [13]
Zn (mg)	Male, female (LPI 300 mg/day) 9.4 mg/day,7.5 mg/day* Male, female (LPI 600 mg/day) 11.7 mg/day,9.3 mg/day Male, female (LPI 900 mg/day) 14 mg/day,11 mg/day Male, female (LPI 1200 mg/day) 16.3 mg/day,12.7 mg/day	PRI	EFSA [14]

Abbreviations: AI-= ADEQUATE INTAKE; PRI= POPULATION REFERENCEINTAKE; RI = REFERENCE INTAKE; *reference value used in current study

Supplemental table 2. Composition of amino acids of plant-based burgers per 100g and per serving, and comparison with requirements for essential amino acids.

		per 100 g					per serving			
	N	Median	QRange	Mg/g	Requirement (mg/g)*	Amino acid score*	Median	QRange	Requirement per day*	% of req
Histidine(mg)	31	68	39	7	15	43	167	203	700	24%
Serine(mg)	41	409	192				1094	523		
Arginine(mg)	41	281	230				810	639		
Glycine(mg)	41	300	146				795	330		
Asparagine(mg)	41	834	421				2273	1278		
Glutamine(mg)	41	2647	1049				6844	2881		
Threonine(mg)	41	178	106	20	23	87	477	340	1050	45%
Alanine(mg)	41	306	138				820	413		
Proline(mg)	41	622	319				1471	884		
Cysteine(mg)	41	<LoD								
Lysine(mg)	38	239	225	22	45	49	525	586	2100	25%
Tyrosine(mg)	41	141	146				368	364		
Meteonine(mg)	2	14	8			-	0	0		-
Valine(mg)	41	290	144	30	39	78	747	487	1820	41%
Isoleucine(mg)	41	222	149	23	30	77	578	470	1400	41%
Leucine(mg)	41	602	285	65	59	110	1573	865	2730	58%
Phenylalanine(mg)	41	297	207				825	510		
Aromatic amino acids(mg)	41	436	335	48	38	127	1146	860	1750	65%
Sulphur amino acids (mg)	41	<LoD			22	0			1050	0%
Amino Acids Sum(g)	41	8	4				21	10		

Aromatic amino acids, tyrosine and phenylalanine; sulphur amino acids, meteonine and cysteine; LoD, limitl of detection

*Calculated as amount of amino acid per 1g protein divided by the reference amount of amino acid per 1g protein [1].

Supplemental figures 1a-d. Distribution of out of home sites selling plant-based burgers for Amsterdam, Copenhagen, Lisbon and London.

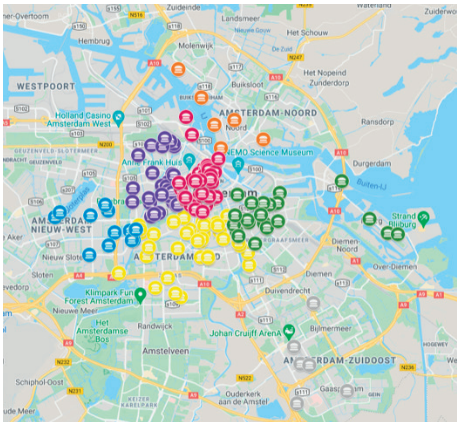

Fig 1a. Distribution of out of home sites, Amsterdam

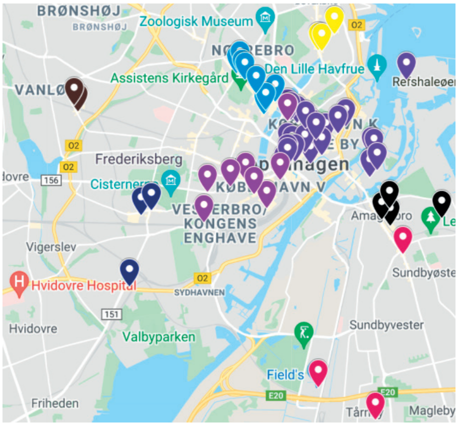

Fig 1b. Distribution of out of home sites, Copenhagen

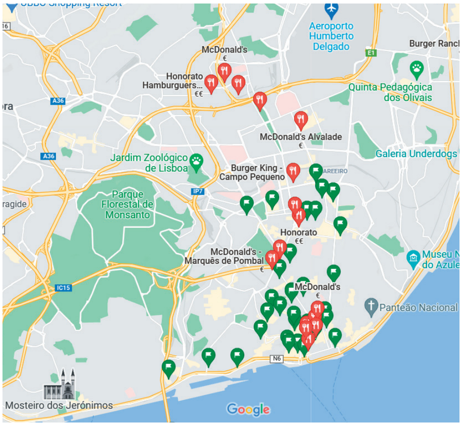

Fig 1c. Distribution of out of home sites, Lisbon

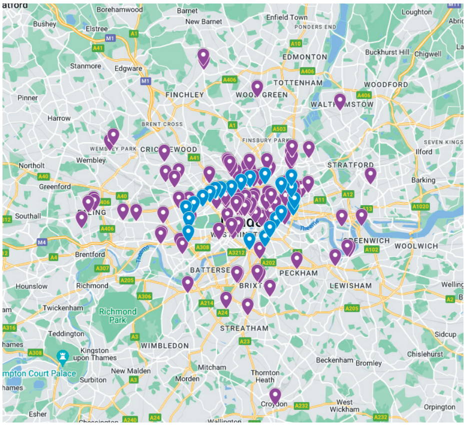

Fig 1d. Distribution of out of home sites, London

Part III

Enabling healthy and environmentally sustainable food choices in retail food environments

Chapter 7

Less meat in the shopping basket. The effect on meat purchases of higher prices, an information nudge and the combination: a randomised controlled trial

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Abstract

Reduced meat consumption benefits human and planetary health. Modelling studies have demonstrated the significant health and environmental gains that could be achieved through fiscal measures targeting meat. Adding other interventions may enhance the effect of a fiscal measure. The current study aimed to examine the effect of higher meat prices, an information nudge and a combination of both measures on meat purchases in a three-dimensional virtual supermarket. A parallel designed randomised controlled trial with four conditions was performed. Participants (≥ 18 years) were randomly assigned to the control condition or one of the experimental conditions: a 30% price increase for meat ('Price condition'), an information nudge about the environmental impact of meat production and consumers' role in that regard ('Information nudge condition') or a combination of both ('Combination condition'). Participants were asked to shop for their household for one week. The primary outcome was the difference in the total amount of meat purchased in grams per household per week. Between 22 June 2020 and 28 August 2020, participants were recruited and randomly assigned to the control and experimental conditions. The final sample included 533 participants. In the 'Combination condition', − 386 g (95% CI: − 579, − 193) meat was purchased compared with the 'Control condition'. Compared to the 'Control condition' less meat was purchased in the 'Price condition' (− 144 g (95%CI: − 331, 43)), although not statistically significant, whereas a similar amount of meat was purchased in the 'Information nudge condition' (1 g (95%CI: − 188, 189)). Achieving the most pronounced effects on reduced meat purchases will require a policy mixture of pricing and an information nudge. Less meat is purchased in a virtual supermarket after raising the meat price by 30% combined with an information nudge. The results could be used to design evidence-based policy measures to reduce meat purchases.

The trial was registered in the Netherlands Trial Register identifier NL8628. Registered on 18/05/2020. ICTRP Search Portal (who.int) NTR (trialregister.nl).

Introduction

A large body of evidence shows that the production and consumption of meat are associated with climate change, loss of biodiversity, occupation of large areas of land and alterations of the nitrogen cycle, and contribute to acidification and eutrophication [1]. Moreover, high red and processed meat consumption, with 100–120 g and 50 g respectively, are associated with a 10–20% greater likelihood of developing cancer, diabetes, stroke, coronary heart disease and heart failure, and substantially contribute to the foodborne burden of disease [2, 3]. Current global consumption levels of red and processed meat exceed the recommendations [4]. A lower consumption of meat could significantly reduce the effects of food consumption on the environment, improve human health and lead to a net societal benefit [5].

Multiple types of food policy interventions (e.g. informative, administrative, behaviour and market-based instruments) can be implemented to steer consumers' dietary choices [6]. A scoping review showed that hardly any currently implemented food policy worldwide focuses specifically on the reduction of meat consumption [6]. Most implemented food policies focus on public health and lower consumption of energy-dense, (micro)nutrient-poor foods and beverages, and higher vegetable and fruit consumption [6]. Policies combining health and sustainability objectives are few and often only implemented via informative measures [6]. Such measures from a freedom-of-choice perspective include, for example, dietary guidelines that recommend a maximum consumption of meat. However, their impact is low, not assessed or difficult to measure [7].

Modelling studies have demonstrated the significant health and environmental gains that could be achieved by lower meat consumption through higher meat prices [5, 8, 9]. A recent social cost and benefit analysis (SCBA) from the Netherlands estimated over a period of 30 years that the average meat consumption decreased by 16% from 107 to 90·3 g per person per day after a 30% price increase on meat [5]. Adding other measures, such as information or nudges to create awareness among consumers, may enhance the effect of a fiscal measure since mixes of instruments are often more effective compared with one specific instrument only [7, 10]. Information nudges alter consumer behaviour from a freedom-of-choice perspective to a more healthy choice and may contribute to improving population dietary behaviours [11].

Food prices are known to be a significant driver for food choices [12]. Systematic reviews show that taxing unhealthy foods to discourage their consumption is an effective measure to improve dietary behaviour [13, 14]. For example, in a systematic review and meta-analysis, Teng et al. (2020) demonstrated with real-life evaluations that the equivalent of a 10% tax on sugar-sweetened beverages was associated with an average decline in beverage purchases and dietary intake of 10% [15]. Fiscal measures such as taxation could be a powerful measure targeting meat reduction as higher prices discourage consumers from purchasing the foods that are taxed [13].

However, limited empirical evidence is available on the effectiveness of higher meat prices as no fiscal policies that aim to reduce meat purchases or consumption have been implemented as yet. Although more literature has become available on small-scale experiments that target meat consumption, these experiments are mostly focused on changing attitudes and intention or willingness to consume meat and not on actual purchases [16, 17]. One small-scale experiment did investigate the effect on purchases of altering prices. Garnett et al. (2021) studied the impact on sales of experimentally altering the price of meat and vegetarian meal options in a college cafeteria in the UK [18]. The price differentiation increased the sales of vegetarian meals but did not affect the sales of meat meals.

Robust evidence on policy measures to decrease meat purchases and consumption is needed, as effective evidence-based interventions are still lacking, and evidence currently relies on modelling studies. Therefore, this study presents a randomised controlled trial (RCT) which examined the effect of a fiscal measure (higher meat prices), an information nudge (information on the environmental impact of meat production and the role of the consumer in that regard) and a combination (higher meat prices and an information nudge) on meat purchases in a Dutch virtual supermarket.

Methods

Study design

A parallel designed RCT with four conditions was conducted. The trial was registered in the Netherlands Trial Register identifier NL8628. Registered on 18/05/2020. Participants were randomised to one of the following conditions:

(i) An experimental condition 'Price condition': prices of meat and meat products (containing at least 80% meat) were increased by 30% at the consumer food purchase level. A price increase of 30% was chosen because it was previously estimated that such a price increase could lead to a net societal benefit for the Netherlands [5]. Forty-four meat products were taxed (Supplemental Table 1). The average price of meat increased from €2·87 to €3·73 per unit as sold. No information was given on the purpose of the revenue. In order to reflect a real-world setting, participants were made aware of the price increase of meat via a notification before entering the supermarket: “The government has increased the tax on meat in the virtual supermarket, leading to a price increase of 30% for meat”.

(ii) An experimental condition ‘Information nudge condition’: participants were exposed to an information nudge, as framed within the typology of interventions in proximal physical micro-environments [19]. The nudge aimed to create awareness regarding the environmental impact associated with meat production and to influence the consumer’s role in that regard. Before entering the virtual supermarket, participants were exposed to the information nudge: “The government wants to reduce the consumption of meat in the Netherlands because meat production damages the environment. You can help to reduce the environmental damage caused by meat production by purchasing less meat”. Regular food prices were used.

(iii) An experimental condition ‘Combination condition’: both higher prices (30% price increase on meat, condition i) and the information nudge (condition ii) were included. Participants were exposed to the notification and nudge before entering the virtual supermarket: “The government wants to reduce the consumption of meat in the Netherlands because meat production damages the environment. You can help to reduce the environmental damage caused by meat production by purchasing less meat. The government has increased the tax on meat in the virtual supermarket, leading to a price increase of 30% for meat”.

(iv) A control condition ‘Control condition’: regular food prices were used, and participants did not receive a notification before entering the virtual supermarket.

The virtual supermarket

The study was conducted in a Dutch virtual supermarket, which is a three-dimensional computer software system simulating the in-store environment of a real supermarket [20]. The tool enables participants to purchase food items and measures food purchasing behaviour in a virtual setting. A validation study, where shopping patterns in the virtual supermarket were compared with those in real life, found that the software is a valid tool for measuring food purchasing behaviour in a supermarket setting [21]. The software was updated in 2019 and is described in detail elsewhere [22]. The updated version includes new functionalities and features to create a more realistic virtual supermarket. The virtual supermarket contained 580 foods and proportionally represented the usual supermarket offer. The selection of available foods was based on the stock of the leading supermarket chain and supplemented with the most frequently consumed foods within the most recent Dutch National Food Consumption Survey 2012–2016 [23]. The leading supermarket chain’s website was assessed in February 2020 and provided information on product weight and food prices. Foods were coded according to the Dutch Food Composition Database (NEVO) (NEVO online version 2019/6.0) [24].

Participants

Eligible participants were adults (≥ 18 years) with an adequate command of the Dutch language, largely or totally responsible for grocery shopping for the household and with access to a laptop or computer. Participants were recruited via an online research panel in the Netherlands (Panel Inzicht) and were rewarded with virtual points which could be redeemed for cash. The study purposes were not mentioned during recruitment nor study execution. Participants for the current study were recruited simultaneously with participants for another project which aimed to evaluate the effects of a sugar-sweetened beverage tax and a nutrient profiling tax on consumer purchases (Netherlands Trial Register registration number NL8616) [22]. This other project determined the total number of included participants per study condition (n = 109). Data from participants who were exposed to the control condition were used in both studies for the control condition. The Research Ethics Review Committee of the Faculty of Sciences, Vrije Universiteit Amsterdam gave its ethical agreement (reference 20,205). Approval from the Dutch Medical Research Involving Human Subjects Act further was not needed.

Procedure

The full procedure of this study is described elsewhere [22]. In short, after participants were recruited and completed the screening questionnaire, they were invited via email to participate in the study. Eligible participants who provided informed consent were sent instructions to download and install the virtual supermarket software. Participants were randomly sent log-in codes in order to be assigned to one of the conditions. After logging in, participants were asked about their household size and composition in order to determine their weekly shopping budget. The National Institute for Family Finance Information (NIBUD) provided standardised household budgets [25]. Instructions were given to do a weekly grocery shop in the supermarket for their household (seven times breakfast, lunch, dinner and snacks). It was explained that participants would not receive the purchased groceries nor budget in real life. Before entering the virtual supermarket, participants in the experimental conditions were exposed to the notifications corresponding to the conditions. After the check-out in the supermarket, participants were directed to a final questionnaire covering various questions about the experiment and participant characteristics. The entire study was executed online.

Outcomes

The difference in the total amount of meat purchased (in g) per household per week was the primary outcome. Information on the purchases was collected for meat purchased (binary: yes/no), meat and total food items purchased (in n), the environmental impact and nutritional outcomes. The environmental impact of foods was derived from the Dutch Life Cycle Assessment (LCA) Food database [26]. The LCA's quantify the environmental impact of a food from cradle to plate and are described in more detail elsewhere [27]. Indicators included were greenhouse gas (GHG) emissions (in kg CO_2-equivalents), blue water consumption (water sources from surface or groundwater resources) (in m^3) and land use (in m^2/year). GHG emissions is used as a proxy for other indicators as GHG emissions highly correlates with other environmental indicators. Blue water consumption and land use had the weakest correlation with GHG emissions in the Dutch LCA Food database and are therefore also included in this study [27]. The LCA's were linked via NEVO codes. For which no primary LCA data were available the LCA's were linked to similar foods based on similarities in types of food, production systems and ingredient composition. For composite dishes, standardized recipes from the Dutch food composition database (NEVO-online version 2016/5.0) were used where available and if not available, recipes were based on label information [24]. The Dutch food composition database (NEVO online version 2019/6.0) was used to determine nutritional composition (via energy content (kcal), carbohydrates (in energy percentage (En%)), mono and disaccharides (in En%), fatty acids (in En%), saturated fatty acids (SFA) (in En%), protein (in En%), fibre (in En%) and salt (in g)) [24].

A final questionnaire was specified for the control and experimental conditions. First, a set of general questions was provided, covering participants' sex, height and weight, educational level, income, living situation, and, for instance, frequency of meat consumption. Depending on the experimental conditions, the questionnaire contained (three or six) additional questions. Participants in the Information nudge condition and Price condition were asked three additional questions as to whether the notification (on the information nudge or price increase, respectively) before entering the virtual supermarket had been read (Yes or No), understood (Yes or No) and whether it had influenced the shopping behaviour (7-point Likert scale: 1 "not at all" to 7 "extremely"). In the Combination condition, the questions on the information nudge as well as on the higher meat prices were asked. Finally, the questionnaire covered questions about participants' understanding of the software (5-point Likert scale: 1 "strongly disagree" to 5 "strongly agree"), whether the participants' virtual supermarket groceries corresponded with their usual groceries (5-point Likert scale: 1 "strongly disagree" to 5 "strongly agree"), and whether the participants' shopping budget was more, the same or less than usual. Also, participants' attention to the prices and the influence of pricing on their purchases were measured (7-point Likert scale: 1 "not at all" to 7 "extremely").

Statistical analysis

Characteristics of the population and secondary outcomes were summarised with descriptive statistics in means and standard deviations (SD) or median and interquartile range (IQR) for continuous variables, and in numbers and percentages for categorical variables. Outcomes were visually inspected for normality using Q,Q-plots and Kolmogorov -Smirnov tests. The primary measure total amount of meat purchases followed a normal distribution. Linear regression models with the total amount of meat purchases as a dependent variable and the conditions as independent variables were used to examine the potential effect modifier education level, as individuals with a lower socio-economic position might respond differently upon the interventions [13]. The variable educational level was added to the unadjusted model with interaction terms between the variable and the intervention conditions to examine effect modification. Interaction terms were not statistically significant ($p > 0{\cdot}05$) and therefore removed from the model. In the first model, the variable household size was added to the model since this variable is a strong predictor for the total amount of (meat) purchases (model 1). Certain imbalances in characteristics were observed between the conditions, although the drop-out across study conditions was similar. In the second model, further adjustments were therefore made for sex, BMI and educational level to correct for imbalances between the conditions (model 2). Parameter estimates were obtained using generalised linear models and included regression coefficients (β) (representing the absolute mean difference in meat purchases (in g per household per week) for the experimental conditions relative to the control condition (reference) and 95% confidence interval (95%CI) of the mean difference. A sensitivity analysis was performed, in which participants in the experimental conditions were excluded who did not read or understand the notifications before entering the supermarket. Furthermore, in a second sensitivity analysis participants were excluded who defined themselves as vegan, vegetarian or pescatarian. Participants were excluded for analysis if fewer than or equal to five different products were purchased since this type of grocery shopping is not representative of a typical weekly shop. The statistical analysis was performed using SAS software, version 9.4 (SAS Institute Inc., Cary, NC, USA). A two-sided p-value of $< 0{\cdot}05$ was considered statistically significant.

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

From 22 June 2020 to 28 August 2020, 150,514 panel members were invited to participate in the study. Of these, 12,901 individuals completed the screening questionnaire (Fig. 1). A total of 5524 participants were eligible for inclusion and randomised and allocated to the control and experimental conditions (n = 3695) or to the research conditions of another project (n = 1829). (Netherlands Trial Register registration number NL8616). Overall, 547 participants were able to complete the virtual shopping (15%). Participants who completed the shopping were on average younger (mean = 48·3, SD= 16·2 y) compared with those who dropped out of the study (mean = 57·4, SD = 15·7 y) (Supplemental Table 2). Moreover, participants included in the study were more often higher educated (50%) compared to those who dropped out of the study (29%). After excluding non-representative shops (n = 14), the final sample for analysis included 533 participants (n = 153 for the 'Control condition', n = 133 for the 'Price condition', n = 126 for the 'Information nudge condition' and n = 121 for the 'Combination condition'). Characteristics of participants are presented in Table 1. Descriptive statistics show that 9·8% of the participants in the 'Control condition' did not purchase meat items in the virtual supermarket. In the 'Price condition', 'Information nudge condition' and 'Combination condition', 12·0, 9·5 and 15·7% of participants did not purchase meat products, respectively.

In linear regression analysis adjusted for household size, − 367 g (95%CI: − 557, − 178) meat per household per week was purchased in the 'Combination condition' compared with the 'Control condition' (model 1) (Table 2). After further adjustments for sex, BMI and education (model 2), the effect remained significant at − 386 g (95% CI: − 579, − 193) meat purchased in the 'Combination condition' compared with the 'Control condition' (Table 2; Fig. 2). In the 'Price condition', less meat (− 144 g (95%CI: − 331, 43)) was purchased compared with the 'Control condition', although not statistically significant. In the 'Information nudge condition', the amount of meat purchased was similar to the 'Control condition' (1 g (95%CI: − 188, 189)). A sensitivity analysis that excluded participants who did not read or understood the notifications before entering the supermarket did not alter the obtained results (Supplementary Table 3 and 4). Furthermore, a sensitivity analysis in which participants were excluded who defined themselves as vegan, vegetarian or pescatarian resulted in a more pronounced difference in meat purchases in the 'Combination condition' compared to the 'Control condition' with − 413 g (95%CI − 606, −219) (Supplementary Table 5).

The mean number of meat items purchased was 4·3 (SD = 3·1) in the 'Control condition', 3·7 (SD = 2·4) in the 'Price condition', 4·2 (SD = 2·8) in the 'Information nudge condition' and 3·2 (SD = 2·4) in the 'Combination condition' (Table 3). Overall, the purchased food items represented 62·3 (SD = 29·3) kg CO_2-eq in the 'Control condition' and, respectively, 56·3 (SD = 24·3) and 54·4 (SD = 25·6) kg CO_2-eq in the 'Price condition' and 'Combination condition'. Shopping baskets in control and experimental conditions contained 30,000–33,000 kcal on average and approximately 13 En% protein, 47–48 En% carbohydrates, 35–36 En% fatty acids, 2 En% Fibre and 74–89 g salt.

Discussion

Results from this RCT showed that a 30% higher meat price combined with an information nudge on the environmental impact of meat production and consumers role in that regard results in a decrease of − 386 g (95%CI: − 579, − 193) meat per household per week in a virtual supermarket. With the singular fiscal measure of 30% higher meat prices less meat was purchased (− 144 g (95%CI: − 331, 43)). Although the difference was not significant, the reduction was in the expected direction. The singular information nudge did not lead to a change in meat purchases. This study demonstrated the beneficial effects of a higher meat price combined with providing information in order to nudge consumers towards lower meat purchases, which has important implications for planetary and public health.

Lately, more literature has become available on the modelled effects of a meat tax [5, 8, 9] and on behaviour oriented studies that investigate willingness or intentions to reduce meat purchases or consumption [16, 17]. Studies that investigate actual reductions in meat purchases or consumption are scarce. To the best of our knowledge, this is the first study that investigated the effect on meat purchases of different policy measures in a supermarket setting. The mixed policy including both the price increase and the information nudge was effective in reducing meat purchases. In line with the literature, singular or informative measures are often less effective in achieving dietary change compared with more robust measures such as fiscal measures or mixed policies with more pronounced effects [7, 28].

One study was identified that examined the effect on meat meals of higher meat prices in a real-life setting. In the experiment of Garnett et al. (2021), the effect on meal choices of altering the prices of meals with or without meat was studied in a university cafeteria in the UK [18]. The difference between the price of meals with or without meat was 8 %, corresponding to £0·40 (€0·46). In contrast, the price increase in our study was 30% or on average €0·96 per meat item as sold. Similar to the present study, participants were aware of the price increase. During the study period, the price changes were advertised (e.g. on screens on campus, on the menus). The advertisement stated that the prices of meals were changing to reflect the cost of ingredients. Although sales of vegetarian meals increased by 3·2%, the sales of meat meals did not change compared with the baseline [18]. In the study of Garnett et al. only a fiscal measure was studied; we also included an information nudge. This might explain why we observed a significant reduction in meat purchases.

In our study, the singular measure of 30% higher meat prices led to the expected result of less meat purchases, although not statistically significant compared with the 'Control condition'. This result is more in line with the experiment of Garnett et al. [13] In general, taxing unhealthy foods to discourage their consumption, with or without other intervention components, are effective measures in improving diets and healthy behaviour [13, 14]. Modelling studies have demonstrated the effectiveness of meat taxes previously; however, they did not include an information nudge in their modelling strategy [5, 8, 9, 16]. Our results suggest that including an information nudge may enforce the effect of a fiscal measure.

With the ‘Information nudge condition’, we did not observe any difference in meat purchases compared with the ‘Control condition’. Previous systematic reviews investigating experiments that targeted changing attitudes demonstrated that providing information was successful in changing the intention or willingness to reduce meat purchases or consumption. However, actual reductions in meat purchases or consumption were not observed or measured [16, 17]. In a meta-analysis of experiments, information nudges (framed as cognitive nudges) were found to be the least effective type of nudges in affecting selection and consumption outcomes [29]. In contrast, Harbers et al. (2020) examined the effect of information nudges (providing information on the foods at the point of choice in real-life supermarkets or messages via posters in cafeterias) in real-life food purchase environments. The effects of those information nudges on purchases were heterogeneous but showed modest benefits [11]. The information nudge in the current study was provided shortly before entering the supermarket and not at the point of choice or for a longer period of time nor more frequently exposed, which might be a reason for our contradictory results.

Significant strengths of this RCT include the design and the empirical evidence on consumer changes in meat purchases as a result of a price increase, simultaneously with the information nudge in a virtual supermarket. Previous studies often focused solely on behavioural factors such as willingness or intention to purchase or consume less meat and often relied on self-reported measures [16, 17].

Some limitations should be noted when interpreting our study results. Firstly, the experiment was conducted in a virtual supermarket, which has its limitations. The virtual supermarket has a smaller grocery offer compared to a real-life supermarket. Moreover, participants’ shopping behaviour might be influenced in the virtual supermarket as participants did not spend their own money and they did not receive the groceries. Nevertheless, the New Zealand version of the virtual supermarket, which uses the same methodology as the Dutch version, is previously validated. The validation study compared within persons the real-life groceries with shopping patterns in the virtual supermarket and showed that purchased foods in the virtual supermarket were a good reflection or representation of purchases in a real supermarket [21]. Furthermore, in our study, participants reported that they mostly agreed that their shop reflected their usual groceries (mean score of 4·05 on a 5-point Likert scale). Secondly, although the research team had conducted several steps to minimize drop out, there was a large but equal drop-out of study participants across the study conditions after randomisation. This might have implications for the interpretation of the study results and their external validity. Participants who dropped out of the study were on average older and often had a lower educational level. Since elderly or those with a lower educational level are often less computer literate, this might explain the higher drop-outs among those older or lower educated participants [30]. Despite the drop-out across study conditions was similar, certain imbalances in characteristics between the conditions were observed. To correct for those imbalances we have adjusted the models for the imbalanced variables (sex, BMI and educational level). Moreover, in general selection bias occurs in trials. To minimize selection bias, participants were recruited via a large online research panel with more than 100,000 members, not aware of study aims and were randomised to the control and experimental conditions. Furthermore, the recruitment of participants and study execution was partly during the lockdown in the COVID-19 pandemic. During the recruitment period there were certain restrictions for grocery shopping in the Netherlands. We expect that the COVID-19 pandemic did not have a major influence on our study outcomes since 82·9% of the participants reported that their food purchases were not changed due to the COVID-19 pandemic. The potential effects of a reduction of meat consumption on human and planetary health could be significant. For instance, a Swedish modelling study with an environmental tax of 8·9% to 33·3% on three meat products (beef, pork and chicken) and four dairy products showed 12% lower GHG emissions from the livestock sector [8]. Furthermore, the recent SCBA from the Netherlands that modelled and monetised the 30-year societal effects of 30% higher meat prices demonstrated that daily meat consumption would decrease by 17 g or 16% [5]. As a result, 5550–29,398 cases for diabetes type 2 prevalence would be averted, 2122–6691 QALYs were gained, and the environmental impact (assessed via GHG emissions, acidification, eutrophication of marine and fresh water, and water and land use) decreased by 16%. Overall, this resulted in benefits of between €4100 - €12,300 million over 30 years [5]. In comparison, we found a 23-g reduction per person per day based on the conditions' average household size of 2·4 persons and a decrease of 386 g meat per week. Furthermore, when taking into account the average adjusted meat purchases in the 'Control condition' and 'Combination condition' with 1084 g and 698 g, respectively, this can be translated into a relative decrease of 36% in meat purchases per household per week. Therefore, it can be expected that the impact on human and planetary health would be even more significant compared with modelling results from Broeks and colleagues [5]. Future large-scale research is needed to confirm our results in real-life supermarkets.

In conclusion, achieving the most pronounced effects on reductions in meat purchases requires a policy mixture of pricing and informational nudging. This study demonstrated that a 30% price increase for meat is effective in decreasing meat purchases when combined with an information nudge on the environmental impact of meat production and the consumers' role in that regard. The results could be used to design evidence-based policy measures to reduce meat purchases.

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Tables and figures

Table 1. Population characteristics for control and experimental conditions.

	Total population (n=533)		Control condition (n=153)		Price condition (n=133)		Information nudge condition (n=126)		Combination condition (n=121)	
Sex										
Male	253	47%	75	49%	67	50%	58	46%	53	44%
Female	278	52%	78	51%	65	49%	67	53%	68	56%
Other	2	0%	0	0%	1	1%	1	1%	0	0%
Age (years)	48·3	16·2	48·6	16·3	48·4	15·9	46·9	16·7	49·3	15·8
Household size	2·3	1·2	2·3	1·3	2·2	1·1	2·4	1·3	2·4	1·2
% persons >13 y	29·1	28·4	28·5	26·8	29·7	29·7	28·4	28·7	29·9	29·0
Educational level										
Low	83	16%	20	13%	23	17%	23	18%	17	14%
Moderate	180	34%	45	29%	41	31%	42	33%	52	43%
High	270	51%	88	58%	69	52%	61	48%	52	43%
BMI (kg/m^2)	26·5	5·8	27·5	6·0	25·9	5·5	26·7	5·9	25·6	5·5
Weight status[1]										
Normal weight <25	243	46%	65	42%	64	48%	58	46%	56	46%
Overweight (≥25-30)	171	32%	50	33%	39	29%	38	30%	44	36%
Obese (>30)	107	20%	37	24%	25	19%	28	22%	17	14%
Meat consumption (frequency/week)										
0	34	6%	9	6%	8	6%	6	5%	11	9%
<1	8	2%	3	2%	2	2%	1	1%	2	2%
1-2	71	13%	22	14%	18	14%	15	12%	16	13%
3-4	179	34%	38	25%	51	38%	42	33%	48	40%
5-7	241	45%	81	53%	54	41%	62	49%	44	36%
Type of (meat) consumer										
Vegan	7	1%	0	0%	4	3%	1	1%	2	2%
Vegetarian	20	4%	8	5%	3	2%	4	3%	5	4%
Pescatarian	5	1%	1	1%	1	1%	1	1%	2	2%
Flexitarian	20	4%	48	31%	46	35%	45	36%	49	40%
Meat consumer	313	59%	96	63%	79	59%	75	60%	63	52%
Purchased meat										
Yes	471	88%	138	90%	117	88%	114	90%	102	84%
No	62	12%	15	10%	16	12%	12	10%	19	16%
Grocery responsibility										
Entirely	337	63%	99	65%	87	65%	78	62%	73	60%
Largely	196	37%	54	35%	46	35%	48	38%	48	40%

Household monthly income (gross in €)										
Low (0-2000)	136	26%	38	25%	34	26%	26	21%	38	31%
Moderate (2000-3000)	135	25%	37	24%	41	31%	33	26%	24	20%
High (3000+)	262	49%	78	51%	58	44%	67	53%	59	49%
Household weekly food expenditures (in €)										
0-59	170	32%	52	34%	42	32%	40	32%	36	30%
60-99	205	38%	55	36%	49	37%	53	42%	48	40%
≥100	158	30%	46	30%	42	32%	33	26%	37	31%
Changed purchases due to COVID-19										
No	442	83%	124	81%	112	84%	99	79%	107	88%
Yes	91	17%	29	19%	21	16%	27	21%	14	12%
Shopping budget in virtual supermarket (in €)	87.10	31.69	87.11	34.37	85.05	30.28	89.33	34.52	87.02	26.34
% of budget spent	83·4	21·7	84·2	19·8	84·6	21·4	83·4	22·3	81·3	23·6
Total expenditure (€)	71.24	28·23	72.28	30.40	70.29	26.37	72.58	27.78	69.58	28.06
Appreciation of shopping budget										
More than usual	165	31%	49	32%	32	24%	47	37%	37	31%
Same as usual	256	48%	71	46%	67	50%	62	49%	56	46%
Less than usual	112	21%	33	22%	34	26%	17	13%	28	23%
Price awareness [2]	4·0	1·6	3·9	1·6	4·1	1·6	3·8	1·7	4·1	1·6
Understanding virtual supermarket[3]	4·6	0·6	4·5	0·6	4·6	0·6	4·5	0·6	4·6	0·7
Comparability to real-life purchases[4]	4·1	0·8	4·0	0·8	4·1	0·8	4·1	0·8	4·0	0·8

Data are n (%) or mean (SD). BMI=Body Mass Index

[1] 12 missing values;

[2] Measured by one item “The program was easy to understand” indicated on a five-point Likert scale ranging from 1 “strongly disagree” to 5 “strongly agree”;

[3] Measured by two items “To what extent did you notice prices in the virtual supermarket?” and “To what extent did prices influence your choices in the virtual supermarket?” indicated on a seven-point Likert scale ranging from 1 “not at all” to 7 “extremely”;

[4] Measured by one item “The products I have purchased in the virtual supermarket are comparable to my regular food purchases in real-life” indicated on a five-point Likert scale ranging from 1 “strongly agree” to 5 “strongly agree”.

Table 2. Effects of price, information nudge and combination condition on total meat purchases (in gram per household per week) in the virtual supermarket using linear regression analyses.

	Price condition (n=133)			Information nudge condition (n=126)			Combination condition (n=121)		
Model 1	-162	-347	23	-10	-198	178	-367	-557	-178
Model 2	-144	-331	43	1	-188	189	-386	-579	-193

Data are regression coefficients (β) with 95% confidence intervals. The adjusted amount of meat purchases per household per week (and per person per day based on the conditions' average household size) were 1084 g (67 g) in the control condition, 940 g (61 g) in the 'price condition', 1085 g(65 g) in the 'Information nudge condition' and 698 g (42 g) in the 'Combination condition'.

Model 1 = adjusted for household size;

Model 2 = model 1 + adjusted for gender (male, female, other), BMI (continuous), education (low, moderate, high)

β represents average difference in gram per household per week compared with the control condition.

Table 3. Descriptive statistics for total food purchases, and environmental and nutritional outcomes per household per week for the total population and the control and experimental conditions in the virtual supermarket.

	Total population (n=533)		Control condition (n=153)		Price condition (n=133)		Information nudge condition (n=126)		Combination condition (n=121)	
Purchases										
Purchased food items (n)	39·7	16·4	40·5	15·5	37·6	14·7	41·8	17·3	38·6	15·7
of which meat (n)	3·6	2·8	4·3	3·1	3·7	2·4	4·2	2·8	3·2	2·4
Environmental impact										
Greenhouse gas emission (kg CO_2-eq)	58·9	26·8	62·3	29·3	56·3	24·3	61·9	26·6	54·4	25·6
Land use (m^2/year)	38·3	19·6	39·6	21·4	37·1	18·5	40·1	17·5	36·2	20·2
Blue water use (m^3)	1·70	1·07	1·72	1·02	1·59	1·01	1·76	1·05	1·74	1·21
Nutritional outcomes										
Energy (kcal)	32,054	16,164	33,043	18,007	30,710	14,050	33,750	1,6072	30,517	15,896
Protein, En%	12·8	3·6	12·7	3·5	12·8	3·4	13·0	3·8	12·8	3·9
Carbohydrates, En%	47·5	10·3	47·7	10·7	47·1	10·8	46·9	9·6	48·2	10·0
Mono- and disaccharides, En%	20·9	8·0	21·8	8·7	20·2	7·8	20·3	7·5	20·9	7·8
Fatty acids, En%	35·7	11·6	35·6	11·0	35·9	11·9	36·3	11·1	35·0	12·3
Saturated fatty acids, En%	11·6	3·7	11·7	3·3	11·5	4·2	11·7	3·5	11·2	3·8
Fibre, En%	2·3	0·8	2·2	0·8	2·3	0·8	2·3	0·8	2·5	0·9
Salt (g) (median(IQR))	81	65	83	65	80	60	89	65	74	66

Data are n(%), mean (SD) or median (IQR). CO_2-eq=CO_2 equivalents; En%=Energy percentage

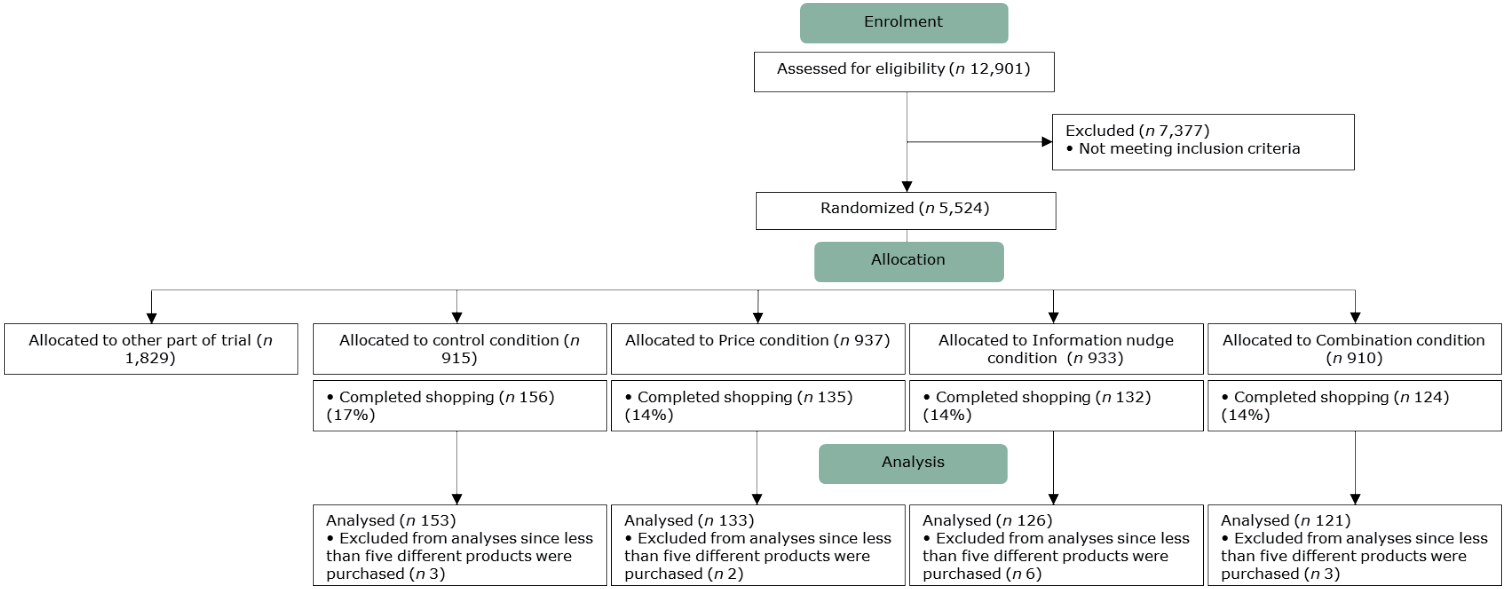

Figure 1. Flowchart of enrolment and allocation of the study participants.

*1,829 participants were randomised for the purpose of another project (Netherlands Trial Register registration number NL8616)

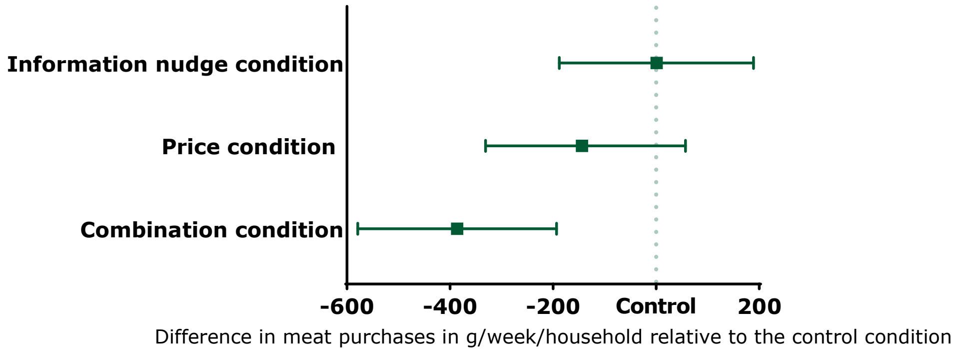

Figure 2. Mean difference in meat purchases (in g/week/household) for the experimental conditions compared with the control condition.

Estimates are derived from linear regression models adjusted for sex, BMI and educational level. The reference indicates the control condition. Error bars indicate 95% confidence intervals.

Supplemental files

Supplemental Table 1. Overview of meat products being sold in the Virtual Supermarket with unit and price for control and experimental conditions.

Supplemental Table 2. Characteristics of participants randomized, dropped out and included in the study.

Supplemental Table 3. Overview of participants in the experimental condition that have read and understand the information nudge that they were exposed to in the conditions.

Supplemental Table 4. Sensitivity analysis excluding participants who did not read the information nudge or notification on price increase. Effects of the price condition, information nudge condition and condition on total meat purchases (in gram) using linear regression analyses.

Supplemental Table 5. Sensitivity analysis excluding participants who reported themselves as vegan, vegetarian or pescatarian. Effects of the price condition, information nudge condition and condition on total meat purchases (in gram) using linear regression analyses.

Supplemental Table 1. Overview of meat products being sold in the Virtual Supermarket with unit and price for control and experimental conditions.

Product	Quantity as being sold		Regular price (€/unit)	30% price increase (€/unit)	Product group
Chickenwings (frozen)	750 g		2,55	3,32	Poultry
Turkey fillet	250 g		3,25	4,23	Poultry
Chicken drumsticks	600 g		2,45	3,19	Poultry
Chicken burger	205 g	(2 pieces)	1,73	2,25	Poultry
Chicken breast	300 g	(2 pieces)	3,25	4,23	Poultry
Bratwurst	240 g	(2 pieces)	2,49	3,24	Pork
Gelderland smoked sausage	200 g		2,04	2,65	Pork
Frankfurters (can)	400 g		1,62	2,11	Pork
Lean smoked sausage	200 g		2,00	2,61	Pork
Lean bacon strips	300 g		2,69	3,50	Pork
Shoulder chop (pork)	360 g		2,78	3,61	Pork
Spareribs (frozen)	750 g		5,79	7,53	Pork
Pork fillet slices	260 g	(2 pieces)	3,04	3,95	Pork
Steak (fresh)	275 g		5,14	6,68	Beef
Roast beef	120 g		3,12	4,06	Beef
Hamburger (fresh)	400 g	(4 pieces)	2,99	3,89	Beef
Hamburgers (frozen)	840 g		2,52	3,28	Beef
Ground beef (fresh)	300 g		2,29	2,98	Beef
Beef tartare (fresh)	200 g	(2 pieces)	2,19	2,85	Beef
Unox Hamburgers	160 g		2,39	3,11	Beef
Frikadellen (frozen)	340 g	(4 pieces)	1,48	1,92	Miscellaneous
Frikandellen (frozen)	1360 g	(16 pieces)	3,59	4,66	Miscellaneous
Chopped half and half	300 g		1,99	2,59	Miscellaneous
Venison steak	250 g		9,25	12,03	Miscellaneous
Lamb chop	230 g	(4 pieces)	7,42	9,65	Miscellaneous
Ham (slices)	250 g		3,59	4,67	Cold meat cuts
Farmer’s sausage	190 g		3,49	4,54	Cold meat cuts
Sandwich sausage (slices)	150 g		1,99	2,59	Cold meat cuts
Carpaccio	123 g		2,69	3,50	Cold meat cuts
Cervelate (slices)	105 g		2,01	2,61	Cold meat cuts
Chorizo	250 g		2,53	3,29	Cold meat cuts
Fillet American	160 g		2,49	3,24	Cold meat cuts
Roast chicken fillet (slices)	125 g		2,80	3,64	Cold meat cuts
Guelderian boiled sausage	250 g		2,09	2,72	Cold meat cuts
Gold salami (slices)	125 g		2,49	3,24	Cold meat cuts
Liver pate (canned)	168 g	3 x 56 g	1,29	1,68	Cold meat cuts
Liverwurst	500 g		2,83	3,68	Cold meat cuts

Breakfast bacon (smoked)	150 g	2,89	3,76	Cold meat cuts
Ox sausage	200 g	2,60	3,38	Cold meat cuts
Pate	170 g	2,24	2,91	Cold meat cuts
Salami (sausage)	250 g	1,51	1,96	Cold meat cuts
Shoulder ham (slices)	150 g	2,29	2,98	Cold meat cuts
Smac (can)	250 g	2,29	2,98	Cold meat cuts
Sliced sausage	105 g	2,01	2,61	Cold meat cuts

Supplemental Table 2. Characteristics of participants randomized, dropped out and included in the study.

	Total randomized (n=3,695)		Dropped-out (n=3,248)		Included (n=547)	
Age (y)	56·0	16·1	57·4	15·7	48·3	16·2
Responsibility grocery						
Totally responsible	2425	66%	2076	66%	349	64%
Largely responsible	1270	34%	1072	34%	198	36%
Educational level						
Low	1239	34%	1151	37%	88	16%
Moderate	1279	35%	1094	35%	185	34%
High	1177	32%	903	29%	274	50%
Data are mean (SD) or n (%).						

Supplemental Table 3. Overview of participants in the experimental condition that have read and understand the information nudge that they were exposed to in the conditions.

	Price condition (n=133)		Information nudge condition (n=126)	Combination condition (n=121)	
Did you read the following sentence before you entered the virtual supermarket? The government has increased the tax on meat in the virtual supermarket, which led to a price increase of 30% for meat.’					
Yes	122	92%		115	95%
No	11	8%		6	5%
Did you understand this message?					
Yes	129	97%		121	100%
No	4	3%			
To what extent has this message influenced your choice? [1]	2·7	1·7		2·9	1·9

Did you read the following sentence before you entered the virtual supermarket? 'The government wants to reduce the consumption of meat in the Netherlands because meat production damages the environment. You can help reduce environmental damage by purchasing less meat.'				
Yes	119	94%	106	88%
No	7	6%	15	12%
Did you understand this message?				
Yes	126	100%	120	99%
No			1	1%
To what extent has this message influenced your choice?	2·2	1·4	2·8	1·7

Data are mean (SD) or n (%).

[1] measured on a 7- point Likert scale: 1 "not at all" to 7 "extremely".

Supplemental Table 4. Sensitivity analysis excluding participants who did not read the information nudge or notification on price increase. Effects of the price condition, information nudge condition and condition on total meat purchases (in gram) using linear regression analyses.

	Price condition (n=122) [1]			**Information nudge condition (n=119) [2]**			**Combination condition (n=106) [3]**		
	β	**95%CI**		**β**	**95%CI**		**β**	**95%CI**	
Model 1	-159	-353	36	16	-178	210	-341	-545	-138
Model 2	-177	-369	14	-6	-198	187	-331	-530	-131

Model 1 = adjusted for household size (continuous);

Model 2 = model 1 + adjusted for gender (male, female, other), BMI (continuous), education (low, moderate, high);

[1] = 11 participants excluded; [2] = 7 participants excluded; [3] = 15 participants excluded.

Supplemental Table 5. Sensitivity analysis excluding participants who reported themselves as vegan, vegetarian or pescatarian. Effects of the price condition, information nudge condition and condition on total meat purchases (in gram) using linear regression analyses.

	Price condition (n=122) [1]			**Information nudge condition (n=119) [2]**			**Combination condition (n=106) [3]**		
	β	**95%CI**		**β**	**95%CI**		**β**	**95%CI**	
Model 1	-198	-401	6	6	-200	212	-373	-583	-163
Model 2	-181	-369	7	-35	-225	155	-413	-606	-219

Model 1 = adjusted for household size (continuous);

Model 2 = model 1 + adjusted for gender (male, female, other), BMI (continuous), education (low, moderate, high);

[1] = 8 participants excluded; [2] = 6 participants excluded; [3] = 9 participants excluded.

Chapter 8

General discussion

General discussion

The overall aim of this thesis is to provide a comprehensive understanding of the associations between dietary choices, health, environmental sustainability, and economic factors within Dutch diets, including the role of ultra-processed foods and drinks (UPFD). The research aims to contribute to scientific evidence that can underpin effective governmental policies to promote healthier and more environmentally sustainable diets while considering economic implications. This chapter first provides a contextualization to broaden the perspective. First the main thesis findings are summarized and discussed. Finally, methodological considerations, implications for policy, future steps, and the conclusions are provided.

As underpinned in **chapter 1**, the critical state of both the environment and public health can be attributed to dietary patterns. The simultaneous improvement in both health and the environment necessitates a comprehensive transformation of the food system. Food systems encompass different facets and dimensions, including but not limited to agriculture and farming, food processing, and consumption, as well as health, environmental sustainability, socio-economic factors, and their interconnections [1]. Effectively addressing the complexities in food systems requires collaborative efforts from actors, such as the agri-food industry, consumers, and governments. Their competing interest, e.g. profit motives, consumer preferences, and societal interests underscores the importance of developing and implementing regulatory and effective policies. Agri-food companies, generally driven by private economic motives, play key roles in food production [2]. Multinational corporations have significant power and influence, shaping market trends, pricing, availability, and consumer preferences through employment of pricing, marketing, production incentives, branding, and advertising [2]. Consumers, on the other hand, are primarily concerned with accessibility to tasty, convenient, and affordable foods that fit into their cultural context [2]. Consumers operate within the food environment and respond to supply and demand dynamics but bear no primary responsibility for them. The Dutch government, with its constitutional duty to safeguard the health of the population [3] and ensure environmental protection and improvements [4], has the power due to financial resources, capabilities, and policy instruments to facilitate this food system transition. Despite these governmental responsibilities, along with additional national [5, 6], and international commitments [7], the current landscape lacks effective policies aimed at improving public health and safeguarding the planet.

Part I - Health, environmental sustainability, and costs of current and future diets

The first part of this thesis investigated the healthiness, environmental sustainability, and costs of current and future diets. In **chapter 2** we evaluated the dietary environmental impacts and its association with healthiness of diet for 4313 participants aged 1 to 79 years. Data was derived from a representative study sample from the Dutch National food consumption survey (DNFCS) 2012-2016. For a subsample of the population, 2078 adults aged ≥19 years, the Dutch Healthy Diet 2015 index (DHD15) was used to assess adherence to national dietary guidelines. The average daily diet contributed 5.0 kg CO_2-equivalents to GHG emissions and 0.14 m^3 to consumptive blue water use (irrigation water). Meat, dairy, and non-alcoholic beverages contributed with more than half of daily GHG emissions, while non-alcoholic beverages, fruits, and meat contributed most to blue water. Healthier diets, according to the DHD15, were significantly associated with less GHG emissions but with higher blue water. In **chapter 3** we investigated how dietary patterns can be improved among adults with different socioeconomic backgrounds, and how these changes might affect the costs of their diets. In a modelling exercise, current diets of 1747 adults (DNFCS 2019-2021), were optimized through linear combinations of existing diets within socio-economic subgroups in order to achieve realistic replacements and diets. The optimization aimed to minimize GHG emissions and maximize adherence to the dietary guidelines (DHD15), along with constraints to keep dietary change close to current consumption. The optimized diets, across all socio-economic subgroups, had a 19-24% lower GHG emission, and a 52-56% improvement in diet quality. Diets of low educational subgroups contained more vegetables (6%), whereas diets of all educational subgroups included more fruits (10 to 16%), and less grains (-5 to -8%), dairy (-12 to -17%), and red and processed meat (-25 to -27%). The diet costs for the optimized diet remained comparable to those of current diets across all socio-economic subgroups. The pursuit of even healthier diets, yielded less pronounced reductions in GHG emissions compared to the optimal diets, while diet costs would increase with 2-8%.

Improving diet quality and environmental sustainability

In chapters 2-3 we found that diets with higher adherence to Dutch dietary guidelines were more environmentally sustainable. Consequently, healthier diets not only reduce the risk of cardiovascular diseases, overweight, and obesity [8], but also hold the potential to mitigate adverse environmental outcomes associated with food consumption. Our findings align with a substantial body of evidence, showing a well-established link between healthier diets and environmental sustainability in high-income countries [9-13]. However, low GHG emission diets do not necessarily implicate a healthy diet [14]. Consistent with previous studies the environmental benefits are largely attributable to reductions in red and processed meat, while the health benefits stem from increases in plant-based foods

[9-13]. While the optimized diets in chapter 3, resulted in substantial improvements of diets across all socio-economic subgroups, differences in dietary patterns were evident. For instance, optimal diets of lower educated individuals increased in vegetables from 150g to 159g and reduced meat from 104g to 78g in the optimal situation. While diets of higher educated individuals maintained the amounts of vegetable with 197g, and reduced meat from 78g to 57g. Despite concerns regarding potential compromises in nutritional needs (e.g. vitamin B12, iron) [15], we did not identify substantial reductions in nutrient intakes, aligning with prior research [16].

Alongside the reduction in GHG emissions, land use, acidification, and eutrophication of marine and freshwater, associated with healthier diets in **chapters 2-3**, we also identified increases in blue water use. This increase in primarily related to the consumption of plant-based foods such as fruits and unsalted nuts. While the optimal optimized diets did not fully adhere to dietary guidelines, usage of blue water substantially increased by 7-15% (**chapter 3**). Our findings align with prior research, although many studies tend to emphasize the outcomes related to GHG emissions more prominently than those of other indicators [10, 17]. A comprehensive review that explored over 200 scenarios, found that in several scenarios where meat was replaced with plant-based foods, water footprints increase [10]. It is important to note that water stress and scarcity are becoming critical issues [18], and is anticipated to worsen due to climate change and droughts [18]. This underscores the need for a nuanced approach when promoting the shift towards plant-based diets, considering the interconnected environmental impacts beyond GHG emissions.

Healthy and environmentally sustainable diets can be affordable

The affordability of healthier and more environmentally sustainable diets is a critical consideration, as underscored by the findings in **chapters 3-4**. Despite the general notion that nutritious foods are often more expensive than their less healthy counterparts (supported by **chapter 4**), our research in **chapter 3** shows that healthier and more environmentally sustainable diets are not more expensive than current diets across all socio-economic subgroups. Previous studies demonstrated the higher costs associated with healthier diets [19, 20], and while the specific costs of sustainable diets are not widely explored, modelling studies have shown the potential to improve diet quality and environmental impacts, while opting for low-costs [21, 22]. The feasibility of healthier and more environmentally sustainable diets without increasing expenses is primarily attributed to reduced spending on animal-based foods, as indicated by both previous research and our results (**chapter 3**) [17, 23, 24]. Notably, our findings suggest a shift in expenses from animal-based foods to plant-based foods, resulting in comparable net costs across all socio-economic subgroups. As diet quality is influenced by economic factors, especially for individuals with a lower socioeconomic position [25, 26], the identification of cost-neutral diets holds major importance. The affordability of alternative dietary choices plays a key role in acceptance of the dietary shift and is essential for achieving the intended health and environmental benefits [27]. This aspect often goes unnoticed in nutritional research. Nevertheless, our study emphasizes that costs should not be perceived as a barrier for the adoption of a healthy and sustainable diet.

To conclude, the first part of this thesis investigated the relationship between the healthiness, environmental sustainability, and costs of current and future diets. Healthier diets are associated with less GHG emissions, land use, acidification and eutrophication of marine and freshwater. Substantial improvements in healthiness and environmental sustainability, without affecting diet costs, can be achieved across all socio-economic subgroups. This requires modest dietary changes towards less animal-based foods and more plant-based foods. Subsequently, along with this shift towards more plant-based diets, blue water use increases.

Part II – The role of ultra-processed foods and drinks in healthy and environmentally sustainable diets

The second part of this thesis investigated the role of ultra-processed foods and drinks (UPFD) in healthy and environmentally sustainable diets. In **chapter 4**, we examined ultra-processed foods (UPF) and drinks (UPD) in Dutch diets within the DNFCS 2012-2016 for 4313 children and adults aged 1-79 y. Per 100g, UPF and UPD were associated with comparable GHG emissions, while with lower blue water use compared to unprocessed or minimally processed alternatives. Additionally, it was observed that UPF were more affordable, and UPD were less affordable than unprocessed or minimally processed foods and drinks. UPFD contributed to 29% of daily consumption, and particularly UPD consumption was high among younger age. UPFD consumption determined 61% of total energy intake, 45% of GHG emissions, 23% of blue water, and 39% of diet costs. Moreover, UPFD consumption substantially contributed to the daily sodium (72%), sugar (64%), and SFA (56%) intake, while also to dietary fibre (60%) and protein (46%) intake. With respect to health outcomes, the analyses conducted within the EPIC-NL cohort in **chapter 5**, showed a significant positive association between high UPD consumption and an increased risk of all-cause mortality by 16% (Hazard rate (HR) for highest vs lowest quartile: 1.16, 95% CI: 1.07, 1.26), and with environmental indicators (up to 7%), except for land use. In contrast, a high UPF consumption was not significantly associated with all-cause mortality (HR highest vs lowest: 1.06, 95% CI: 0.97, 1.15), and was inversely associated with environmental impacts (up to -13%). The combined effect of UPFD on mortality was comparable to the effect of UPD alone. **Chapter 6** focused on evaluating of the nutritional quality of ultra-processed plant-based foods in the out-of-home environment, with plant-based burgers as example. The findings demonstrate the multifaceted nutritional profile of ultra-processed plant-based burgers, as they are a source of protein, dietary fibre, and essential minerals, whereas they also contain high levels of energy, sodium, and (saturated) fat.

Consumption of ultra-processed foods and drinks

The widespread availability and consumption of unhealthy foods drive poor dietary choices [28, 29]. In **chapter 4-5** we showed that Dutch diets contain substantial amounts of UPFD. During the period of 1993-1997, UPFD determined approximately 30% of total energy intake (**chapter 5**), and during the period of 2012-2016, UPFD accounted for over 50% (**chapter 4**). This aligns with other studies in high-income countries [30]. The consumption of UPFD across Europe was highest among the Netherlands, together with the UK, Sweden and Germany [31]. Furthermore, evidence from **chapter 4-5** shows higher UPFD consumption among younger aged individuals and those with lower educational levels, aligning with previous studies, that consistently showed higher UPFD consumption among children and adolescents, and individuals with lower educational backgrounds [32]. The observed inverse association between age and UPFD consumption may reflect younger individuals' incline to embrace new foods and dietary habits, while older individuals may maintain their habits. Furthermore, the high consumption of UPFD may be influenced by the availability, affordability, and convenience of those foods. Acknowledging the pivotal role of the food environment in shaping dietary patterns, places responsibility on both the food industry and government.

Nutrition and health implications of ultra-processed foods and drinks

Our research shows the substantial contribution of UPFD consumption to the intake of salt, (saturated) fat, and sugar intake, as well as dietary fibre and protein, as discussed in **chapters 4-5**. This is also evident in other high-income countries [33-36], with exceptions for protein and dietary fibre. The relatively high levels of protein and dietary fibre can be attributed to the considerable amounts of bread in Dutch diets, often categorized as UPF. Suggesting that UPFD are not inherently unhealthy. Furthermore, while UPFD typically contain lower levels of micronutrients [37], high consumption can still substantially contribute to overall nutrient intake [38, 39]. Regarding the health outcomes of UPFD consumption, **chapter 5** showed that the consumption of UPD was associated with a 16% increased mortality risk. Conversely, no statistically significant association was observed for UPF, attributed to the marginal contrasts in UPF consumption between high and low groups, and the consumption of healthier UPF, as found in other research [40]. Two meta-analyses based on recent food consumption data, reported a significant 25%-29% increase in all-cause mortality risks associated with highest vs lowest UPFD consumption [41, 42]. The extent to which this risk is attributed specifically to UPD was not examined. Consistent with our findings, meta-analyses showed mortality risks of 11-14% associated with the high consumption of UPD-like foods such as artificially and sugar-sweetened beverages [41, 42]. Furthermore, our findings are supported by a large prospective cohort study from seven European countries, including the cohort from chapter 5 [40]. The study demonstrated that only certain food groups of UPFD were associated with health outcomes. For instance, artificially and sweetened-sugared beverages were positively associated with adverse health outcomes, breads and cereals showed inverse associations, and sweets and desserts, savoury snacks, plant-based alternatives, ready-to eat or heat and mixed dishes showed no associations [40]. Hence, it is plausible that the association between UPFD and mortality may be primarily driven by UPD.

While a substantial body of evidence highlights the adverse health effects associated with the consumption of UPFD, as discussed in **chapters 4-6**, the current state of evidence lacks causality, and is predominantly based on observational studies [43-47]. The understanding of the health effects of ultra-processing remains limited, prompting questions regarding the effects of food processing vs food formulations [38, 48]. Food processing and formulations are independent aspects, each having both beneficial and detrimental effects. For instance, food processing may enhance nutrient bioavailability or reduce antinutritional factors [49], but may also lead to nutrient loss or generate trans fatty acids [50]. Similarly, formulating foods through the independent addition of sugar, salt, fat, and additives such as colours and flavours [48], may prolong shelf life, but may introduce high levels of unhealthy nutritional factors [48, 51]. The absence of causal evidence linking specifically the processing of UPFD to health outcomes, coupled with the recognition that UPFD are not inherently unhealthy, has diminished the relevance of this concept. Consequently, this does not enable to draw general conclusion about UPFD. Instead, attention should be directed towards unhealthy formulated foods with elevated levels of (saturated) fat, sugar and salt. However, focusing on formulations, and for instance reformulation practices, may neglect the impact of processing on food structure, texture and its implications for digestion, absorption, and satiation [52], and therefore both (re)formulations as processing should be considered.

Environmental impact of ultra-processed foods and drinks

In **chapter 4**, we showed that the environmental impact of UPFD per 100g is multifaced and depends on the type of food and environmental indicator. To date, the quantification of the environmental impact of UPFD remains limited [53]. However, previously it was demonstrated that unhealthy foods generally have a low GHG emission [12]. In general, the primary production (until farmgate), determines 80% of the environmental impacts [54]. Conversely, stages such as processing, transportation, packaging, and distribution play a more significant role in determining the environmental impact of UPFD [55, 56]. This can be attributed to aspects such as the type of ingredients (e.g. soy, palm oils) , energy-intensive processing methods (e.g. remove dietary fibre, extrusion), excessive packaging, long transportation chains, or storage methods (e.g. frozen, cooled) [53, 57-59]. Furthermore, **chapter 4** showed that UPFD consumption contributed with a quart to almost half of daily environmental impacts. Previous studies that estimated the environmental impact of UPFD consumption, attributed significant effects [60-63]. For instance, in an Australian study UPFD consumption contributed with approximately one-third to dietary environmental impacts [60]. Similarly, in Brazil, the contribution of UPFD to the environmental impact had tripled over the past decades, driven by increased availability and consumption of UPFD compared to decades ago [63]. Additionally, **in chapter 5**, we found that high UPD consumption was associated with higher environmental impacts, whereas high UPF consumption was associated with lower environmental impacts. This suggest that UPFD can be less healthy than foods they replace but may have a lower environmental impact (and costs) (**chapter 4**). Studies from Brazil and France reported a positive association between high UPFD consumption and environmental impacts [61, 62]. However, these associations disappeared or reversed when adjusted for energy intake [61, 62], aligning with our conclusion. The findings imply that the environmental impact is not solely attributable to UPFD but is also influenced by factors such as energy intake and the amount and type of other foods in diets (e.g. meat). The link between UPFD and overconsumption underscores that UPFD lead to avoidable environmental impacts [46, 64]. Therefore, prioritizing a focus on balancing energy intake in relation to requirements, and healthy and environmentally sustainable foods, rather than fixating on processed versus unprocessed foods, is essential.

Costs of UPFD

Chapter 4 highlights that UPF were generally cheaper than unprocessed and minimally processed foods, whereas UPD were approximately twice as expensive as unprocessed and minimally processed beverages. Previous research has demonstrated that UPFD tend to be more affordable than less processed, and more nutritious foods [65, 66]. As discussed in Part I, the higher costs associated with healthier foods may function as barrier, hindering individuals from adopting healthier diets. Contrarily, the affordability of unhealthy foods contributes to unhealthy dietary habits. This has implications for public health, particularly for individuals with lower socioeconomic positions [67-69]. The cost-effective production methods employed by the food industry result in accessible, affordable and convenient though generally unhealthy foods for consumers and substantial profits for the industry [58]. Consequently, the food industry has a vested interest in promoting and encouraging the widespread consumption of unhealthy foods, as evidenced by recent studies [70]. This underscores the competing interest between the food industry and governmental entities. Regrettably, viable profit models for promoting healthy and sustainable dietary habits are currently not in place, posing a challenge in shifting towards healthier and more sustainable food choices.

To conclude, the second part of this thesis focused on the role of UPFD in healthy and environmentally sustainable diets and emphasized the need for critical evaluation of their nutritional profile, environmental impact, and costs. Reducing the consumption of UPFD, particularly UPD, supports the reduction in (saturated) fat, sugar, and salt intakes, thereby improving diet quality, and reduces mortality rates and environmental impacts. However, not all UPF are inherently unhealthy; some have a low environmental impact and are also affordable. Therefore, initiatives promoting the substitution of UPF require mindful consideration its definition, environmental sustainability and economic factors, as it may have unintended effects. Furthermore, while the availability and consumption of ultra-processed plant-based foods may be a step towards a more sustainable diet, they do not necessarily support healthy dietary habits. Instead, efforts should be directed towards reduction of unhealthy formulated foods, characterized by high levels of (saturated) fat, sugar, and salt.

Part III – Enabling healthy and environmentally sustainable food choices in a retail food environment

In addition to the evidence presented in **chapters 2 to 6** of this thesis, it is important to consider how the needed diet transition can effectively be addressed through policies. In **chapter 7** the effectiveness of different policy measures on meat purchases was investigated in an RCT conducted in a virtual supermarket. Participants were exposed to either a control scenario, a 30% price increase on meat, an informative nudge or a combination of the price increase and informative nudge. Their combination led to a decrease of -386g (95%CI: -579, -193) meat purchases per household per week, which was equal to -36% or -23g per person per day. A price increase alone had a lesser, albeit not statistically significant, impact on meat purchases (-144 g (95%CI: -331, 43)), and the informative nudge alone did not affect meat purchases.

Implementation of effective measures

In **chapter 7** we demonstrated the potential of a combination policy, including a fiscal measure, to reduce meat purchases, contributing to both health and the environment. Although one intervention study specifically examined the effects of price increments on meat purchases [71], numerous modelling studies consistently support the potential impact of fiscal measures on health, environmental impact, and revenues [72]. In the Netherlands, a 30% price incremental on meat over 30 years can avert among others 5,550 to 29,398 type 2 diabetes cases per year, reduce environmental impacts by 6%, and resulted in overall benefits between €4,000-12,300 million [73]. In addition, previous research has consistently shown a responsiveness to price increments of meat, showing that a 10% price increase resulted in a decrease ranging between 4.4% to 8.7% [74-76].

Nevertheless, literature in the nutrition and health domain suggests that prevailing evidence is insufficient to draw definitive conclusions regarding the impact of price increments on meat purchases [77, 78]. This contrasts with economic theory and evidence from consumer economics, substantiating that an increased price of a commodity typically results in a decline in its purchase by consumers [79]. Therefore, it would be unreasonable to pose that meat consumption would remain unaffected to the influence of price increases [79]. Despite the widespread scientific consensus on the need, there is a noticeable reluctance in political circles to effectively address meat consumption as current efforts are mainly informative [80]. However, evidence shows that these long-used and predominantly informational policies such as campaigns or food-based dietary guidelines, may not always prove effective [80], and have limited effect on behaviour change (e.g. **chapter 7**) [81, 82]. While fiscal measures may be perceived as patronizing, a substantial body of evidence has demonstrated their effectiveness [83-85], and cost-effectiveness [84], particularly within the context of grocery shopping [86]. In contrast to other sectors such as health and fossil fuels where efforts are more stringent [72], the lack of effective policies focusing on environmentally sustainable food choices may be attributed to conflicting interests of actors, such as economic interests, and the electoral importance of the agri-food sector [87, 88].

Coherent policy mixture

The evidence from **chapter 7** showed that the effect of the fiscal measure was enhanced by the informative nudge, proving the most effective strategy for achieving dietary change. This aligns with prior research showing that mixtures of policies are essential to achieve desired health and environmental benefits [89, 90]. Previous studies show that a combination of informative and administrative policies, complemented by fiscal measures, prove effective in dietary change [83-85, 91, 92]. Drawing from practice-based experience and scientific research, it is evident that fiscal measures are notably effective [91, 93]. Additional strategies can reinforce the effects [91, 93], even though they may be more time-consuming, e.g. providing information, and educational programs. In this context, fiscal measures function as price signals [72], while informational or behavioural measure enhance consumer awareness, acceptance, or willingness to embrace dietary change [89]. The transformative power of measures often necessitates a gradual shift of social norms [94]. This was also observed in health campaigns to reduce tobacco and alcohol consumption [83, 93]. Such experiences offer valuable lessons for shaping effective strategies for dietary change, underscoring the need for a multifaceted approach. Furthermore, they demonstrated that implementing policies aiming to change behaviours takes time. This emphasizes that postponing the implementation of effective measures is detrimental given the urgent need to enhance both the environment and public health.

To conclude, the third part of this thesis delved into the implementation of dietary changes through policies. To facilitate the shift of consumers' food choices towards healthy and sustainable diets, a coherent mixture of policies, including fiscal measures, are likely most effective in achieving dietary change.

Methodological considerations

In **chapters 2 to 7**, specific strengths and limitations of the research in this thesis have been addressed. This section describes the methodological considerations most relevant to the overall thesis.

Assessment of sustainability

In **chapters 2 to 5, and 7,** the environmental impact was determined for single environmental problems and was assessed by life-cycle assessments (LCA) for generic foods, which have their limitations. Firstly, the use of so-called midpoint indicators assessed isolated environmental problems, such as climate change (GHG emissions), water consumption, and land use, and can overlook the intended endpoints: effect on biodiversity loss, resource depletion, and human health. Converting midpoints to endpoints could simplify the interpretation of the inventory results of LCAs [95]. This allows for a more nuanced and holistic evaluation of the environmental implications, albeit with an acknowledgment of increased uncertainty compared to the midpoint characterization [95]. Furthermore, to achieve a comprehensive understanding of sustainability, it is crucial to consider a wide range of factors such as pesticide and chemical use, soil health, fish stocks, fair trade, animal welfare, and social and economic impacts. Accurate and reliable data on these factors is currently lacking, though in development. Secondly, the accuracy and reliability of LCAs heavily depend on the quality and availability of data. For instance, more recent large-scale data is not available thus water consumption factors in this thesis are from 2011 [96], though it is likely that both water use and data quality has improved over the past decade. Furthermore, the LCAs used an attributional approach, linking environmental impact to current practices. However, for studying diet shifts, consequential approaches prove more insightful by revealing the wider environmental consequences of changes in the food chain [97]. At last, LCA modelling involves making many assumptions regarding system boundaries, allocation methods e.g. monetary value of by-products, timeframe e.g. LCAs are snapshots and ignore changes in time, introducing uncertainties into the assessment that also limit comparability of different study results.

Food classifications

To investigate associations between dietary patterns and diet quality, environmental impact, food costs, or degree of processing, foods need to be classified in groups. Accurate food classification forms the basis for understanding dietary patterns and their association with health outcomes. For instance, foods are often classified according to the degree of food processing, however there is no universally agreed definition of ultra-processed foods nor a classification system. Though the NOVA classification is widely applied, it is challenging to apply, as dietary consumption surveys are often not designed to assess UPFD specifically [98]. This introduces risk of misclassification and complicates the distinction of processing effects from other dietary factors [99, 100]. Furthermore, concerns arise about the rational and potential health equity implications, as costly artisanal foods are considered healthier according to the classification [98]. Establishing clear and scientifically rigorous criteria for classifying foods is crucial, relying on well-defined characteristics. Nutrient profiling systems, by evaluating both beneficial and potentially harmful components, can provide a comprehensive assessment of the nutritional quality of foods, extending beyond processing levels. Utilizing food ingredient lists to determine processing levels and integrating various classification schemes, considering nutrient composition and culinary use may offer a more nuanced understanding of foods. Finally, such classifications focus on food items. Nevertheless, it is important to acknowledge the interactions between different foods and their cumulative effects on health outcomes, providing a broader perspective on dietary habits and their associations with health.

Policy implications

Current dietary habits have considerable detrimental effects on the environment and public health, as they are a major driver of climate change, biodiversity loss, environmental degradation, and contribute significantly to poor diet quality, adverse health outcomes, morbidity and mortality, and substantial health care costs [101]. Despite health and environmental sustainable aspects of dietary choices often align, and healthy, sustainable diets can be cost neutral, current Dutch diets are too low in plant-based foods, whereas too high in animal-based foods and energy, (saturated) fat, sugar, and salt dense UPFD with avoidable nutritional and environmental impacts (**chapters 2-4**). Recognizing its legal mandate to safeguard both public health and the environment, the government is responsible to implement measures that address the detrimental effects of food systems. The government has a broad array of policy instruments available, including information-based, administrative, fiscal, and behavioural strategies [102], which vary in intrusiveness and effectiveness [103]. The ladder of intervention compares the intrusiveness of measures, with the initial step involving the least intrusive measures such as do nothing or monitor, and progressing towards more intrusive measures such as restrict or eliminate choice (**Table 1**) [103]. Substantive evidence indicates that measures higher on the ladder are more effective [91, 104-108] compared to those lower on the ladder (e.g. **chapter 7**) [80-82]. Yet, existing policies predominantly rely on informative instruments for consumers [5, 6, 109]. It is essential to note that food choices are habitual, frequently unfold subconsciously and are influenced by food environments [28, 29], which largely promote unhealthy and environmentally unsustainable foods [110]. Therefore, changing food environments emerges as a pivotal strategy to achieve substantial improvements in dietary choices and overall diet quality [111-116]. Consequently, safeguarding both public health and the environment necessitates a policy shift oriented to food systems rather than to consumers and individual dietary change. This transformative shift toward healthy and sustainable diets, acknowledges the multifaceted considerations of health, environment, affordability, and effective policy implementation, supported by recent research findings.

Before delving into the specific policy implications that emerge from our findings, which are categorized according to the ladder of intervention (**Table 1**), several key policy conditions are addressed.

Policy conditions and principles

While not explicitly studied in this thesis, achieving the intended beneficial effects of the diet transition requires a comprehensive strategy that extends beyond ministerial boundaries, and encompasses evidence-based policies with measurable objectives, collaboration, prioritization, and the allocation of sufficient financial resources. Firstly, it is crucial to recognize that current policies are often tailored to fit within the typical four-year governmental cycles. However, changing dietary habits are inherently time-intensive, necessitating a long-term strategy that extends beyond these conventional cycles. Secondly, the existing policies suffer from fragmentation, with responsibilities divided among different ministries: health matters are overseen by the Ministry of Health, Welfare, and Sport (VWS); environmental concerns are within the jurisdiction of the Ministry of Agriculture, Nature, and Food Quality (LNV); while the profit model is managed by the Ministry of Economic Affairs and Climate Policy (EZ). Furthermore, aligning with EU-wide policies becomes crucial in transforming food systems within a broader context [72]. Thirdly, historical policy strategies lacked measurable objectives, and current agendas lack effective instruments [109]. Measurable objectives, and its systematic monitoring and periodically evaluation, are essential to assess efficacy and identify unintended consequences. A mixture of evidence-based policies may include both hard and soft instruments, which are interconnected and complementary [117]. Fourthly, current activities related to policy implementation and monitoring are conducted by entities that operate independently, while collaborative efforts among these entities acknowledge their collective potential and foster the enhancement of common goals. Finally, increased government commitment, both in budgetary allocation and prioritization holds significant economic and societal consequences for governments. In 2019, healthcare expenditures in the Netherlands exceeded 100 billion euros, whereas only 2.2 billion euros were allocated to prevention [118]. Additionally, an annually 12 million euro supplement to a 20 million budget for food system sustainability may double the four-year budget [109], this contrasts with the annual industry spendings of 1.6-1.7 billion euros on the promotion of predominantly unhealthy foods [119].

Table 1. Examples of policies to improve the environment and public health according to the level of intrusiveness.

Greater levels of intrusiveness →	Eliminate choice	• Removal of unhealthy nutritional factors, unsustainable ingredients from foods, or entire foods
	Restrict choice	• Prohibit (imported) foods from regions where production significantly damages the environment
	Guide choice through disincentives	• Disincentivize unhealthy and (environmentally) unsustainable foods by making them less affordable, by e.g. carbon tax, nutritional profile system tax, eco-label tax, internalizing external costs. (chapter 3,4,7)
	Guide choice through incentives	• Incentivize healthy and (environmentally) sustainable foods by making them more affordable, by e.g. subsidizing or application of lower VAT rates on specific food groups, nutritional profile systems. (chapter 3,4,7)
	Guide choice through changing the defaults	• Public procurement and standards opting for healthy and sustainable foods. • Change defaults in out-of-home settings by making healthy and sustainable choices the standard. • Reduce portion sizes in supermarkets and out-of-home settings.
	Enable choice	• Increase the availability of healthy and (environmentally) sustainable foods, by nutritional profile systems or eco-labelling. • Minimize (or prohibit) the availability of imported foods from regions where production significantly damages the environment. • Mandatory food reformulation on (saturated) fat, sugar, salt and animal-based ingredients and unsustainable ingredients. • Increase promotion of healthy and (environmentally) sustainable foods, by regulations on marketing, price promotions and advertisement. (chapter 2-5)
	Provide information	• Better information for informed choice by providing information on nutritional and environmental aspects. • Better information for informed choice by legislation of sustainability claims. (chapter 2-6)
	Do noting or monitor	• Monitor policy objectives and effect of policies on food consumption, demand and supply, and unintended side-effects. • Research on consequential LCAs, integrative nutritional and environmental label; innovations; strengthening and accelerating the implementation of effective policy actions; citizen science and consumer acceptance on policy implications. (chapter 2-7)

Make healthy and sustainable foods more affordable for consumers

While adopting a healthier, environmentally sustainable diet can be cost-neutral, high prices of nutritious foods and the affordability of unhealthy alternatives (**chapters 3-4**) may hinder consumers in making a dietary transition. Fiscal instruments, which either encourage of discourage specific food purchases, prove effective in shaping dietary choices and have the potential to enhance the adoption of healthy and sustainable diets [91, 104-108]. Research has shown that lowering the price of healthy foods leads to increased sales and availability [91, 104-107]. This can be achieved through measures such as subsidizing nutritious foods identified by nutritional profile systems or applying reduced VAT rates. Furthermore, these instruments may also ensure the affordability of organic foods, as their availability is mandated to increase by the government but are typically more expensive than conventional alternatives [109]. On the other hand, research has shown that increasing the price of foods leads to decreased demand, sales, and consumption levels (**chapter 7**) [75, 91, 104, 120, 121]. In 2024, the Netherlands introduces a tax on sugar-sweetened beverages (SSB); however comparable environmentally focused instruments are lacking. Moreover, fiscal instruments encounter resistance due to difficulties in categorizing taxable foods [122], unclear substitution effects [123], low acceptance [90], and disproportionate impact on low-income households, although these households stand to benefit the most due to their generally poorer diet quality and healthiness [124]. Adopting comprehensive fiscal instruments, including mechanisms such as a carbon tax, nutrient profiling system tax or internalizing externalities, and combining incentives and disincentives, may decrease these objections. Despite the acknowledged potential of fiscal instruments, as recognized by the scientific community, decisions concerning the implementation of such instruments and their economic burden represent political choices, complicated by diverse ministry responsibilities.

Make healthy and sustainable foods the default

Promoting healthy and sustainable dietary choices involves implementing food procurements, establishing defaults to shape decisions, fostering awareness and influencing social norms [77, 125]. Enforcing food procurement regulations and standards, especially in public settings such as government offices, school, childcare facilities, hospitals and canteens, contributes to enhancing diet quality through positive shifts in food purchasing and consumption [125]. This could also contribute to more sustainable food choices. Moreover, altering defaults has proven to be an impactful measures [77]. Research indicates that modifying defaults can be effective [126]. For instance, reducing portion sizes of meat in restaurants and supermarkets has been demonstrated to lower meat consumption [77].

Increase the availability of health and sustainable foods

Current consumption patterns are far from healthy nor sustainable (**chapters 2-5**). Dietary choices are significantly influenced by food environments, including the predominantly availability of foods that are not recommended [28, 29]. In the Netherlands, a substantial portion of available foods – ranging from 70% to 80% in supermarket and 91% in the out-of-home environment- are considered unhealthy [127, 128]. Increasing the availability of healthy and sustainable food options improves dietary choices and diets [112]. An effective strategy to achieve this is through mandatory reformulation, with a focus on reducing components such as salt, (saturated) fat, and sugar, and unsustainable ingredients such as animal-based foods and soy or palm fats derived from unsustainable sources. Currently, food reformulation primarily targets nutrients on a voluntary basis progresses slowly [129]. The adoption of mandatory reformulation can consistently achieve larger enhancements in the nutritional quality of foods, leading to subsequent improvements in diets and well-being [130]. Another approach to increase the availability of recommended foods involves regulating foods based on nutrient profile systems, or minimizing or prohibit imported foods from regions where production significantly damages the environment. For example, nuts and fruits from water-scarce areas or fish from unsustainable fishing practices. These regulations extend the EU Deforestation Regulation, emphasizing deforestation-free products [131].

Increase the promotion of healthy and sustainable foods

Dietary choices are significantly influenced by the marketing, price promotions and advertisement of foods [28, 29]. Currently, promotion efforts are predominantly focused on unhealthy and unsustainable foods [119], which are highly present in Dutch diets (**chapter 2-5**). Increasing the promotion of healthy and sustainable food options may improve dietary choices and diets [112]. Furthermore, a voluntary code of conduct on the marketing of unhealthy foods exists; however research suggest that these guidelines are often insufficient, non-adherent, or lack transparency [90, 132-134].

Better information for informed food choices by food labelling

Public campaigns and food labelling strategies serve as means to inform and empower consumers in making informed food choices. These interventions may be ineffective in isolation but could enhance the impact of fiscal measures (e.g. **chapter 7**), nonetheless, it represents a significant improvement compared to the current state. The effect of such interventions may not be consistently effective across all individuals [135, 136], and as we found differences in diet quality across socio-economic subgroups (**chapter 3**), tailored efforts could aim to inform specific subgroups. In 2024, the Netherlands will introduce a voluntary front-of-pack (FOP) Nutri-Score. This system aims to provide consumers with information about the nutritional content of products, empowering them to make informed and healthier choices. FOP labels also have the potential to provide insight into environmental sustainability, such as eco-labelling [137]. However, the absence of well-established, and standardized methods poses a challenge [138], and consumers generally have low understanding of such labels [90, 139]. Ongoing efforts are in place to develop harmonized methodologies to assess environmental impacts, utilizing 16 midpoint indicators derived from LCAs, with applicability down to specific product or brand levels [140]. Though it should be noted that displaying both a nutritional and environmental oriented FOP label may be too burdensome for consumers [141]. Beyond the concept of true costs accounting, there is a lack of initiatives on developing FOP labelling strategies that simultaneously emphasize nutritional and sustainability aspects.

Better information for informed food choices by legislation of sustainability claims

Ultra-processed plant-based foods may have poor nutritional quality as demonstrated in our study (**chapter 6**). However, there is a tendency to label ultra-processed plant-based foods as 'plant-based' [142]. Plant-based is not equal to healthy nor environmentally sustainable, and therefore such information may lead to misconceptions by consumers [142]. To provide consumers with reliable information on sustainability concerns in addition to nutritional labels, sustainability claims may be regulated based on legal frameworks. However, the current state of EU legislation lacks a standardized approach to assess the environmental impacts and a framework for sustainability claims. While there are existing legal definitions and pre-market authorization systems for nutrition and health claims, no harmonized approach or definition for environmental or green claims exists.

Update of the national dietary guidelines

Dutch national dietary guidelines already promote healthy diets and include to a limited extend sustainability aspects [8]. Higher adherence to dietary guidelines is associated with less environmental impacts (except for blue water use) (**chapters 2-3**), while still exceed the planetary boundaries' targets [101]. By including sustainability objectives in the dietary guidelines, such as the planetary boundaries [101], guidelines simultaneously promote healthy and sustainable diet, but may incur in large deviations compared to current guidelines and diets. This may pose significant challenges for consumers to adhere to, making it crucial for food environments to support these choices through availability, accessibility, and affordability of food.

More specific key points derived from this thesis include discriminating and dissemination of environmental impacts, promotion of healthy plant-based protein alternatives, setting consumption ranges to discourage overconsumption and discouraging the consumption of foods high in (saturated) fat, sugar or salt. Large variation in environmental impact between and within food groups (**chapter 2-5**) calls for discriminating between foods with high and low environmental impact. Since both health and environmental considerations motivate individuals to make better food choices [143], this may opt for fruits and nuts lower in blue water usage e.g., local apples over oranges and ground nuts over Californian almonds. Furthermore, plant-based protein alternatives, such as ultra-processed plant-based foods are not always healthy (**chapter 6**). The promotion of healthy plant-based protein sources (e.g. legumes, nuts, tofu) may prevent the shift to unhealthy plant-based foods. In addition, energy intake is positively associated with higher environmental impacts (**chapter 2**). Setting consumption ranges for all food groups establishes new norms and may discourage overconsumption. At last, UPFD are multifaceted in terms of nutritional quality, environmental impact and costs (**chapters 4-5**). Therefore, efforts should be redirected towards the discouragement of unhealthy formulated foods, characterized by high levels of (saturated) fat, sugar, and salt.

Monitoring effects of the diet transition

The transition to a healthier and more sustainable has trade-offs, including but not limited to affordability issues and the increase demand for blue water use due to increased plant-based food consumption (**chapters 2-6**). Monitoring the shifts in supply and demand, as well as the substitution effects, and assessing the consequences for instance on irrigation water demands, long-term health effects of (processed) plant-based foods, nutrient intake, and food costs and affordability, is needed to provide insight in the beneficial and adverse effects of the diet transition. Monitoring and policy evaluations may increase transparency and awareness among consumers and offer insight into achieving predefined objectives and unintended consequences.

Future steps

Future steps encompass the continuation of fundamental research, and research related to the implementation and acceleration of effective policies. Fundamental research related to healthy and sustainable diets, food systems, and innovations, along with their interrelatedness and data requirements, remain an ongoing area of investigation. These research efforts may focus among others on harmonized approaches to assess and disseminate environmental impacts, integrative nutritional and environmental labels, consequential LCAs and, food and diet affordability across socio-economic positions. At the same time a large body of evidence substantiates the justification for formulating and implementing policy instruments. There is a broad scientific consensus that current food systems are unsustainable and unhealthy [12, 101]. They are a major driver of climate change, biodiversity loss and environmental degradation, and contribute significantly to poor diet quality, adverse health outcomes, morbidity and mortality, and health care costs [101]. To simultaneously improve the environment and public health a redesign of current food systems is urgently needed. Furthermore, a well-defined understanding of the policy instruments for addressing current challenges is warranted [111-116]. From this perspective, the primary emphasis of research should be on innovative research and strengthening and accelerating the implementation of effectives policy actions, rather than repetition of end-of-pipeline research efforts that lead to postponement of the required policy decisions.

Overall conclusions

The evidence presented in this thesis supports that adopting a healthier and in general more environmentally sustainable diet, including more plant-based foods and less animal-based foods, is feasible and can be cost-neutral across all socio-economic subgroups, although blue water use increases. Furthermore, diet quality and environmental sustainability can be improved by reducing the (over)consumption of some ultra-processed foods and drinks, but this requires mindful consideration of its definition, and the increased environmental impacts and diet costs of alternatives. This diet transition would provide significant benefits to both public health and the environment.

It is a key governmental responsibility to prioritize preventative public health and the environment. Facilitating consumers to make healthy and sustainable dietary choices requires increased government involvement, including a coherent policy mixture, with hard and soft measures, targeting entire food systems rather than individual consumers. It is inevitable that such measures intervene with interests of the agri-food industry and affect consumers. However, without changing the food environment the diet transition will not gain traction. Achieving the intended beneficial effects requires a comprehensive strategy that extends beyond ministerial boundaries, and encompasses evidence-based policies with measurable objectives, collaboration, prioritization, and the allocation of sufficient financial resources.

To facilitate the diet shift, fiscal instruments could make healthy and sustainable foods more affordable, and unhealthy and unsustainable foods less affordable. Although proven ineffective in isolation, informative interventions such as food labelling and updated national dietary guidelines could enhance the impact of such fiscal measures. With respect to food choices, healthy and sustainable diets could be enabled by regulating the availability and promotion (marketing, price promotions, advertisement) of foods, and by legislation of sustainability claims, while food quality can be improved by mandatory reformulation. During this system transition, continuous monitoring of developments, changes in food consumption, supply and demand is needed to identify and manage unintended side effects of the implemented policies whenever they emerge.

Adopting a healthier, environmentally sustainable, and cost-neutral diet in the Netherlands is urgently needed and feasible. It does, however, require a fundamental transformation of the food system, and therefore critically depends on a clearcut political will to implement effective policy instruments.

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Appendices

Summary

Current dietary habits are a major driver of climate change, biodiversity loss, environmental degradation, and contribute significantly to poor diet quality, adverse health outcomes, and substantial health care costs. The average Dutch diet, characterized by excessive caloric intake, high levels of salt, saturated fat, and sugar, high red and processed meat consumption, and low consumption of whole grains, vegetables, legumes, fruit, and nuts, is not healthy nor sustainable, and contributes substantially to the detrimental effect on both the environment and public health. In light of these challenges, this thesis focuses on the associations between dietary choices, health, environmental sustainability, and economic factors within Dutch diets. It also emphasizes the role of ultra-processed foods and drinks (UPFD) in this context. The research aims to contribute to scientific evidence that can underpin effective governmental policies to promote healthier and more environmentally sustainable diets while considering economic implications.

Part I - Health, environmental sustainability, and costs of current and future diets

The first part of this thesis studied the healthiness, environmental sustainability, and costs of current and future diets. Chapter 2 evaluated the dietary environmental impacts and its association with healthiness of the average diet derived from the Dutch national food consumption survey (DNFCS) 2012-2016. The average daily diet contributed 5.0 kg CO_2-equivalents to greenhouse gas (GHG) emissions and 0.14 m^3 to consumptive blue water use (irrigation water). Meat, dairy, and non-alcoholic beverages contributed more than half of daily GHG emissions, while non-alcoholic beverages, fruits, and meat contributed most to usage of blue water. The Dutch Healthy Diet Index 2015 (DHD15) was used to assess adherence to national dietary guidelines. The results demonstrated that healthier diets were associated with less GHG emissions, but with higher usage of blue water. While health and environmental sustainability often align, higher consumption of plant-based foods such as fruits and nuts may induce increased blue water usage. Chapter 3 investigated how dietary patterns can be improved among adults with different socio-economic backgrounds, and how these changes might affect the costs of their diets. In a modelling exercise, current diets of adults (DNFCS 2019-2021) were optimized by making linear combinations of existing diets within socio-economic subgroups. This optimization aimed to minimize GHG emissions and maximize adherence to the dietary guidelines (DHD15), along with constraints to keep dietary change close to current consumption. The optimal optimized diets across all socio-economic subgroups, contained modest increases of plant-based foods, while less dairy and red and processed meat, and had a 19-24% lower GHG emission, and a 52-56% improvement of adherence to dietary guidelines. The diet costs for the optimized diets were similar to costs of current diets across all

socio-economic subgroups. Therefore, although healthy foods are often more expensive, this study showed that costs may not be a barrier for the adoption of a more healthy and environmentally sustainable diet across all socio-economic subgroups. Based on our findings and supported by previous findings, we conclude in chapter 8 that healthier diets are associated with less GHG emissions, land use, acidification, and eutrophication of marine and freshwater, but with increased usage of blue water. Substantial improvements in healthiness and environmental sustainability can be achieved across all socio-economic subgroups through modest dietary changes towards more plant-based diets, without affecting diet costs.

Part II – The role of ultra-processed foods and drinks in healthy and environmentally sustainable diets

The second part of this thesis investigated the role of ultra-processed foods (UPF) and drinks (UPD) (UPFD) in healthy and environmentally sustainable diets. Chapter 4 evaluated the nutritional quality, environmental impact, and cost of UPF and UPD in daily diets (DNFCS 2012-2016) of adults and children. The environmental impacts of UPFD were multifaceted, as per 100g UPF and UPD were associated with similar GHG emissions, but with lower blue water use compared to unprocessed or minimally processed alternatives. Furthermore, UPF were more affordable, whereas UPD were less affordable than unprocessed or minimally processed foods and drinks. UPFD played a significant role in daily food consumption and contributed 61% to total energy intake, 45% of GHG emissions, 23% of blue water, and 39% of food expenses. Its consumption contributed substantially to the daily intake of sodium (72%), sugar (64%), and SFA (56%), as well as to dietary fibre (60%) and protein (46%) intakes. In chapter 5 the association between levels of UPFD, UPF, and UPD consumption and diet-related environmental impacts and all-cause mortality was assessed. The analyses conducted within the EPIC-NL cohort, showed a significant positive association between high UPD consumption and an increased risk of all-cause mortality by 16%, and with environmental indicators (up to 7%), except for land use. In contrast, a high UPF consumption was not significantly associated with all-cause mortality but was inversely associated with environmental impacts (up to -13%). Therefore, reducing consumption of UPFD, particularly UPD, would be beneficial to health, the environment, and diet costs. However, substituting UPF with less processed alternatives may Increase environmental impacts and diet costs. Chapter 6 focused on evaluating of the nutritional quality of ultra-processed plant-based foods, with plant-based burgers as example. The findings demonstrate the multifaceted nutritional profile of ultra-processed plant-based burgers, as they are a source of protein, dietary fibre, and essential minerals, whereas they also contain high levels of energy, sodium, (saturated) fat. Thus, while the availability and consumption of ultra-processed plant-based foods may be a step towards a more sustainable diet, they do not necessarily support healthy dietary habits. Based on our findings and supported by existing evidence, we conclude in chapter 8 that reducing the consumption of UPFD, particularly UPD, supports the reduction in (saturated) fat, sugar, and salt intakes, thereby improving diet quality, and reduces mortality rates and environmental impacts. However, not all UPF are inherently unhealthy; some have a low environmental impact and are also affordable. Therefore, initiatives promoting the substitution of UPF require mindful consideration of its environmental sustainability, and economic factors, as it may have unintended effects. Instead, efforts should be directed towards reduction of unhealthy formulated foods, characterized by high levels of (saturated) fat, sugar, and salt.

Part III - Enabling healthy and environmentally sustainable food choices in a retail food environment

In the third part of this thesis, the effectiveness of different policy measures on meat purchases in a virtual supermarket was investigated in a randomized controlled trial (RCT), presented in chapter 7. Participants were exposed to either a control scenario, a 30% price increase on meat, an informative nudge, or a combination of the price increase and informative nudge. The combination condition led to a decrease of -386g (95%CI: -579, -193) meat purchases per household per week, which was equal to -36% or -23g per person per day. The price increase alone had a lesser, albeit not statistically significant impact on meat purchases (-144g (95%CI: -331, 43)), and the information nudge alone did not affect meat purchases. The implementation of fiscal measures, in combination with information on the rationale and purpose of fiscal measures, might significantly reduce meat purchases. Based on our findings and supported by previous studies, we conclude in chapter 8 that to facilitate the shift of consumers' food choices towards healthy and sustainable diets, a coherent mixture of policies, including fiscal measures, are likely most effective in achieving dietary change.

General discussion

Chapter 8 provides a contextualization of food systems to broaden the perspective, summarizes and reflects on the main findings, and addresses methodological considerations, implications for policy and future steps.

Despite governmental responsibilities and commitments, the current landscape lacks effective policies aimed at improving public health and safeguarding the planet. Evidence from this thesis shows that adopting a healthier and more environmentally sustainable diet, including more plant-based foods and less animal-based foods, is feasible and can be cost-neutral across all socio-economic subgroups, although blue water use increases. Furthermore, diet quality and environmental sustainability can be improved by reducing the (over)consumption of some ultra-processed foods and drinks, but requires mindful consideration of environmental sustainability and economic factors, when substituted. This diet shift would provide significant benefits to both public health and the environment. Despite certain inherent methodological considerations, our findings support the urgent need for changes in food systems. In addition to the robust evidence, a well-defined understanding of the policy instruments for addressing current challenges is warranted.

It is a key governmental responsibility to prioritize preventative public health and the environment. Facilitating consumers to make healthy and sustainable dietary choices requires increased government involvement, including a coherent policy mixture, with hard and soft measures, targeting key food system actors rather than individual consumers. It is inevitable that such measures intervene with interests of the agri-food industry and affect consumers. However, without changing the food environment the diet transition will not gain traction. Achieving the intended beneficial effects of the diet transition requires a comprehensive strategy that extends beyond ministerial boundaries, and encompasses evidence-based policies with measurable objectives, collaboration, prioritization, and the allocation of sufficient financial resources.

To facilitate the diet shift, fiscal instruments could make healthy and sustainable foods more affordable, and unhealthy and unsustainable foods less affordable. Although proven ineffective in isolation, informative interventions such as food labelling and updated national dietary guidelines could enhance the impact of such fiscal measures. With respect to food choices, healthy and sustainable diets could be enabled by regulating the availability and promotion (marketing, price promotions, advertisement) of foods, and by legislation of sustainability claims, while food quality could be improved by mandatory reformulation. During this system transition, continuous monitoring of developments, changes in food consumption, supply, and demand is needed to identify and manage unintended side effects of the implemented policies whenever they emerge.

Adopting a healthier, environmentally sustainable, and cost-neutral diet in the Netherlands is urgently needed and feasible. It does, however, require a fundamental transformation of the food system, and therefore critically depends on a clearcut political will to implement effective policy instruments.

Samenvatting

Algemene introductie

Huidige voedingsgewoonten spelen een grote rol in klimaatverandering, biodiversiteitsverlies en milieudegradatie. Ook dragen ze aanzienlijk bij aan een ongezonde leefstijl, nadelige gezondheidseffecten en hoge zorgkosten. Het gemiddelde Nederlandse voedingspatroon wordt gekenmerkt door een overmatige calorie-inname, hoge zout-, verzadigd vet- en suikerinname, te veel rood en bewerkt vlees, terwijl de consumptie van volkoren granen, groenten, peulvruchten, fruit en noten onvoldoende is. Dit patroon is niet gezond noch duurzaam en draagt aanzienlijk bij aan schadelijke effecten op zowel het milieu als de volksgezondheid. In het kader van deze uitdaging richt deze thesis zich op de verbanden tussen voedselkeuzes, gezondheid, duurzaamheid en economische factoren van Nederlandse voedingspatronen. De nadruk ligt ook op de rol van sterk bewerkte voedingsmiddelen en dranken (UPFD) in deze context. Het doel van deze thesis is bij te dragen aan wetenschappelijk bewijs dat effectief overheidsbeleid kan ondersteunen om gezondere en duurzamere eetpatronen te bevorderen, met inachtneming van economische implicaties.

Deel I - Gezondheid, milieubelasting en kosten van huidige en toekomstige voedingspatronen

Het eerste deel van deze thesis beschrijft de gezondheid, milieubelasting en kosten van huidige en potentieel toekomstige voedingspatronen. In hoofdstuk 2 werd de milieubelasting van het dagelijkse voedingspatroon en de associatie met gezondheid geëvalueerd, op basis van gegevens uit de Nederlandse voedselconsumptiepeiling (VCP) 2012-2016. Het dagelijkse voedingspatroon 5,0 kg CO_2-equivalenten bij aan de uitstoot van broeikasgassen en droeg gemiddeld met 0,14 m^3 aan het blauw waterverbruik (irrigatiewater). Vlees, zuivel en niet-alcoholische dranken waren verantwoordelijk voor meer dan de helft van de dagelijkse broeikasgasuitstoot, terwijl niet-alcoholische dranken, fruit en vlees de belangrijkste bijdragers waren aan het verbruik van blauw water. De Nederlandse index voor gezonde voeding 2015 (DHD15) werd gebruikt om het opvolgen van nationale voedingsrichtlijnen te beoordelen. De bevindingen toonden aan dat gezondere voedingspatronen waren geassocieerd met een lagere uitstoot van broeikasgassen, maar met een hoger verbruik van blauw water. Hoewel gezondheid en duurzaamheid vaak samengaan, kan een verhoogde consumptie van plantaardig voedsel zoals fruit en noten dus leiden tot een toename van het verbruik van blauw water. Hoofdstuk 3 gaat in op het onderzoek naar hoe voedingspatronen van volwassenen met verschillende sociaaleconomische achtergronden verbeterd kunnen worden en hoe deze veranderingen de kosten van hun voedingspatronen zouden kunnen beïnvloeden. In dit modelleeronderzoek werden huidige voedingspatronen van volwassenen (VCP 2019-2021) geoptimaliseerd door lineaire combinaties te maken van bestaande voedingspatronen binnen sociaaleconomische subgroepen. Het doel van deze optimalisatie was het minimaliseren van de uitstoot van broeikasgassen en het maximaliseren van het opvolgen van nationale voedingsrichtlijnen (DHD15), terwijl de randvoorwaarde was om veranderingen in het voedingspatroon beperkt te houden. De geoptimaliseerde voedingspatronen voor alle sociaaleconomische subgroepen bevatten bescheiden toenames van plantaardig voedsel en verminderde hoeveelheden van zuivel en rood en bewerkt vlees. Hierdoor resulteerden de geoptimaliseerde voedingspatronen in een 19-24% lagere uitstoot van broeikasgassen en een 52-56% verbetering van het opvolgen van de voedingsrichtlijnen. De uitgaven aan voedsel voor de geoptimaliseerde voedingspatronen waren vergelijkbaar met die van de huidige voedingspatronen, dat gold voor alle sociaaleconomische subgroepen. Dit onderzoek toonde aan dat, ondanks de vaak hogere kosten van gezond voedsel, de kosten van voedsel geen belemmering hoeven te vormen voor het aannemen van een gezonder en duurzamer voedingspatroon in alle sociaaleconomische subgroepen. Gebaseerd op onze bevindingen en ondersteund door eerdere bevindingen, wordt in hoofdstuk 8 geconcludeerd dat gezondere voedingspatronen samenhangen met een lagere uitstoot van broeikasgassen, landgebruik, verzuring en eutrofiëring van zout en zoet water, maar met een verhoogd verbruik van blauw water. Aanzienlijke verbeteringen in zowel gezondheid als duurzaamheid zijn mogelijk voor alle sociaaleconomische subgroepen door relatief kleine veranderingen in het voedingspatroon in de richting van meer plantaardige voedingspatronen, zonder de uitgaven aan voedsel te beïnvloeden.

Deel II - De rol van sterk bewerkte voedingsmiddelen in gezonde en milieuvriendelijke voedingspatronen

Het tweede deel van deze thesis gaat in op de rol van sterk bewerkte voedingsmiddelen (UPF) en dranken (UPD) (UPFD) in gezonde en duurzame voedingspatronen. In hoofdstuk 4 werden de voedingswaarde, milieubelasting en kosten van UPF en UPD in dagelijkse voedingspatronen (VCP 2012-2016) van zowel volwassenen als kinderen geëvalueerd. De milieubelasting van UPFD was uiteenlopend: UPF en UPD vertoonden vergelijkbare broeikasgasemissies per 100g, maar met een lager verbruik van blauw water vergeleken met onbewerkte of minimaal bewerkte alternatieven. UPF waren betaalbaarder, terwijl UPD minder betaalbaar waren dan onbewerkte of minimaal bewerkte voedingsmiddelen en dranken. UPFD speelden een aanzienlijke rol in dagelijkse voedselconsumptie, bijdragend aan gemiddeld 61% van de totale energie-inname, 45% van de broeikasgasemissies, 23% van het blauwe water en 39% van de uitgaven aan voedsel. De consumptie van UPFD droeg ook significant bij aan dagelijkse inname van zout (72%), suiker (64%), verzadigd vet

(56%), maar ook aan de inname van voedingsvezels (60%) en eiwitten (46%). In hoofdstuk 5 werd de associatie tussen de consumptie van UPFD, UPF en UPD, de milieubelasting en sterfte onderzocht aan de hand van het EPIC-NL cohort. De bevindingen toonden een significante associatie aan tussen een hogere consumptie van UPD en een verhoogd risico op sterfte (16%) en een hogere milieubelasting (tot 7%), behalve voor landgebruik. Daarentegen was de associatie tussen een hoge consumptie van UPF en sterfte niet significant, maar wel significant geassocieerd met een lagere milieubelasting (tot -13%). Het verminderen van UPFD, vooral UPD, zou gunstig zijn voor gezondheid, milieubelasting en uitgaven aan voedsel. Echter, het vervangen van UPF door minder bewerkte alternatieven kan in sommige gevallen de milieubelasting en uitgaven aan voedsel verhogen. In hoofdstuk 6 werd de voedingswaarde van sterk bewerkt plantaardig voedsel, met een focus op plantaardige burgers, geëvalueerd. De bevindingen toonden aan dat deze burgers een uiteenlopende voedingswaarde hebben, omdat ze een bron waren van eiwitten, voedingsvezels en essentiële mineralen, maar ook hoge niveaus van energie, zout en (verzadigd) vet bevatten. Hoewel de beschikbaarheid en consumptie van sterk bewerkt plantaardig voedsel een stap kunnen zijn naar een duurzamer voedingspatroon, ondersteunen ze niet per se gezonde eetgewoonten. Gebaseerd op deze bevindingen en ondersteund door bestaand bewijs, wordt in hoofdstuk 8 geconcludeerd dat het verminderen van de consumptie van UPFD, vooral UPD, de inname van (verzadigd) vet, suiker en zout kan verminderen, wat de gezondheid van het voedingspatroon verbetert en tegelijkertijd sterftecijfers en milieubelasting verminderen. Niet alle UPF zijn inherent ongezond; sommige hebben een lage milieubelasting en zijn ook betaalbaar. Daarom is het belangrijk dat initiatieven die het vervangen van UPF bevorderen, zorgvuldig rekening houden met de milieubelasting en economische factoren om onbedoelde effecten te voorkomen. In plaats daarvan kunnen inspanningen gericht zijn op het verminderen van ongezonde geformuleerde voedingsmiddelen, gekenmerkt door hoge niveaus van (verzadigd) vet, suiker en zout.

Deel III - Het mogelijk maken van gezonde en duurzame voedselkeuzes in de retail voedselomgeving

Het derde deel van deze thesis beschrijft een gerandomiseerde gecontroleerde studie (RCT) waarin de effectiviteit van verschillende beleidsmaatregelen op vleesaankopen in een virtuele supermarkt zijn onderzocht, zoals beschreven in hoofdstuk 7. Deelnemers werden blootgesteld aan ofwel een controle scenario, een prijsverhoging van 30% op vlees, een informatieve ‘nudge’ of een combinatie van de prijsverhoging en informatieve ‘nudge’. Het combinatiescenario leidde tot een significante afname van -386 g (95% betrouwbaarheidsinterval (BI)CI: -579, -193) vleesaankopen per huishouden per week, wat overeenkomt met een daling van -36% of -23 g per persoon per dag. De prijsverhoging alleen had een minder, zij het niet statistisch significant effect op vleesaankopen (-144 g (95%BI: -331, 43)), en de informatieve ‘nudge’ alleen beïnvloedde vleesaankopen niet. De implementatie van fiscale maatregelen, in combinatie met informatie over de rechtvaardiging en het doel van deze maatregelen, kan aanzienlijk bijdragen aan het verminderen van vleesaankopen. Gebaseerd op onze bevindingen en ondersteund door eerdere studies, wordt in hoofdstuk 8 geconcludeerd dat een samenhangende mix van beleidsmaatregelen, waaronder fiscale maatregelen, waarschijnlijk het meest effectief is om de verschuiving van voedselkeuzes van consumenten naar gezondere en duurzamere voedingspatronen te faciliteren.

Algemene discussie

In hoofdstuk 8 wordt, om het perspectief te verbreden, de context van voedselsystemen geschetst. Daarnaast worden de belangrijkste bevindingen samengevat en reflecties hierop gegeven. Ook worden methodologische overwegingen besproken, samen met de implicaties voor beleid en voor toekomstige onderzoeksstappen.

Ondanks overheidsverantwoordelijkheden en toezeggingen, ontbreken effectieve beleidsmaatregelen gericht op het verbeteren van de volksgezondheid en het beschermen van het milieu in het huidige landschap. Het bewijs uit deze thesis toont aan dat het mogelijk is om een gezonder en duurzamer voedingspatroon te adopteren, met meer nadruk op plantaardig voedsel en minder op dierlijk voedsel. Dit kan kostenneutraal zijn voor alle sociaaleconomische subgroepen, ondanks dat het verbruik van blauw water kan toenemen. Bovendien de gezondheid en duurzaamheid van het voedingspatroon kunnen worden verbeterd door de (over)consumptie van bepaalde UPFD te verminderen; bij vervanging vereist dit een zorgvuldige overweging van zowel de milieubelasting als economische factoren. De verschuiving in het voedingspatroon zou aanzienlijke voordelen opleveren voor zowel de volksgezondheid als het milieu. Hoewel elk onderzoek inherente methodologische overwegingen kent, ondersteunen onze bevindingen de noodzaak van veranderingen in voedselsystemen. Daarbij is een goed gedefinieerd begrip van de beleidsinstrumenten essentieel om de huidige uitdagingen aan te pakken.

Het is een belangrijke overheidsverantwoordelijkheid om preventieve volksgezondheid en het milieu prioriteit te geven. Het faciliteren van consumenten om gezonde en duurzame voedselkeuzes te maken vereist een intensievere betrokkenheid van de overheid. Dit omvat een coherente beleidsmix met zowel harde als zachte maatregelen, gericht op sleutelactoren in het voedselsysteem in plaats van op individuele consumenten. Het is onvermijdelijk dat dergelijke maatregelen ingrijpen in de belangen van de agro-voedsel-industrie en consumenten beïnvloeden. Echter, zonder veranderingen in de voedselomgeving zal het voedingspatroon evenmin veranderen. Het bereiken van de beoogde gunstige effecten van de verschuiving in het voedingspatroon vereist een alomvattende strategie die ministeriële grenzen overstijgt. Deze strategie omvat op bewijs gebaseerd beleid met meetbare doelstellingen, samenwerking, prioritering en toewijzing van voldoende financiële middelen.

Om de verschuiving in het voedingspatroon te faciliteren, zouden fiscale instrumenten gezonde en duurzame voedingsmiddelen betaalbaarder kunnen maken, terwijl ongezonde en niet-duurzame voedingsmiddelen minder betaalbaar worden. Hoewel op zichzelf bewezen ineffectief, kunnen informatieve interventies zoals een voedselkeuzelogo en geüpdatete nationale voedingsrichtlijnen de impact van dergelijke fiscale maatregelen verbeteren. Met betrekking tot voedselkeuzes zouden gezonde en duurzame voedingspatronen mogelijk kunnen worden gemaakt door de beschikbaarheid en promotie (marketing, prijsaanbiedingen, advertenties) van voedingsmiddelen te reguleren, en door wetgeving voor duurzaamheidsclaims. Tegelijkertijd kan de voedingswaarde worden verbeterd door verplichte herformulering. Tijdens deze systeemovergang is voortdurende monitoring van ontwikkelingen, veranderingen in voedselconsumptie, aanbod en vraag nodig om onbedoelde effecten van de geïmplementeerde beleidsmaatregelen te identificeren en bij te sturen wanneer ze zich voordoen.

Het aannemen van een gezonder, duurzamer en kostenneutraal voedingspatroon in Nederland is dringend nodig en mogelijk. Het vereist echter een fundamentele transformatie van het voedselsysteem en is daarom kritisch afhankelijk van een duidelijke politieke wil om effectieve beleidsinstrumenten te implementeren.

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Tijdens onze bachelor Voeding en Diëtetiek in Groningen werden wij op achternaam ingedeeld, puur toeval dat wij bij elkaar in de klas kwamen. Nu, nog steeds verbonden, maar niet alleen door onze studie, maar door mooie avonturen, herinneringen, liefde en leed. Lieve "**RIP**", lieve **Rosan, Noor en Margriet**, (ik doe trouwen nog steeds eer aan de naam), ik wil jullie bedanken voor jullie interesse, steun en afleiding de afgelopen jaren.

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List of publications

Publications in peer reviewed journals

Vellinga RE, van de Kamp M, Toxopeus IB, van Rossum CT, de Valk E, Biesbroek S, Hollander A, Temme EHM. Greenhouse gas emissions and blue water use of Dutch diets and its association with health. Sustainability. 2019 Oct 30;11(21):6027. https://doi.org/10.3390/su11216027

Temme EHM, **Vellinga RE**, de Ruiter H, Kugelberg S, van de Kamp M, Milford A, Alessandrini R, Bartolini F, Sanz-Cobena A, Leip A. Demand-side food policies for public and planetary health. Sustainability. 2020 Jul 23;12(15):5924. https://doi.org/10.3390/su12155924

Hollander A, **Vellinga RE**, de Valk E, Toxopeus, I, van de Kamp, M, Temme, EHM. (2021). The Global Blue Water Use for the Dutch Diet and Associated Environmental Impact on Water Scarcity. World Journal of Food Science and Technology. 2021;5(1):10-8. https://doi.org/10.11648/j.wjfst.20210501.13

Vellinga RE, Sam M, Verhagen H, Jakobsen LS, Ravn-Haren G, Sugimoto M, Torres D, Katagiri R, Thu BJ, Granby K, Hoekstra J, Temme EHM. Increasing Seaweed Consumption in the Netherlands and Portugal and the Consequences for the Intake of Iodine, Sodium, and Exposure to Chemical Contaminants: A Risk-Benefit Study. Frontiers in nutrition. 2022 Jan 6;8:792923. https://doi.org/10.3389/fnut.2021.792923

Eykelenboom M, Olthof MR, Van Stralen MM, Djojosoeparto SK, Poelman MP, Kamphuis CB, **Vellinga RE**, Waterlander WE, Renders CM, Steenhuis IH. The effects of a sugar-sweetened beverage tax and a nutrient profiling tax based on Nutri-Score on consumer food purchases in a virtual supermarket: a randomised controlled trial. Public Health Nutrition. 2022 Apr;25(4):1105-17. https://doi.org/10.1017/S1368980021004547.

Vellinga RE, van Bakel M, Biesbroek S, Toxopeus IB, de Valk E, Hollander A, van ’t Veer P, Temme EHM. Evaluation of foods, drinks and diets in the Netherlands according to the degree of processing for nutritional quality, environmental impact and food costs. BMC Public Health. 2022 May 3;22(1):877. https://doi.org/10.1186/s12889-022-13282-x

Vellinga RE, Eykelenboom M, Olthof MR, Steenhuis IH, de Jonge R, Temme EHM. Less meat in the shopping basket. The effect on meat purchases of higher prices, an information nudge and the combination: a randomised controlled trial. BMC Public Health. 2022 Jun 7;22(1):1137. https://doi.org/10.1186/s12889-022-13535-9

Colizzi C, Harbers MC, **Vellinga RE**, Verschuren WM, Boer JM, Biesbroek S, Temme EHM, van der Schouw YT. Adherence to the EAT-Lancet Healthy Reference Diet in Relation to Risk of Cardiovascular Events and Environmental Impact: Results From the EPIC-NL Cohort. Journal of the American Heart Association. 2023 Apr 18;12(8):e026318. https://doi.org/10.1161/jaha.122.026318

Vellinga RE, van den Boomgaard I, Boer JM, van der Schouw YT, Harbers MC, Verschuren WM, van ’t Veer P, Temme EHM, Biesbroek S. Different Levels of Ultraprocessed Food and Beverage Consumption and Associations with Environmental Sustainability and All-cause Mortality in EPIC-NL. The American Journal of Clinical Nutrition. 2023 May 18. https://doi.org/10.1016/j.ajcnut.2023.05.021

Vellinga RE, Rippin HL, Gonzales GB, Temme EHM, Farrand C, Halloran A, Clough B, Wickramasinghe K, Santos M, Fontes T, Pires MJ. Nutritional composition of ultra-processed plant-based foods in the out-of-home environment: a multi-country survey with plant-based burgers. The British journal of nutrition. https://doi.org/10.1017/s0007114524000023

Eykelenboom M, Mersch D, Grasso AC, **Vellinga RE**, Temme EHM, Steenhuis IH, Olthof MR, PEN Consortium. The effects of health-related food taxes on the environmental impact of consumer food purchases: secondary analysis of data from a randomised controlled trial in a virtual supermarket. Public health nutrition. https://doi.org/10.1017/S1368980024000090.

Submitted manuscripts

Vellinga RE, Sam M, Donkersgoed G, van Klaveren J, Temme EHM. Potential impact of EU-wide food-related policy strategies on protein intake and environmental impact compared to business-as-usual. *Submitted*

Vellinga RE, Heerschop S, Biesbroek S, van ’t Veer P, van Bakel M, Hollander A, Temme EHM. Diets optimized for environmental sustainability and health: Implications for diet costs across socio-economic positions for Dutch adults. *Submitted*

Daas MC, **Vellinga RE**, Pinho MG, Boer JM, Verschuren WM, van der Schouw YT, van ‘t Veer P, Biesbroek S. The Role of Ultra-Processed Foods in Plant-Based Diets: Associations with Human Health and Environmental Sustainability. *Submitted*

Other publications

Podcast - ‘Is gezond eten goed voor het milieu?’. De RIVM Podcast Leefomgeving & Gezondheid. 2022.

Scan the QR code to listen.

Overview of completed training activities

Discipline specific activities		
Name of the course/meeting	**Organizing institute (s)**	**Year**
PhD course ‘Lifecycle analysis livestock’	WIAS	2019
Course ‘Essentials in SimaPro’	PRE Consultancy	2019
13th and 14th European Nutrition Conference FENS (+2 orals, 1 poster)	FENS	2019, 2023
PhD Masterclass ‘ Food environments’	KNAW	2019
Projectmeetings for European projects: FutureFoodS, FNS Cloud, EFSA , Foodcost, Best ReMaP, Seafoodtomorrow, Nitrogen and Food	Various	2019-2023
Nutritional science days (+ 5 orals)	NAV	2019-2023
PhD course ‘Healthy and Sustainable Diets: synergies and trade-offs’ (+1 oral)	VLAG	2021
Guest lecture - Healthy and sustainable diets	Maastricht University	2021-2022
Guest lecture - Healthy and sustainable food-based dietary guidelines	WUR	2021-2023
Project meetings for WHO CC projects	WHO Region Europe	2021-2023
22nd IUNS-International Congress of Nutrition (+1 oral)	IUNS	2022
Guest lecture - course ‘ Healthy and sustainable diets: synergies and trade-offs’	VLAG	2023
Course ‘Protein quality evaluation and application’	VLAG	2023
Plenary lecture ‘Nutritional science days’	NAV	2023

General courses		
Name of the course	**Organizing institute**	**Year**
Course ‘LWT- trusted advisor’	RIVM	2020
Course ‘Academic writing in English’	RIVM/Babel	2020
Course ‘Supervising BSc & MSc thesis students’	WGS	2021
PhD retrete	RIVM/PhD association Proneri	2022
Course ‘Presenting with impact’	WGS	2022
Course ‘Early career academic writing course WHO’	WHO Region Europe	2022
Course ‘PMC’	RIVM	2023

Assisting in teaching and supervision activities		
Code and name of the course	**Organizing institute**	**Year**
HNH32506 Healthy and sustainable food-based dietary guidelines	WUR	2022
Supervising BSc & MSc thesis students	WUR	2019-2023
Susan Lanooij	Internship	2019
Nienke van Velzen	Msc	2020

Iris van den Boomgaard	MSc	2021
Valerie Lalisang	Internship	2021
Tim van den Boom	Msc	2021
Laura Bosman	Msc	2021
Merel Daas	Msc	2021
Mirte Kamphuis	Msc	2022
Matthias van den Brink	Internship	2023

Other activities

Name of the course	**Organizing institute**	**Year**
Chair of weekly department meetings ‘halftientje’ and ‘Keek op de week’	RIVM	2019
Meetings from learned society NAV	NAV	2019-2023
Review papers, peer reviewed journals	RIVM	2019-2023
Preparation of research proposal	VLAG	2021
Coaching	RIVM	2021
Societally relevant exposure (podcast)	RIVM	2021
Member Young-NAV committee activities	NAV	2021-2022
Societally relevant exposure (news articles, podcast)	RIVM	2021-2023
Intervision	RIVM	2022
PhD study tour	VLAG	2022

About the author

Reina Vellinga, born on November 8, 1993, in Sneek, Netherlands, embarked on an academic journey marked by a deep commitment to the fields of nutrition, dietetics, public health, and the environment.

Upon completing her secondary education at the Bogerman scholengemeenschap in Sneek (2006-2011), Reina showcased an early interest in environmental issues, notably through her research project focused on acidification. In 2011, she commenced her Bachelor's degree in Nutrition and Dietetics at Hanzehogeschool Groningen, successfully earning her diploma in 2015. Following her undergraduate studies, she took a gap year and gained practical experience as a dietitian.

Motivated by curiosity and a strong desire for learning, Reina pursued a Master's degree in Nutrition and Health at Wageningen University (WU), specializing in Epidemiology and Public Health (2016-2018). During this period, especially through her MSc thesis at WU and internship at the National Institute for Public Health and the Environment (RIVM), Reina's interests in healthy and sustainable diets grew.

Following her graduation, Reina initiated her professional career as a researcher at the department Health and Nutrition of the RIVM. She concentrated on addressing societal challenges, with a particular emphasis on promoting healthy and sustainable diets. Her work included in-depth analyses of the healthiness, environmental impact, and costs of Dutch diets, as well as contributions to projects related to the Dutch LCA food database and initiatives promoting sustainable consumption, such as Loket Duurzaam Eten. Reina's expertise extends to her involvement in European projects, including WHO Collaborating Centre for Nutrition, Nitrogen and Food, Seafoodtomorrow, JANPA best remap, Foodcosts, FNS Cloud, and FutureFoodS.

In January 2021, Reina was appointed as an external PhD candidate in the Division of Human Nutrition, Department of Global Nutrition, at WU. Under the guidance of Prof. Dr. P. van 't Veer (WU), Dr. E.H.M. Temme (RIVM), and Dr. S. Biesbroek (WU), Reina delved into her doctoral research. She actively participated in academic initiatives, becoming a member of VLAG Graduate school, joining the PhD program Proneri at RIVM, and contributing to the youth committee of the Dutch Academy of Nutritional Sciences.

Upon successful completion of her thesis, Reina will continue her contributions to the field of healthy and sustainable diets. She continues her role as a researcher at the department Healthy and Sustainable Nutrition of the RIVM, continuing her commitment to improve human and planetary health.

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