TOWARDS
HEALTHY AND ENVIRONMENTALLY SUSTAINABLE DIETS FOR EUROPEAN CONSUMERS

ELLY Mertens

Propositions

1. In Europe, the first gains for human health and environmentally sustainability are achieved by partly replacing beef with other animal-sourced foods, rather than by plant-sourced foods.
   (this thesis)

2. Lack of data quality and harmonisation in scientific research has a serious impact on diet models and hinders effective food and health policy.
   (this thesis)

3. Citizen engagement in research increases the credibility of science.

4. Biodiversity conservation is a key issue for economic prosperity.

5. Lunchtime walks are essential to happiness.

6. Leaving home will bring you home.

Propositions belonging to the thesis, entitled
Towards healthy and environmentally sustainable diets for European consumers

Elly Mertens
Wageningen, 8 January 2020

TOWARDS HEALTHY AND ENVIRONMENTALLY SUSTAINABLE DIETS FOR EUROPEAN CONSUMERS

Elly Mertens

Thesis Committee

Promotors
Prof. Dr J.M. Geleijnse
Personal Chair, Nutrition and Disease
Wageningen University & Research

Prof. Dr P. van ‘t Veer
Professor of Nutrition, Public Health and Sustainability
Wageningen University & Research

Co-promoter
Dr A. Kuijsten
Researcher / Teacher, Division of Human Nutrition and Health
Wageningen University & Research

Other members
Dr M. Zurek, Oxford University, UK
Dr C. van Dooren, Voedingscentrum, The Hague
Prof. Dr C. de Graaf, Wageningen University & Research
Prof. Dr J.G.A.J. van der Vorst, Wageningen University & Research

This research was conducted under the auspices of the Graduate School VLAG (Advanced Studies in Food Technology, Agrobiotechnology, Nutrition and Health Sciences).

TOWARDS HEALTHY AND ENVIRONMENTALLY SUSTAINABLE DIETS FOR EUROPEAN CONSUMERS

Elly Mertens

Thesis
submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus,
Prof. Dr A.P.J. Mol
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Wednesday 8 January 2020
at 4 p.m. in the Aula.

Elly Mertens
Towards healthy and environmentally sustainable diets
for European consumers
293 pages

PhD thesis, Wageningen University, Wageningen, the Netherlands (2020)
With references, with summary in English

ISBN: 978-94-6395-153-1
DOI: https://doi.org/10.18174/502018

CONTENTS

PART I *Methodological aspects of assessing health and environmental sustainability of diets*

PART II *Health and environmental sustainability of European diets*

PART III *Identification of dietary improvement options for European consumers that integrate health, environmental sustainability and dietary preferences*

About the author

CHAPTER 1

General introduction

In Europe, overconsumption and unhealthy diets cause a massive burden of non-communicable diseases, such as cardiovascular diseases, type 2 diabetes and various cancers. In 2017, the age-standardised mortality rate attributable to dietary risks in European adults was around 315 deaths per 100,000 persons [1]. While the European region faces an alarming prevalence of overweight and obesity [2], nutrient deficiencies are also observed, particularly among vulnerable population subgroups [3, 4]. Modern diets not only impact health, but also the environment. Currently, the land area needed to produce an average European diet is roughly around half the size of a football pitch per person per year [5]. There is thus an urgent need to transform both European food production systems and food consumption patterns [6, 7]. This thesis focusses on the design of healthier and more environmentally sustainable diets for European consumers.

HEALTHY DIETS

Healthy diets should provide adequate energy, nutrients and foods in order to prevent nutrient deficiencies and reduce non-communicable disease risk, and simultaneously maintain a healthy body weight [8]. In Europe, on average more than half of the adults are either overweight or obese [9, 10], and a quarter of all deaths are attributable to unhealthy diets [1]. This burden of disease is potentially preventable by improvement of the diet, as there is a gap between current and optimal intakes. In particular, high intake of sodium, low intake of whole grains, fruit and vegetables are the foremost factors, accounting for more than half of all diet-related deaths in Europe (Figure 1) [1, 11]. Comparisons between observed intakes and recommended intakes for a healthy diet are important to identify priorities in diet-related public health solutions. Dietary surveillance is therefore essential to assess the healthiness of dietary intakes.

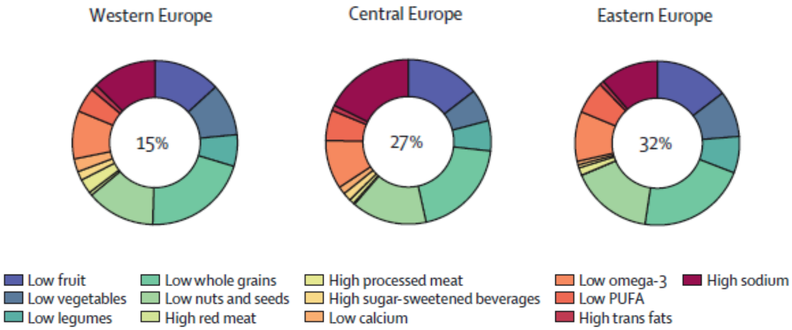


Figure 1 Age-standardised proportions of deaths attributable to dietary risks in Europe, 2017 (data source: Global Burden of Disease [1]).

The percentages in each pie chart are the total proportion of disease-specific mortality attributable to dietary risk factors in the different regions.

A healthy diet from nutrients to foods

Healthy diets help maintain or improve overall health, and are compliant with nutrient recommendations and food-based dietary guidelines. Nutrient recommendations combine minimum recommended nutrient intakes, and are closely linked to healthy growth and development [12]. However, it is the sum of not only nutrients, but also bio-actives and the food matrix present in foods that affect non-communicable disease risk, and thus there is a need for a holistic approach that addresses foods, food groups and diets as a whole [13].

Food-based dietary guidelines are evidence-based messages on healthy eating in terms of foods, food groups and dietary patterns, aimed at the general population for the prevention of non-communicable diseases [14, 15]. In most European countries, food-based dietary guidelines have been established for consumer education and information, and they serve as a basis for public health policies [15, 16]. Because diets are shaped by social, economic, agricultural and environmental factors that affect food availability and choice, these food-based dietary guidelines are tailored to country- or region-specific habits to enhance their effectiveness [16]. Still, in European countries, they include many generic dietary key elements [14, 15], i.e. increase the intake of whole grains, fruit and vegetables, nuts and seeds, and legumes, and decrease the intake of red and processed meat, and sugar-sweetened beverages, and salt [17].

Indicators for a healthy diet

A healthy diet relies on both the quantity and the composition of food consumed (Figure 2). From the nutritional point of view, the quantity of consumer diets considers the energy balance, i.e. the balance between energy intake and energy requirement. This balance between energy intake and energy requirement cannot be assessed directly, as energy intake cannot be properly assessed by methods of dietary assessment due to misreporting [18]. Nevertheless, a prolonged pattern of overconsumption leads to a positive balance, hence a higher body weight, and vice versa. A measure that reflects this is the body mass index (BMI), which is often used as a proxy for body fatness in adult populations [19].

The quality of consumer diets is assessed by the comparison of both nutrient and food intakes with recommended intakes for a healthy diet. To allow for a fair comparison of diet quality between populations, it is important to apply the same standards for recommended intakes of nutrients and foods. For the European Union, compliance with nutrient recommendations can be assessed using dietary reference values as set by the European Food Safety Authority (EFSA). EFSA, however, does not set Europe-wide food-based dietary guidelines, because they include country-or-region-specific habits related to food availability and dietary preferences in the different Member States. Adherence to food-based dietary guidelines can thus be assessed using generic dietary food groups that are overarching the country-or-region-specific food-based dietary guidelines.

Indicators on energy balance, compliance with nutrient recommendations and adherence to food-based dietary guidelines serve as a basis for the assessment of the healthiness of consumer diets [20]. Such indicators may be useful to communicate the current status of dietary intake in a descriptive way with the aim to better inform policymakers [21]. Quantifying the current status of dietary intake requires detailed data on consumer diets.

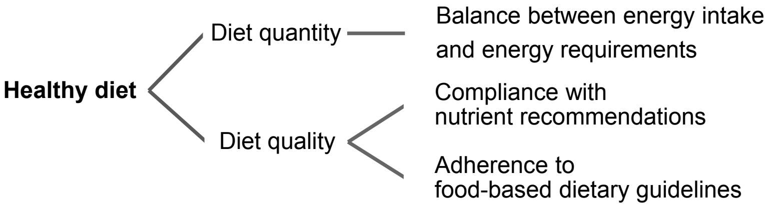


Figure 2 The assessment of healthy diets involves quantity and quality from a nutritional point of view.

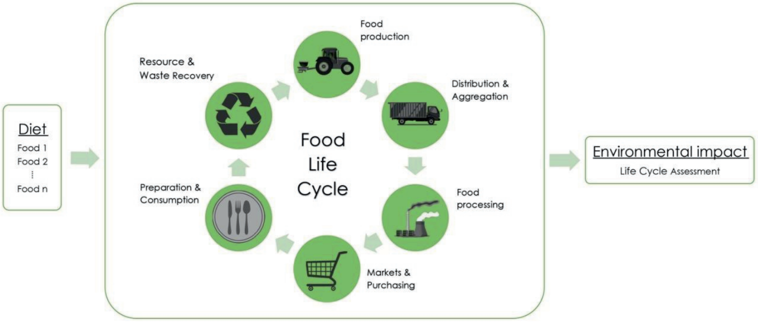
ENVIRONMENTALLY SUSTAINABLE DIETS

Food systems are held responsible for a total greenhouse gas emission of 8.7-13.7Gt of carbon dioxide equivalents (CO_2eq) per year [22-24]. This includes emissions of carbon dioxide from energy use in agricultural machinery and from conversion of natural ecosystems, and of non-carbon dioxide gases (methane and nitrous oxide) from agricultural production. Together this accounts for circa 20-30% of total anthropogenic greenhouse gas emissions [22-24]. Greenhouse gases, including carbon dioxide, methane and nitrous oxide, are the gases in the atmosphere which absorb and re-emit heat, and thereby have an influence on the temperature of the earth's atmosphere. CO_2eq is a standard unit for expressing the quantity of different greenhouse gases, and it signifies for any greenhouse gas the amount of CO_2 that would have an equivalent global warming effect. Food production is also the world's largest water-consuming sector using 70% of freshwater for agriculture [25]. Furthermore, it is the largest driver of land use and land-use change, mainly through agricultural expansion, and it disrupts the nitrogen and phosphorous cycles [26]. Therefore, the need for a transition towards a more sustainable food production system has become widely recognised [5, 27]. This concept of a sustainable food production system has been expanded by the inclusion of planetary boundaries for impacts of food production, using the concept of a safe operating space for humanity [28]. Quantification of these planetary boundaries is still in its initial stages, and it is influenced by existing know-how and available measurement equipment. That is why studies assessing diet-related environmental impacts mostly consider greenhouse gas emissions [29].

Indicators for an environmentally sustainable diet

Diet-related environmental impacts, such as greenhouse gas emissions and land use, are commonly assessed using life cycle analysis (LCA). LCA is a tool to assess environmental impacts accounting for emissions and resource use throughout all the stages of a product's life cycle [30] (Box 1). Even though LCA has been defined and standardised through international guidelines, there is still a substantial degree of flexibility in the method which limits the comparability of food-item LCA studies. To allow a fair and meaningful comparison of environmental impact of consumer diets across Europe, a food-item LCA database that is applicable for a European-wide context is needed.

Box 1 Components of the life cycle assessment to assess the environmental impact of consumer diets.



Life Cycle Assessment (LCA) is an internationally accepted standardised methodology that aims to assess environmental impacts associated with all the stages of a product’s life cycle [30]. The stages in a food product’s life cycle, from cultivation of (feed) crop to consumption at home, typically includes primary production, i.e. crop production and animal breeding, food processing, packaging, transportation, distribution and storage, preparation and consumption, and waste management [31].Thus, to assess environmental impacts of diets, each food in the diet is linked to its primary products. Starting from its primary products, impacts of all the life cycle stages are summed in order to obtain an overall estimate of the environmental impact of this food. Environmental impact of the total diet is subsequently calculated by multiplying for each food its intake with its environmental impact, and summed across all foods consumed. Methodological choices related to the functional unit, system boundaries, allocation methods, agricultural management practices as well as practices at other life cycle stages are important sources of inherent variability in food-item LCA data [32].

Environmental impact of consumer diets

In European countries, studies in the consumer domain using individual-level intake data show that the greenhouse gas emissions of an average diet varies between 3 – 8 kg CO_2eq per day [33, 34]. These studies on consumer diets consistently show that diets higher in animal-sourced foods, in particular meat from beef, have a higher environmental impact [34-36]. Although the internal validity of those studies might be good, comparison between studies and countries should be done cautiously. This is because of differences in not only the methods of dietary assessment, but also in the underlying food-item LCA databases [32]. For comparing and developing European policies, this highlights the need for standardised individual-level dietary intake data, as described below, and a need for standardised LCA databases to obtain comparable estimates of diet-related environmental impact.

METHODS OF DIETARY ASSESSMENT

Assessment of the consumer diets can be done using food supply data at the national level, food purchases at the household level or food intake at the individual level [37, 38]. Food supply data represent the national quantity of primary commodities that are available for human consumption, such as rice, milk and meat, expressed as kilograms per capita per day. Food supply data include food losses at production level and food wastages at consumption level, and therefore represents food availability for consumption rather than actual food intake. Food purchase data provide information on the expenses and the purchased quantities of the foods and beverages in households. Food supply and food purchase data are indirect methods of dietary assessment and have little connection to the individual. On the other hand, dietary assessment methods on the individual level directly assess the individual intakes of foods and beverages, i.e. the food consumed and their consumption amounts and/or frequencies. Moreover, these individual-level methods include a wide variety of realistic food choices in the consumer domain that reflect individual dietary preferences.

Methods to estimate an individual’s diet include diet records, 24-hour recalls and food frequency questionnaires (FFQ). Diet records and 24-hour recalls are usually applied in dietary surveillance aimed to obtain quantitative estimates of intake, such as amounts consumed, whereas large scale epidemiological studies usually use an FFQ to obtain frequencies of consumption [38]. These methods rely on self-report and are prone to bias, resulting from omission and/or inclusion of unconsumed foods and inaccurate estimation of portion size eaten. Yet, individual-level food intake assessments are the best available standards to assess consumer diets, as no independent reference methods are available [39, 40].

In this thesis, individual-level dietary data from national surveys are used to assess the healthiness of dietary intake across European countries. Cross-country comparison of European dietary intake is, however, hampered by differences in dietary survey methodologies [41]. EFSA has set out to collect detailed, harmonised food consumption data in the European Union Member States by 2020 [42], for which it defined the following standards:

- Detailed dietary data should be collected on two non-consecutive days for each individual.
- Reported foods should be described in accordance with the EFSA FoodEx2 food classification and description system.
- Additional information on less frequently consumed foods, food supplements, age, gender, weight, height and physical activity levels should be collected.

The FoodEx2 food classification and description system by EFSA is an important step in the alignment of surveys across European Union Member States [41]. FoodEx2 is a hierarchical system of 21 main food groups, which are further divided into subgroups up to a maximum of six levels [43]. Several Member States have already linked intakes from their national dietary survey to FoodEx2 for the development of the EFSA Comprehensive European Food Consumption Database [41]. This database is thus built from available national food consumption data, and it is the best available source of food consumption information data on a European wide basis. However, in the absence of a uniform pan-European surveillance system, that accounts for the quality of dietary data collection, further harmonisation and standardisation of available dietary data are needed to allow cross-country comparisons [44].

DIETARY CHOICES

Dietary choices are influenced by multiple complex factors involving an interplay of multilevel determinants (Figure 3) [45]. This complex network of determinants is therefore regarded as not only a potential barrier, but also a promising opportunity for encouraging healthy and environmentally sustainable diets. Understanding the question 'why we eat what we eat?' is a key issue for unravelling the triple malnutrition burden, and would provide a framework for evidence-based policy making [46, 47].

Examples of important determinants for dietary choice at the individual level are taste preferences, visual appeal, familiarity, price, convenience, nutritional knowledge and skills, and habitual behaviour [48, 49]. Nevertheless, all the multilevel determinants of dietary choice play a role in the observed diversity of diets within and between consumers in a given population [45]. This diversity of diets provides valuable examples for consumers to choose healthier and more environmentally sustainable diets in different ways. In view of this, such dietary improvements that are based on existing diets are assumed to be realistic and feasible for the population under study. The assumption underlying this is that valid information about appropriate eating is provided by similar others or those with whom they affiliate [50, 51]. This highlights the possibility of using existing dietary patterns that are both healthy and environmentally sustainable as a practical guide for dietary improvement in a given population.

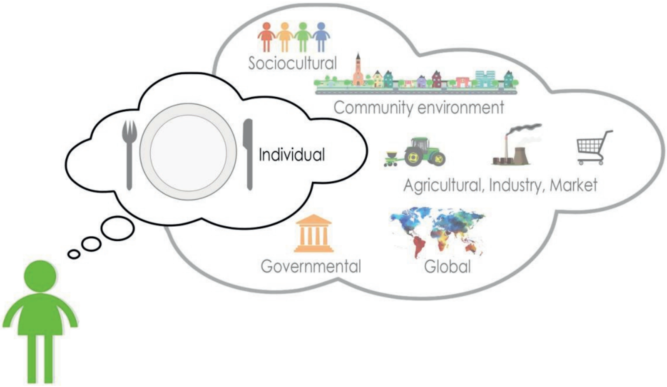


Figure 3 Complex network of determinants at different levels influencing dietary choices - Adapted from Mozaffarian 2016 [45].

TOWARDS MORE HEALTHY AND ENVIRONMENTALLY SUSTAINABLE DIETS

In 2010, the Food and Agriculture Organisation (FAO) proposed a definition of a sustainable diet: “Sustainable diets are those diets with low environmental impacts, which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimising natural and human resources” [52]. This definition clearly illustrates the complexity of a sustainable diet, which goes beyond health and environment, and embraces the socio-cultural and economic dimensions of the diet as well. This thesis provides the first steps towards the design of such diets for European consumers, and hereby focuses on the dimensions of both health and environmental sustainability.

Guidelines for healthy and environmentally sustainable diets

Several European countries have started integrating environmental sustainability aspects in their food-based dietary guidelines [53-57]. Such guidelines mostly emphasise the reduction of greenhouse gas emissions through promoting a shift towards plant-based foods at the expense of animal-based foods. More recently, an integrated framework for the global adoption of a healthy reference diet, as proposed by the EAT-*Lancet* Commission, would provide essential support for feeding ten billion people a healthy diet within safe planetary boundaries for food production by 2050 [58]. This healthy reference diet outlines a global average and ranges of food group intakes that would benefit human health. Like for food-based dietary guidelines, these ranges of intakes are based on the best available evidence on healthy diets, which make it possible that not all diets within the healthy eating ranges meet environmental targets.

Consumer options for an environmentally sustainable diet

The impact of consumer-oriented strategies to reduce diet-related environmental impact highly depends on the amount and type of meat included in the diet, but also on the environmental impact of the foods replacing the meat [34, 35]. Such replacements are beneficial for the intake of saturated fats and sodium, but put critical nutrients that are mainly derived from animal-sourced foods, such as zinc, vitamins B12 and B2, under pressure [59-61]. This suggests that their contribution to diet quality could to some extent compensate for their higher environmental impact [62]. It is therefore worthwhile to explore potential trade-offs between health and environment when moving towards healthy and environmentally sustainable diets.

Identifying diets that are healthy and environmentally sustainable

Integrating health with environmental sustainability aspects of a diet in a realistic way requires advanced modelling tools [63, 64]. Commonly used modelling tools for designing diets are mathematical optimisation models. In mathematical diet optimisation, the aim of the diet problem is to compose a diet that is (more) optimal according to certain criteria, such as satisfying guidelines for a healthy diet, minimising the environmental impact, and minimising deviations from the current diet [65, 66]. However, to arrive at diets that are acceptable to consumers, there is a need to introduce additional constraints on food intake to the diet optimisation model [67]. Defining these food intake constraints involves arbitrary expert-based choices on basic food interrelationships and acceptable food quantities. This highlights the need for a diet model that formulates diets that implicitly fit dietary preferences, thus without specifying additional constraints. The key challenge for such a diet model is therefore to design future diets that not only meet guidelines for a healthy diet, but also reduce environmental impact of the diet.

OUTLINE OF THIS THESIS

The main challenge facing nutrition research is to design a diet that integrates health and environmental sustainability, and at the same time takes dietary preferences into account. For this journey towards more healthy and environmentally sustainable diets, there is a need for a consumer-oriented diet model that implicitly accounts for dietary preferences. Box 2 and Figure 4 summarise the aim, objectives and outline of the thesis. In addition, the context of the thesis in the SUSFANS- and the SHARP-project is briefly described.

Box 2 Aim and specific objectives of this thesis.

Main aim of this thesis:

> To develop a methodology to design the first steps towards more healthy and environmentally sustainable diets that are acceptable for European consumers.

Specific objectives:

1. To operationalise the methodology for assessing health and environmental sustainability of European diets (Chapter 2 and Chapter 3).
2. To assess the current status of European diets in terms of health and environmental sustainability (Chapter 4 and Chapter 5).
3. To identify options for dietary improvement in Europe that integrate health, environmental sustainability and dietary preferences (Chapter 6 and Chapter 7).

Figure 4 depicts the outline of this thesis. The basic idea is to compare diets with respect to healthiness (Y-axis) and environmental sustainability (X-axis), and this comparison is made for the observed and for modelled consumer diets.

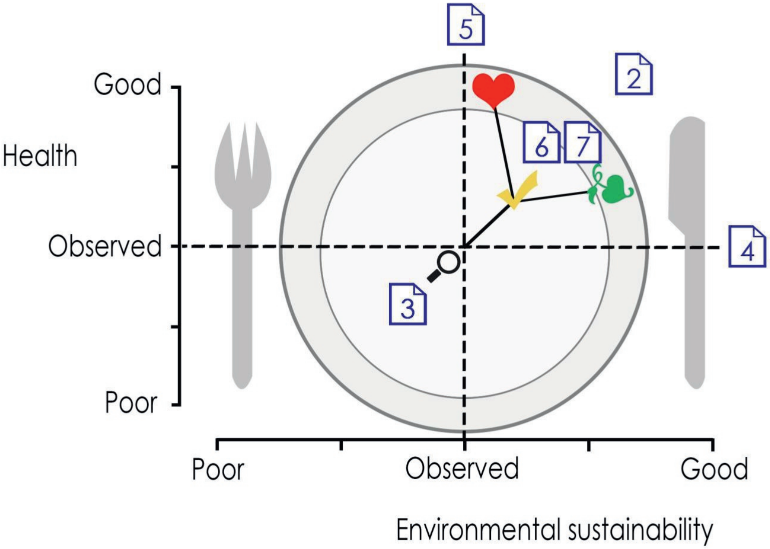


Figure 4 Outline of this thesis “Towards healthy and environmentally sustainable diets for European consumers”.

Chapter 2 gives an overview on how previous studies addressed the health aspect of environmentally sustainable diets. In Chapter 3, Chapter 4 and Chapter 5, observed diets are addressed in terms of environmental sustainability and its association with health (Chapter 3), in terms of health (Chapter 4), and in terms of environmental sustainability (Chapter 5). Chapter 6 introduces a diet model that is applied to dietary intake data of the four European countries in Chapter 7.

The first objective, related to the assessment of health and environmentally sustainability in consumer diets, is addressed in Chapter 2 and Chapter 3. In Chapter 2, current approaches to operationalise health aspects in the context of environmentally sustainable diets are reviewed. In Chapter 3, the performance of a food frequency questionnaire for estimating the environmental impact of the diet is compared with that of a 24-hour recall. In addition, the association between environmental impact and dietary quality is investigated in observed consumer diet.

Chapter 4 and Chapter 5 address the second objective of this thesis, related to assessing the current status of European diets. Using four European countries, i.e. Denmark, Czech Republic, Italy and France, the current status of observed diets is studied with regard to health (Chapter 4) and environmental sustainability (Chapter 5).

The topics of health and environmental sustainability are integrated in Chapter 6 and Chapter 7, related to the third objective of this thesis. Chapter 6 provides a description of the diet model for the design of improved diets that fit within the range of existing diets. In Chapter 7, more healthy and environmentally sustainable diets that fit within dietary patterns of European diets were identified using a diet model. In addition, this diet model provides insight in trade-offs between dietary preferences against health and environmental sustainability.

Chapter 8 summarises the main findings of this thesis, followed by a discussion of the methodological considerations and implications for future research and public health policies.

Context of this thesis

The present thesis was embedded in the SUSFANS project (European Union's H2020 Programme) and the SHARP-BASIC project (TiFN). The database for environmental sustainability indicators and the benchmarking diet model were developed in the SHARP-BASIC project, and the applications to the dietary data were conducted within the SUSFANS project.

SUSFANS' overall objective was to develop the conceptual framework, the evidence base and analytical tools for underpinning European-wide and Member State food policies with respect to their impact on consumer diets and their implications for public health, environmental, economic and social outcomes [68]. The project is based on three inter-related pillars of the assessment, modelling and foresight of sustainable food and nutrition security. In particular, the project integrates macro-level agricultural, trade and environmental impact analyses with micro-level consumer diet and health analyses. This thesis addresses all three pillars at the micro-level of consumer diets.

The SHARP-BASIC project's overall objective is to provide a scientifically underpinned knowledge and data platform to build models for deriving SHARP diets, i.e. environmentally Sustainable, Healthy, Affordable, Reliable and Preferred. Related to the project's objective is to provide standardised high quality data and the modelling tools in order to create a common ground for addressing the SHARP dimensions of consumer diets.

Central to both projects is the assessment of consumer diets and the identification of more healthy and environmentally sustainable diets that fit within the cultural context of European consumers. The European context focussed on four European Union Member States that have made their dietary survey data available to EFSA and represents the diversity of food habits in Europe (Figure 5). Included are national survey data from Denmark (2005-2008), Czech Republic (2003-2004), Italy (2005-2006), and France (2006-2007).

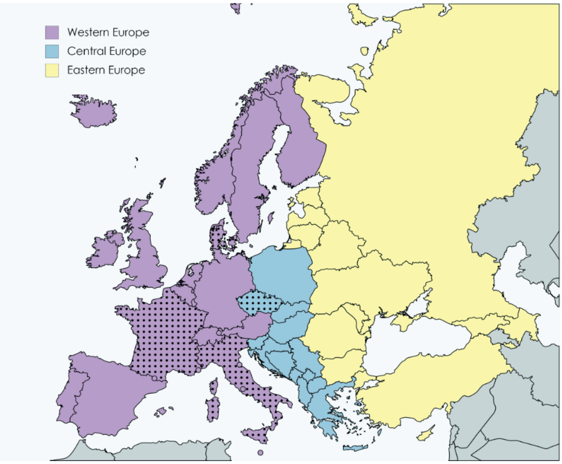


Figure 5 Included in this thesis were dietary data from Denmark, Czech Republic, Italy, France. Countries with a dotted pattern represent the four countries included in this thesis. Western (purple), Central (blue) and Eastern (yellow) European regions are based on the regions as defined by the World Health Organisation.

REFERENCES

1. Afshin A, Sur PJ, Fay KA, Cornaby L, Ferrara G, Salama JS, Mullany EC, Abate KH, Abbafati C, Abebe Z *et al*: **Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017**. *The Lancet* 2019, **393**(10184):1958-1972.
2. GBD 2017 Risk Factor Collaborators: **Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017**. *The Lancet* 2018, **392**(10159):1923-1994.
3. Mensink G, Fletcher R, Gurinovic M, Huybrechts I, Lafay L, Serra-Majem L, Szponar L, Tetens I, Verkaik-Kloosterman J, Baka A: **Mapping low intake of micronutrients across Europe**. *Br J Nutr* 2013, **110**(04):755-773.
4. Roman Vinas B, Ribas Barba L, Ngo J, Gurinovic M, Novakovic R, Cavelaars A, De Groot L, van't Veer P, Matthys C, Serra Majem L: **Projected prevalence of inadequate nutrient intakes in Europe**. *Annals of Nutrition and Metabolism* 2011, **59**(2-4):84-95.
5. European Environment Agency (EEA): **Food in a green light - A systems approach to sustainable food**. In. Copenhagen, Denmark; 2017.
6. Lartey A, Meerman J, Wijesinha-Bettoni R: **Why Food System Transformation Is Essential and How Nutrition Scientists Can Contribute**. *Ann Nutr Metab* 2018, **72**(3):193-201.
7. HLPE: **Nutrition and Food Systems. A Report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security**. In. Rome; 2017: 152.
8. World Health Organization (WHO): **Diet, nutrition, and the prevention of chronic diseases: report of a joint WHO/FAO expert consultation**, vol. 916: World Health Organization; 2003.
9. EUROSTAT: **Health determinant Body Mass Index (BMI)**. In. Luxembourg: EUROSTAT, the statistical office of the European Union; 2017.
10. World Health Organisation (WHO): **European Health Report 2018 More than numbers - evidence for all**. In. Edited by Europe WROf. Copenhagen, Denmark; 2018.
11. World Health Organisation (WHO): **European Food and Nutrition Action Plan 2015-2020**. In. Edited by Europe WRcf. Copenhagen, Denmark; 2014.
12. EFSA (European Food Safety Authority): **Panel (EFSA Panel on Dietetic Products, Nutrition and Allergies), 2010. Scientific Opinion on principles for deriving and applying Dietary Reference Values**. *EFSA Journal 2010* 2010, **8**(3):1458
13. Mozaffarian D, Ludwig DS: **Dietary guidelines in the 21st century--a time for food**. *JAMA* 2010, **304**(6):681-682.
14. Herforth A, Arimond M, Álvarez-Sánchez C, Coates J, Christianson K, Muehlhoff E: **A Global Review of Food-Based Dietary Guidelines**. *Advances in Nutrition* 2019.
15. Bechthold A, Boeing H, Tetens I, Schwingshackl L, Nothlings U: **Perspective: Food-Based Dietary Guidelines in Europe-Scientific Concepts, Current Status, and Perspectives**. *Advances in nutrition (Bethesda, Md)* 2018, **9**(5):544-560.
16. EFSA Panel on Dietetic Products N, Allergies (NDA),: **Scientific Opinion on establishing Food-Based Dietary Guidelines**. *EFSA Journal* 2010, **8**(3):1460.
17. Kromhout D, Spaaij CJ, de Goede J, Weggemans RM: **The 2015 Dutch food-based dietary guidelines**. *Eur J Clin Nutr* 2016, **70**(8):869-878.
18. Freedman LS, Commins JM, Moler JE, Arab L, Baer DJ, Kipnis V, Midthune D, Moshfegh AJ, Neuhouser ML, Prentice RL *et al*: **Pooled results from 5 validation studies of dietary self-report**

instruments using recovery biomarkers for energy and protein intake. *Am J Epidemiol* 2014, **180**(2):172-188.

19. Flegal KM, Shepherd JA, Looker AC, Graubard BI, Borrud LG, Ogden CL, Harris TB, Everhart JE, Schenker N: **Comparisons of percentage body fat, body mass index, waist circumference, and waist-stature ratio in adults**. *Am J Clin Nutr* 2009, **89**(2):500-508.
20. Zurek M, Leip A, Kuijsten A, Wijnands J, Terluin I, Shutes L, Hebinck A: **Sustainability metrics for the EU food system: A review across economic, environmental, and social considerations. SUSFANS. Project deliverable D1. 3. of the EU H2020**. In.: SFS-19-2014: Sustainable food and nutrition security through evidence based …; 2017.
21. Zurek M, Hebinck A, Leip A, Vervoort J, Kuiper M, Garrone M, Havlík P, Heckelei T, Hornborg S, Ingram J *et al*: **Assessing Sustainable Food and Nutrition Security of the EU Food System—An Integrated Approach**. *Sustainability* 2018, **10**(11):4271.
22. Smith P, Bustamante M, Ahammad H, Clark H, Dong H, Elsiddig EA, Haberl H, Harper R, House J, Jafari M: **Agriculture, forestry and other land use (AFOLU)**. In: *Climate change 2014: mitigation of climate change.* vol. IPCC Working Group III Contribution to AR5. Cambridge: Cambridge University Press; 2014.
23. Vermeulen SJ, Campbell BM, Ingram JS: **Climate change and food systems**. *Annual review of environment and resources* 2012, **37**:195-122.
24. Bennetzen EH, Smith P, Porter JR: **Decoupling of greenhouse gas emissions from global agricultural production: 1970–2050**. *Global change biology* 2016, **22**(2):763-781.
25. HLPE: **Water for food security and nutrition**. In. Rome: Food and Argiculture Organization of the UN; 2015.
26. UNEP: **The critical role of global food consumption patterns in achieving sustainable food systems and food for all.** . In. Paris, France: Discussion Paper, United Nations Environment Programme; 2012.
27. Bas-Defossez F, Allen B, Weigelt J, Marechal A, Meredith S, Lorant A: **Feeding Europe: Agriculture and sustainable food systems, Policy Paper produced for the IEEP Think2030 conference**. In. Brussels; 2018.
28. Rockström J, Steffen W, Noone K, Persson Å, Chapin III FS, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ: **A safe operating space for humanity**. *Nature* 2009, **461**(7263):472.
29. Jones AD, Hoey L, Blesh J, Miller L, Green A, Shapiro LF: **A Systematic Review of the Measurement of Sustainable Diets**. *Adv Nutr* 2016, **7**(4):641-664.
30. Ekvall T, Azapagic A, Finnveden G, Rydberg T, Weidema BP, Zamagni A: **Attributional and consequential LCA in the ILCD handbook**. *The International Journal of Life Cycle Assessment* 2016, **21**(3):293-296.
31. Guinée JB GM, Heijungs R, Huppes G, Kleijn R, De Koning A, Van Oers L, Wegener Sleeswijk A, Suh S, Udo De Haes HA, De Bruijn H, Van Duin R, Huijbregts MAJ, Lindeijer E, Roorda AAH, Van der Ven BL, Weidema BP ,: **Life cycle assessment: an operational guide to the ISO standards**. In. Edited by Centrum voor Milieukunde Leiden University. Leiden; 2002.
32. Notarnicola B, Sala S, Anton A, McLaren SJ, Saouter E, Sonesson U: **The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges**. *Journal of Cleaner Production* 2017, **140**:399-409.
33. Heller MC, Keoleian GA, Willett WC: **Toward a life cycle-based, diet-level framework for food environmental impact and nutritional quality assessment: A critical review**. *Environmental science & technology* 2013, **47**(22):12632-12647.

34. Perignon M, Vieux F, Soler L-G, Masset G, Darmon N: **Improving diet sustainability through evolution of food choices: review of epidemiological studies on the environmental impact of diets**. *Nutr Rev* 2017, **75**(1):2-17.

35. Hallström E, Carlsson-Kanyama A, Börjesson P: **Environmental impact of dietary change: a systematic review**. *Journal of Cleaner Production* 2015, **91**:1-11.

36. Aleksandrowicz L, Green R, Joy EJ, Smith P, Haines A: **The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review**. *PLOS ONE* 2016, **11**(11):e0165797.

37. Food and Agriculture Organisation (FAO): **Dietary Assessment: A resource guide to method selection and application in low resource settings**. In. Rome; 2018.

38. Thompson FE, Subar AF, Coulston A, Boushey C: **Dietary assessment methodology**. *Nutrition in the Prevention and Treatment of Disease* 2008, **2**:3-39.

39. Slimani N, Bingham S, Runswick S, Ferrari P, Day NE, Welch AA, Key TJ, Miller AB, Boeing H, Sieri S *et al*: **Group level validation of protein intakes estimated by 24-hour diet recall and dietary questionnaires against 24-hour urinary nitrogen in the European Prospective Investigation into Cancer and Nutrition (EPIC) calibration study**. *Cancer Epidemiol Biomarkers Prev* 2003, **12**(8):784-795.

40. Kipnis V, Subar AF, Midthune D, Freedman LS, Ballard-Barbash R, Troiano RP, Bingham S, Schoeller DA, Schatzkin A, Carroll RJ: **Structure of Dietary Measurement Error: Results of the OPEN Biomarker Study**. *Am J Epidemiol* 2003, **158**(1):14-21.

41. European Food Safety Authority (EFSA): **Use of the EFSA Comprehensive European Food Consumption Database in Exposure Assessment**. *EFSA Journal* 2011, **9**(3):2097.

42. European Food Safety Authority (EFSA): **Guidance on the EU Menu methodology**. *EFSA Journal* 2014, **12**(12):3944.

43. European Food Safety Authority (EFSA): **The food classification and description system FoodEx 2 (revision 2)**. *EFSA Supporting Publications* 2015, **12**(5):804E.

44. De Boer E, Slimani N, Veer PvT, Boeing H, Feinberg M, Leclercq C, Trolle E, Amiano P, Andersen L, Freisling H: **Rationale and methods of the European food consumption validation (EFCOVAL) project**. In.: Nature Publishing Group; 2011.

45. Mozaffarian D: **Dietary and Policy Priorities for Cardiovascular Disease, Diabetes, and Obesity**. *Circulation* 2016, **133**(2):187-225.

46. Stok FM, Hoffmann S, Volkert D, Boeing H, Ensenauer R, Stelmach-Mardas M, Kiesswetter E, Weber A, Rohm H, Lien N *et al*: **The DONE framework: Creation, evaluation, and updating of an interdisciplinary, dynamic framework 2.0 of determinants of nutrition and eating**. *PLoS One* 2017, **12**(2):e0171077.

47. Brug J, van der Ploeg HP, Loyen A, Ahrens W, Allais O, Andersen LF, Cardon G, Capranica L, Chastin S, De Bourdeaudhuij I *et al*: **Determinants of diet and physical activity (DEDIPAC): a summary of findings**. *Int J Behav Nutr Phys Act* 2017, **14**(1):150-150.

48. Leng G, Adan RAH, Belot M, Brunstrom JM, de Graaf K, Dickson SL, Hare T, Maier S, Menzies J, Preissl H *et al*: **The determinants of food choice**. *The Proceedings of the Nutrition Society* 2017, **76**(3):316-327.

49. Renner B, Sproesser G, Strohbach S, Schupp HT: **Why we eat what we eat. The Eating Motivation Survey (TEMS)**. *Appetite* 2012, **59**(1):117-128.

50. Higgs S: **Social norms and their influence on eating behaviours**. *Appetite* 2015, **86**:38-44.

51. Cruwys T, Bevelander KE, Hermans RC: **Social modeling of eating: a review of when and why social influence affects food intake and choice**. *Appetite* 2015, **86**:3-18.

52. Food Agriculture Organisation (FAO): **Sustainable diets and biodiversity - directions and solutions for policy research and action**. In. Edited by FAO. Rome; 2010.

53. German Nutrition Society: **Ten guidelines for wholesome eating and drinking from the German Nutrition Society (German: Vollwertig essen und trinken nach den 10 Regeln der DGE).** . In. Bonn: Deutsche Gesellschaft für Ernährungs e.V.; 2013.

54. The Swedish National Food Agency (Livsmedelsverket): **Find your way to eat greener, not too much and to be active! (Hitta ditt sätt att äta grönare, lagom mycket och röra på dig!)**. In. Uppsala: Livesmedelsverket; 2017.

55. Health Council of the Netherlands: **Guidelines for a Healthy Diet: The Ecological Perspective**. In. The Hague: Health Council of the Netherlands; 2011.

56. Macdiarmid J, Kyle J, Horgan G, Loe J, Fyfe C, Johnstone A, McNeill G: **Livewell: a balance of healthy and sustainable food choices. WWF-UK**. In.; 2011.

57. Vlaams Instituut Gezond Leven: **De Voedings- en bewegingsdriehoek: hoe en waarom?** In. Laken (Brussel); 2017.

58. Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A *et al*: **Food in the Anthropocene: the EAT-*Lancet* Commission on healthy diets from sustainable food systems**. *The Lancet* 2019, **393**(10170):447-492.

59. Springmann M, Wiebe K, Mason-D'Croz D, Sulser TB, Rayner M, Scarborough P: **Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail**. *The Lancet Planetary health* 2018, **2**(10):e451-e461.

60. White RR, Hall MB: **Nutritional and greenhouse gas impacts of removing animals from US agriculture**. *Proceedings of the National Academy of Sciences* 2017, **114**(48):E10301-E10308.

61. Seves SM, Verkaik-Kloosterman J, Biesbroek S, Temme EH: **Are more environmentally sustainable diets with less meat and dairy nutritionally adequate?** *Public Health Nutr* 2017, **20**(11):2050-2062.

62. Drewnowski A, Rehm CD, Martin A, Verger EO, Voinnesson M, Imbert P: **Energy and nutrient density of foods in relation to their carbon footprint**. *The American journal of clinical nutrition* 2015, **101**(1):184-191.

63. Buttriss JL, Briend A, Darmon N, Ferguson EL, Maillot M, Lluch A: **Diet modelling: How it can inform the development of dietary recommendations and public health policy**. *Nutrition Bulletin* 2014, **39**(1):115-125.

64. Dantzig GB: **The Diet Problem**. *INFORMS Journal on Applied Analytics* 1990, **20**(4):43-47.

65. Stigler GJ: **The cost of subsistence**. *J Farm Econ* 1945, **27:303**.

66. Gazan R, Brouzes CMC, Vieux F, Maillot M, Lluch A, Darmon N: **Mathematical Optimization to Explore Tomorrow's Sustainable Diets: A Narrative Review**. *Advances in Nutrition* 2018, **9**(5):602-616.

67. Smith VE: **Linear Programming Models for the Determination of Palatable Human Diets**. *Journal of Farm Economics* 1959, **41**(2):272-283.

68. Rutten M, Achterbosch TJ, de Boer IJ, Cuaresma JC, Geleijnse JM, Havlík P, Heckelei T, Ingram J, Leip A, Marette S: **Metrics, models and foresight for European sustainable food and nutrition security: the vision of the SUSFANS project**. *Agricultural Systems* 2016.

PART I

Methodological aspects of assessing health and environmental sustainability of diets

CHAPTER 2

Operationalising the health aspect of sustainable diets: a review

Elly Mertens

Pieter van 't Veer

Gerrit J Hiddink

Jan MJM Steijns

Anneleen Kuijsten

Published in: Public Health Nutrition 2017; 20(4):739-757

ABSTRACT

Objective: Shifting towards a more sustainable food consumption pattern is an important strategy to mitigate climate change. In the past decade, various studies have optimised environmentally sustainable diets using different methodological approaches. The aim of this review is to categorise and summarise the different approaches to operationalise the health aspects of environmentally sustainable diets.

Design: Conventional keyword and reference searches were conducted in PubMed, Scopus, Web of Knowledge and CAB abstracts. Inclusion criteria were (1) English language publication; (2) published between 2005 and October 2015; (3) dietary data collected for the diet as a whole at the national, household or individual level; (4) comparison of the current diet with dietary scenarios; and (5) for results to consider the health aspect in some way.

Setting: Consumer diets

Subjects: Adult population

Results: We reviewed 49 studies that combined the health and environmental aspects of consumer diets. Hereby, Five approaches to operationalise the health aspect of the diet were identified: (1) food item replacements; (2) dietary guidelines: (3) dietary quality scores; (4) diet modelling techniques; and (5) diet-related health impact analysis.

Conclusion: Although the sustainability concept is increasingly popular and widely advocated by nutritional and environmental scientists, the journey towards designing sustainable diets for consumers has only just begun. In the context of operationalising the health aspect, diet modelling might be considered as the preferred approach since it captures the complexity of the diet as a whole. For the future, we propose SHARP diets: environmentally Sustainable (S), Healthy (H), Affordable (A), Reliable (R) and Preferred from the consumers' perspective (P).

INTRODUCTION

To provide an adequate diet to the growing world population, estimates indicate that an increase in the global food production is needed, at a rate of 1.2% per year [1]. At the same time, the food production system is recognised as a major threat to the environment, including climate change and depletion of the planet's natural resources [2]. This is partly driven by the habitual consumption patterns tending towards a higher consumption of animal-based products [3]. It is thus an important global challenge to secure adequate diets within a sustainable food production system [4]. In this regard, an adequate diet implies that it meets energy requirements and provides sufficient nutrients in line with the dietary guidelines for healthy growth and ageing [5]. Because the diet is an important modifiable factor for well-being and disease prevention [6], both the adequacy of nutrient intake and the observed or projected prevalence and/or occurrence of health-disease outcomes are of importance.

Shifting towards a more sustainable food consumption pattern is considered as an important factor to tackle the challenge of harmonising the rapidly changing food demand for the larger and more affluent population and its supply [7]. A recently published review suggested that a reduction of up to 50% in diet-related greenhouse gas emission and land use can be realised by dietary changes in areas with affluent diet[8]. Especially the reduction of animal-based products is often regarded as the main option for lowering diet-related environmental impact [2, 7, 8]. However, severe reductions without an inclusion of appropriate meat- and/or dairy-substitutes might lead to inadequacies of several nutrients (e.g. vitamin B12, zinc, iron, etc.) across the population groups [9]. Therefore, the concept of a sustainable diet, as defined by the Food and Agriculture Organisation (FAO), is briefly described as a diet that has a low impact on the planet's resources and the environment, including respectfulness for biodiversity and animal welfare, and contributes to an adequate diet that is promoting a healthy life. Sustainable diets are also featured by characteristics such as cultural acceptability, accessibility, economic fairness and affordability [10]. This definition highlights the connection between the health, the environmental sustainability and the food production aspects of a diet, with the dietary pattern of consumers as a common denominator. The design of those diets asks for a collaboration between nutritional and environmental sciences along with the agricultural food chain [11].

The aim of this review is to categorise and summarise the different approaches that are currently used to operationalise the health aspects of environmentally sustainable diets. Also, the relevance of these approaches for research on environmentally sustainable diets will be discussed; each approach addresses a particular research question, but is built upon some assumptions which should be taken into account when using the approach. This review provides an overview of the way in which such diets have been addressed in research, particularly the relation between health and environmental sustainability of a diet. On the basis of this overview, recommendations for future research on designing sustainable diets are given and discussed.

METHODS

The literature search was performed in October 2015 and identified relevant articles through conventional keyword searching strategies using the search terms ‘diet’ or ‘food’ and ‘climate’ or ‘greenhouse gas’ or ‘land’ or ‘sustain’ in PubMed, Scopus, Web of Knowledge, CAB abstracts and through bibliographies of published papers. Articles included in this review met the following five inclusion criteria: (1) English language publication; (2) published between 2005 and October 2015; (3) dietary data collected for the diet as a whole at the national, household or individual level; (4) comparison of the current diet with dietary scenarios; and (5) for results to consider the health aspect in some way. The selection of articles that meet the inclusion criteria was based on information available in titles and abstracts of the articles, without restrictions on the geographical location. Given the aim of the review to categorise and summarise the different methodological approaches, some articles that inadvertently may have been missed were not expected to influence the results of the approaches identified.

RESULTS

In the period 2005 – 2015, we identified 49 papers that studied diet as related to health and environmental sustainability.

Dietary data collected for the diet as a whole included food availability estimates at the population and household level, and actual food intake at the individual level. The food availability estimates included data on the food supply at the population level using Food Balance Sheets of the FAO or Economic Research Service [12-27] and data on the food purchases at the household level using Household Budget Surveys [21, 28-32]. Regarding individual-level food intake assessments, diet records were the most frequently used dietary survey method [20, 33-49] with recording ranging from 2 to 14 days; followed by a single or replicated 24-hour recalls[49-56], and Food Frequency Questionnaires (FFQs) [57-60]. The number of food items in these dietary assessments generally ranged from 25 to 100 in Food Balance Sheets, and from 130 in FFQs to 1314 in diet records or 24-hour recalls. However, sustainability indicators (e.g. greenhouse gas emission, land use) were only available for a limited number of foods, meaning a higher food aggregation level has been used. This food aggregation level was specified in 45 studies, of which only 17 studies applied a more precise level of aggregation into food items, with the number of food items ranging between 7 and 391 food items [12, 13, 16, 35-41, 43, 45, 52-54, 56, 60]. For two studies, it was specified that this covered 71% of the total food weight intake (including all solid foods and excluding foods typically consumed as beverages, such as milk, juices and other drinks), and 66% of total energy intake of all the foods and beverages [37, 38]. In most studies, food items without a sustainability value were assigned a value from a similar food item within the same food group to cover the total food consumption. Sustainability was mainly operationalised by greenhouse gas emission [12, 15, 21, 25, 26, 29-38, 40-42, 44-48, 51-57, 60]; followed by land use [14-16, 40, 41, 43, 50, 52, 60] and other sustainability indicators including livestock production, biodiversity and use of planet's resources [12-15, 17-30, 39, 42, 49, 52, 58, 59], which is partially biased towards the search terms used to define sustainability.

Approaches for operationalising the health aspect could be categorised into three main categories representing how the health aspects of the diet were operationalised (Figure 1 and Table 1): simple approaches focussing on a single nutritional aspect (A); approaches capturing the complexity of the diet (B); and approaches evaluating the health impact (C). More specifically, the simple approach refers to food item replacements. Three approaches were identified to capture the complexity of the diet: dietary guidelines (B1), dietary quality scores (B2), and diet modelling techniques (B3). For diet-related health impact one approach was identified. Studies generally did not address policy options to achieve dietary changes, the time dimension for environmental effects to occur (except for direct greenhouse gas emission), or the robustness of alternative dietary options in different socio-economic and ecological contexts.

A. Simple approaches

• Food item replacement	10 studies	Table 2

B. Approaches capturing the complexity of the diet

• B1. Dietary guidelines	17 studies	Table 3
• B2. Dietary quality scores	7 studies	Table 4
• B3. Diet modelling techniques	8 studies	Table 5

C. Approaches evaluating the diet-related health impact

• Diet-related health impact analysis	7 studies	Table 6

Figure 1 Conceptual overview showing the approaches used to operationalise the health aspect of environmentally sustainable diets when using population-, household- or individual-level food intake assessment.

Table 1 Approaches used to consider the health aspect in research on environmentally sustainable diets.

Approaches	Question addressed by the approach	Considerations for selection
A. Simple approaches:		
Food item replacement	What would be the change in environmental sustainability when replacing a particular food item or food group in the diet by a more sustainable alternative food item or food group?	- Omit dietary composition and micronutrient intake - Focus on sustainability and therefore lack the consumers' perspective to develop acceptable diets
B. Approaches capturing the complexity of the diet:		
B1. Dietary guidelines	What would be the change in environmental sustainability when dietary guidelines are met?	- The recommended diet is considered as the optimised diet for nutritional health, and not necessarily for environmental sustainability. - Not yet a consensus on what a healthy diets includes, resulting in a variety of dietary recommendations and thus recommended diets.
B2. Dietary quality scores	How is dietary quality – as assessed by a score – related to environmental sustainability?	- One overall score reflects dietary intake as a whole, however score-related limitations (e.g. inclusion of a selected number of dietary components, arbitrary penalties for unmet criteria, the failure of the overall score to accentuate specific nutrient deficiencies). - A need for detailed nutritional data to calculate the score - Focus on dietary health
B3. Diet modelling techniques	What would be the food composition of a diet when aiming at the optimisation of multiple diet-related factors (e.g. health, environmental sustainability, acceptability, affordability, accessibility, etc.)	- Possibly, the calculated diet is still a sub-optimised diet as it is driven by acceptability constraints based on current dietary intake and the data-availability of diet-related sustainability. - Outcome of the optimised diet is presented as a list of food items in a specified quantity; hence the need for translation into dietary guidelines that can be communicated in a coherent way to the public.
C. Approaches evaluating the diet-related health impact:		
Diet-related health impact analysis	What would be the change in health impact based on nutrient adequacy and/or health-disease outcome when individuals adopt a diet that is more environmentally sustainable?	- Health impact analyses are usually based on published meta-analyses by modelling counterfactual diets. - Nutrient adequacy and diet-related health/disease outcomes are the most predictive for the future of dietary change.

Simple approach: food item replacements

Food item replacement is a ready-to-use and illustrative approach that addresses the question “What would be the change in environmental sustainability when replacing a particular food item or food group in the diet by a more environmentally sustainable alternative food item or food group?” Ten studies used this approach and replacement of food items was either food weight based [50], protein based [14] or energy based [12, 13, 15, 28, 33-36] (Table 2). To develop a more environmentally sustainable diet, all studies focussed on a replacement of the animal-based products in the diet, varying from a shift to a moderate reduction or a total elimination of these products. In some replacement diets, total meat consumption was kept constant, shifting the consumption from higher carbon-intensive meats (i.e. beef and lamb) to less carbon-intensive meats (i.e. pork and poultry) [12, 34]. More commonly used replacement diets were those in which the total meat consumption was moderately reduced [14, 15, 28, 34, 35, 50] or completely eliminated [12-14, 28, 33, 34, 36, 50]; the former decreasing the meat intake by keeping the same types of meat in the diet and the latter being vegetarian or vegan options depending on their dairy content. In these replacement diets, meat (and dairy) substitutes can include either a single food group (e.g. dairy or fruit/vegetables, cereals etc.) [15, 33, 35, 36] or a combination of different food groups (e.g. pasta, rice, pulses, cereals, breads, salads, fruit and vegetables, dairy, eggs, nuts and seeds, etc.) [12-14, 28, 33, 34, 36, 50].

However, simple replacement is seldom possible in practice, not only because physiological feedback loops interfere with the total amount of food eaten and/or energy intake; but also due to behavioural feedback loops that affect food choices, nutrient composition and/or energy density of the diet as a whole. Food item replacement is thus likely to modify the dietary pattern as a whole. For example, decreasing the meat consumption and replacing it by plant-based substitutes might be beneficial for the environmental sustainability aspect of the diet, but raises concerns about the health aspect, in particular the intake of micronutrients that are largely derived from animal-based products (e.g. vitamin B12, D, iron, zinc, selenium).

Also, from a consumers’ perspective, questions have been raised about the acceptability of replacing meat, because meat is usually an embedded food item in a consumer’s habitual dietary pattern. Nevertheless, nowadays, a substantial number of consumers belongs to the segment of meat reducers or flexitarians, showing the feasibility of adopting a lower-level meat consumption [61]. In particular, potential change strategies incorporate the inclusion of meatless days with or without meat substitutes, and the promotion of a smaller portion of meat; and if possible a combination with using sustainably produced (meat) products and/or a larger portion of plant-based products, i.e. fruits and vegetables [61-63].

Apart from changing the dietary composition, just proportionally reducing food intake has been shown to lead to fewer calories while keeping the same overall nutrient density, as applied in one study [35]. A shortage of energy is not a common problem in Western countries where overconsumption is contributing to overweight, obesity and related diseases [64]. However, adequate micronutrient intake is still a major challenge in these Western-oriented diets due to its non-optimal composition [65], and micronutrient intake is often neglected in the nutritional evaluation of the ‘less meat’ diets.

Table 2 Food item replacement for the development of environmentally sustainable diets based on current diet.

Reference country	Health considerations				Environmental considerations	
	Dietary data	Replacement diets	Replacement compensated by means of	Health evaluation of whole diet based on	Food aggregation level [a]	Environmental indicator
Eshel et al., 2006 [12] US	Population level Per capita daily food disappearance data (FAOSTAT 2005)	Lacto-ovo-vegetarian Omnivore with fish Omnivore with red meat Omnivore with poultry	Total energy intake; meat kcal replaced by kcal from dairy and eggs in the lacto-ovo-vegetarian, and by kcal from the sole source given by the diet name	/	7 items	Energy efficiency GHGE
Baroni et al., 2007 [13] Italy	Population level (Eurostat 2000, Euromeat 2001, FAO 2001)	Omnivorous diet Vegetarian diet Vegan diet	Total energy intake; meat and dairy (and eggs) kcal replaced by unspecified plant-based food items	Total energy Macronutrients (protein, carbohydrates, fat) Dietary fibre	18 items	Eco-indicator 99W (including damages to human health, ecosystems quality and resources)
Collins et al., 2007 [28] Wales	Household level (Household and Expenditure Survey of food and drink, 2001)	Organic diet Footprint diets Vegetarian diet	Total energy intake; inorganic food items, food items with an ecological footprint ≥0.006 gha/kg, ≥ 0.004 gha/kg, or ≥0.002 gha/kg, and meat products respectively replaced by organic and low impact alternatives, and dairy and eggs	Total energy Macronutrients Micronutrients	12 categories	Total ecological footprint (demand from nature)
Stehfest et al., 2009 [14] 24 world regions	Population level Per country agricultural production data (FAOSTAT 2006)	No ruminant meat No meat No animal products Less meat	Protein intake; animal-proteins from ruminant meat, white meat, milk and eggs respectively replaced by plant-proteins from pulses and soybeans	/	7 crop groups and 5 animal categories	Livestock production Land use Crop production Radiative forcing

Reference country	Health considerations				Environmental considerations	
	Dietary data	Replacement diets	Replacement compensated by means of	Health evaluation of whole diet based on	Food aggregation level [a]	Environmental indicator
Berners-Lee et al., 2012 [33] United Kingdom	Individual level 4-day diet record (UK National Diet and Nutrition Survey, 2010), scaled to per capita supply intake FAO data)	3 vegetarian 3 vegan	Total energy intake; meat (and dairy) kcal replaced by kcal from dairy or plant-based meat-substitutes [b]	Macronutrients (protein, carbohydrates, fat) Added sugar Sodium	61 groups	GHGE
Vieux et al., 2012 [35] France	Individual level 7-day diet record (Individual National Survey and Food Consumption, 2006 – 2007)	Less meat intake - 20% less - Max 50 g/d	Total energy intake; meat kcal replaced by either kcal from fruit and vegetables, milk and dairy or mixed dishes	Total diet weight Total energy intake Energy density	73 items	GHGE
Hoolohan et al., 2013 [34] United Kingdom	Individual level 4-day diet record (UK National Diet and Nutrition Survey, 2010), scaled to per capita supply intake FAO data)	Decrease meat Eliminate meat Eliminate ruminant	Total energy intake; meat kcal replaced by kcal from plant-based meat-substitutes [b] or by lower-carbon intensive meat products (i.e. pork and poultry)	Macronutrients (protein, carbohydrates, fat) Added sugar Sodium	61 groups	GHGE
Temme et al., 2013 [50] The Netherlands	Individual level 2-day 24-hour recalls (Dutch National Food Consumption Survey, 2003)	Less meat and dairy intake - 30% less - 100% less	Diet weight; dairy and meat consumption replaced by the same amount of plant-based dairy or meat-replacing foods[c]	Saturated fatty acids Total iron	/	Land use

Reference country	Health considerations				Environmental considerations	
	Dietary data	Replacement diets	Replacement compensated by means of	Health evaluation of whole diet based on	Food aggregation level [a]	Environmental indicator
Werner et al., 2014 [36] Denmark	Individual level 7-day diet record (Danish National Dietary Survey, 1995 – 2006)	6 omnivorous [d] 1 vegetarian 1 vegan	Total energy intake; dairy (and meat and fish) kcal replaced by kcal from marmalade, soy drinks and/or beans.	Macronutrients [e] Micronutrients	71 items	GHGE
Westhoek et al., 2014 [15] EU27	Population level Per capita food supply data (FAOSTAT 2010)	25 and 50% less livestock - Beef and dairy - Pig, poultry and eggs	Total energy intake; kcal from meat, dairy and eggs replaced by cereals (and pulses if protein intake lower than recommended level)	Protein Saturated fat	12 commodity groups	Feed demand Land use Reactive nitrogen emissions
		All meat, dairy and eggs				GHGE

Abbreviations: GHGE, greenhouse gas emission.

[a] Food aggregation level; the number of food items or groups (depending on author's terminology) for which environmental sustainability data of food intake was available.

[b] Preferably plant-based meat-substitutes that might reasonably be considered to be healthy alternatives, i.e. pasta, rice, pulses, cereals, breads, salads, vegetables, fruits, nuts and seeds.

[c] Replacement with plant-based products that have a similar use to the reference food and therefore assumed to be consumed in similar amounts: liquid dairy foods were replaced by similar soya-based foods, meat products and cheese used as sandwich filling by a variety of other sandwich fillings/toppings, meat products in hot meal by a variety of meat replacers (e.g. vegetarian meat substitutes, egg dishes, pulses or tofu/tempeh), and soft cheese used as snack by popcorn.

[d] The theoretical diets were based on the current diet adjusted for the Danish Dietary Guidelines: 6 omnivorous diets with various quantities for dairy, 1 vegetarian diet with no cheese and meat products, and 1 vegan diet with no milk products, meat products and fish.

[e] The nutritional composition of each alternative diet was evaluated against the Nordic Nutrition Recommendations 2004 for macronutrients (protein, carbohydrate, added sugar, fat, saturated fat, mono- and poly-unsaturated fat, and alcohol) and micronutrients (including dietary fibre, vitamin A, D, E, C, B12, B1, B2, B3, B6, folate, magnesium, Iron, Zinc, Phosphorous, Calcium, Iodine and Selenium).

Approaches capturing the complexity of the diet:

(B1) Dietary guidelines

Dietary guidelines are considered as a descriptive approach that addresses the question “What would be the change in environmental sustainability when dietary guidelines are met?” Seventeen studies used this approach to compare current diets with the recommendations for a healthy diet with regard to their health and environmental sustainability aspects (Table 3). Dietary recommendations initially provided dietary guidance with the aim to promote health and well-being, and to prevent diet-related conditions and chronic diseases [6], without considering the environmental sustainability of these diets - until recently [66, 67]. The design of the recommended diet (e.g. the inclusion of food groups and the quantification of portion sizes) is highly dependent on the dietary guidelines used. However, when studying recommended diets in relation to environmental sustainability, the contribution of the following food groups was usually captured by the various recommended diets: bread, pasta, cereals and potatoes; fruit and vegetables; milk and milk products; meat, fish and egg products; legumes, nuts and seeds; fats and oils; and sugar, whereas alcohol was only included in the Mediterranean diets. Two studies additionally included the guidelines on total energy intake (and macronutrient composition) [16, 42], and nine studies constructed multiple recommended diets standardised for energy intake (and protein intake) [18, 19, 22-26, 58, 59], however one study only focussed on guidelines for total energy intake and macronutrient intake to design the recommended diet [27]. None of these studies explicitly addressed the advice on lowering salt intake, while this, in turn, might have an impact on food production, processing and consumption, hence environmental sustainability. This is because salt possesses certain crucial technological functions in food processing and preservation, and an important sensory function[68]. Additionally, when using the approach of dietary recommendations, the food aggregation level was quantified at a high level of food aggregation (ca. 20 food groups) which allowed for a rough estimation of the environmental sustainability for a broader range of indicators, not only including greenhouse gas emission but also the use of natural resources such as land, water, phosphorous and primary energy.

Table 3 Dietary guidelines in relation to the environmental sustainability for a descriptive analysis on environmentally sustainable diets.

	Health considerations				Environmental considerations	
Reference Country	Dietary data	Recommended diets	Dietary guidelines [a]	Health evaluation of whole diet based on	Food aggregation level [b]	Environmental indicator
Gerbens-Leenes et al., 2005 [16] The Netherlands	Population level (Eurostat 1993, FAO 1999, LEI/CBS 1981/1986/1996/1998, Vereniging voor Nederlandse Koffiebranders en Theepakkers 1961/1998)	Recommended diet, providing nutritional energy and nutrients (Voedingscentrum 1998)	Total energy intake Food group based	/	25 items	Land requirement
Buzby et al., 2006 [17] US	Population level Per capita food availability data series (Economic Research Service, 2003)	The 2005 Dietary guidelines for Americans on a 2,000 kilocalories per day diet	Food group based [c]	/	/	Agricultural needs
Tukker et al., 2011 [18] and Wolf et al., 2011 [19] EU27	Population level Per capita daily food supply data(FAOSTAT 2008)	WHO diet World Cancer Research Fund diet Mediterranean diet	Food group based Total energy intake Protein intake	Protein Total fat Saturated fat	50 groups 24 commodities	Aggregated environmental impact [h] Global warming
Capone et al., 2013 [20] Italy USA Finland	Individual level 3-day diet record (INRAN-SCAI survey, 2005 – 2006) scaled to per capita supply intake FAO data) Population level Per capita daily food supply data (FAOSTAT 2006)	Mediterranean diet model adapted for Italians (Institute of Food Sciences of La Sapienza University)	Food group based	Food groups	25 groups	Water footprint

Reference Country	Health considerations				Environmental considerations	
	Dietary data	Recommended diets	Dietary guidelines [a]	Health evaluation of whole diet based on	Food aggregation level [b]	Environmental indicator
Friel et al., 2013 [29] Australia	Household level Per household weekly food purchases (National Nutrition Survey 1995; Household Expenditure data 2003 – 2004)	Australian Guide to Healthy Eating adapted for environmental sustainability principles	Food group based	/	7 groups	GHGE Water use Biodiversity
Meier et al., 2013 [58] and Meier et al., 2014 [59] Germany	Individual level FFQ (54-item semi-quantitative) (National Nutrition Survey I, 1985 – 1989) Diet history + 2-day 24-hour recalls + 2 x 4-day diet record (National Nutrition Survey II, 2006)	2 recommended diets for Germany 2 dietary patterns adopted from USDA/USDHHS guidelines; lacto-ovo-vegetarian and vegan	Food group based [d] Total energy intake	Food groups	43 commodities	Global warming potential Ammonia emissions Land use Blue water use Phosphorus use Primary energy use
Sáez-Almendros et al., 2013 [21] Spain	Population level Per capita food supply data (FAOSTAT 2007) Household level Per capita daily or monthly food purchases (Household Consumption Survey 2006)	Mediterranean diet using the minimum servings of each food group recommended (New Mediterranean Diet Pyramid)	Food group based	Food groups	9 groups	GHGE Resource use (including agricultural land use, energy and water consumption)
Saxe et al., 2013 [22] Denmark	Population level Per capita annual food supply data	Nordic Nutritional recommendations New Nordic Diet based on Danish dietary guidelines and OPUS dietary guidelines	Food group based Total energy intake Protein intake	Food categories	31categories	Global warming potential

	Health considerations				Environmental considerations	
Reference Country	Dietary data	Recommended diets	Dietary guidelines [a]	Health evaluation of whole diet based on	Food aggregation level [b]	Environmental indicator
Vanham et al., 2013 [23, 24] EU28 Austria	Population level Per capita annual food supply data (FAOSTAT 2012)	Healthy diet [e] DGE, German dietary recommendations	Food group based Total energy intake Protein intake	Food groups	9 groups	Water footprint
Germani et al., 2014 [42] Italy	Individual level 3-day diet record (INRAN-SCAI survey, 2005 – 2006)	Mediterranean diet model adapted for Italians (Institute of Food Sciences of La Sapienza University and Livelli di Assunzione di Referimento Di Nutrient ed energia per la populazione italiana)	Food group based Macronutrient based [f] Total energy intake	Food groups	19 groups	Carbon footprint Ecological footprint Water footprint
Heller et al., 2014 [25, 26] US	Population level Per capita loss adjusted food availability data series (USDA ERS 2012)	The 2010 Dietary Guidelines for Americans - Omnivorous diet on a 2,534 and a 2,000 kilocalories per day diet - Vegetarian diet - Vegan diet Healthy Eating Plate diet (Harvard School of Public Health)	Food group based Total energy intake	Food groups	100 commodities	GHGE Carbon footprint
Hendrie et al., 2014 [55] Australia	Individual level 1-day 24-hour recall FFQ (Australian National Nutrition Survey, 1995)	Recommended diet Australian Dietary Guidelines [g]	Food group based	Food groups Total Energy intake Macronutrients Micronutrients	14 groups	GHGE

Reference Country	Health considerations				Environmental considerations	
	Dietary data	Recommended diets	Dietary guidelines [a]	Health evaluation of whole diet based on	Food aggregation level [b]	Environmental indicator
Pairotti et al., 2015 [30] Italy	Population Per household monthly food basket of Italian products (National Statistics Institute)	Modern Diet Mediterranean Food Pyramid (INRRAN, the National Institute of Research on Food and Nutrition) Healthy diet and vegetarian diet (Italian Nutrition Society (SINU))	Food group based	Food groups	5 categories	Energy consumption GHGE

Abbreviations: GHGE, greenhouse gas emission.

[a] When using food-based dietary guidelines, the contribution of the following food groups was usually captured by the various recommended diets: bread, pasta, cereals and potatoes; fruit and vegetables; milk and milk products; meat and meat products, fish and eggs; legumes, nuts and seeds; fats and oils; and sugar; while alcohol was only included in the Mediterranean diets.

[b] Food aggregation level; the number of food groups, categories or commodities (depending on author's terminology) for which environmental sustainability data of food intake was available.

[c] The recommended diet was only focussed on meeting the guidelines for the intake of fruits and vegetable, total and whole grains, and dairy.

[d] 2 German dietary recommendations: D-A-C-H (official recommendation of the German Nutrition Society) and UGB (alternative recommendations by the Federation for Independent Health Consultation with less meat, but more legumes and vegetables). The lacto-ovo-vegetarian dietary patterns adopted from USDA/USDHHS guidelines excluded the food groups on meat products and fish products, and included an additional food group for nuts and seeds and a separate food group for legumes. The vegan one additionally excluded the food groups on butter, high- and low-fat dairy products, and egg products, and included an additional food group for vegan soy drink products.

[e] In addition, dietary scenarios such as a healthy diet with no meat and a healthy diet with less meat were investigated; in which the meat products were replaced by pulses and oil crops.

[f] The recommended diet has an energy intake of 2,000 kcal per day with a macronutrient share of 55 – 60 %E from carbohydrates, 10 – 12 %E from proteins and 30%E from fats.

[g] Additional food groups included in the recommended diet were the non-core foods for example snack foods, processed meats, sugar, tea, coffee and miscellaneous, alcohol, and saturated fats and oils. In addition, dietary scenarios such as the current diet with minimal non-core foods and the foundation recommended diet were also investigated. The former scenario contained similar foods and quantities as the current diet with minimal inclusion of energy-dense processed non-core foods, thus excluding processed meat, snack foods, confectionery, soft drinks, saturated fats and oils, and alcohol; and the latter was derived from the recommended diet consistent with Australian Dietary Guidelines, however included only core foods in similar amounts to the recommended diet, while meeting minimum nutrient and energy requirements for the population. All scenarios were evaluated on macro- and micronutrient intake: energy, carbohydrate, protein, total and saturated fat, dietary fibre, vitamin A, folate, calcium, magnesium, zinc and potassium.

[h] The aggregated environmental impact includes 8 environmental impact categories: abiotic depletion, global warming, ozone layer depletion, human toxicity, eco-toxicity, phytochemical oxidation, acidification and eutrophication, all expressed as the relative changes in impact per dietary scenario to status quo diet 2003. This aggregated environmental impact and the global warming were given in absolute numbers and relative to the status quo diet.

Most studies have found that the recommended diet might have a lower environmental impact than the current diet, and thus a shift in the direction of the recommended diet might have beneficial impacts on both health and environmental sustainability. However, it is still open to debate whether the recommended diet might be the ideal solution for health and environmental sustainability combined.

(B2) Dietary quality scores

A dietary quality score (e.g. diet score [69] or nutrient profile [70, 71]) is a summary measure of adherence to a set of dietary guidelines for nutrients and/or food groups. Using this score can be regarded as an application of the dietary guidelines with the aim to identify whether different diets and/or groups of the population are consuming a diet that is close to the dietary guidelines. Seven studies used this score to address the question “How is dietary quality – as assessed by a score – related to environmental sustainability?” (Table 4). In these studies, this approach was merely applied for descriptive purposes as the aim was to compare nutritional quality of the diet by a score [39-41, 51] or by population strata [37, 38, 57], and subsequently to assess the environmental sustainability of the different diets or population strata. Out of these seven studies, three studies directly investigated the combination of a healthy and an environmentally sustainable diet by applying a dietary quality score and a sustainability score [38, 40, 41]. This sustainability score was either calculated with a composite score including diet-related greenhouse gas emission and land use [40, 41] or based on strata for the diet-related greenhouse gas emission [38, 54]. For example, Masset et al. [38] identified the “more sustainable” diets by applying both a diet score and a sustainability score, dividing the population into strata of nutritional quality and strata of greenhouse gas emission in order to describe the diets that were ranked high on both the health and the sustainability aspect of the diet.

While this approach expresses the health aspect of the diet in one overall score, the interpretation is limited by score-related limitations e.g. the inclusion of a selected number of dietary components, arbitrary penalties for unmet criteria, and the failure of the overall score to accentuate specific nutrient deficiencies. However, although such scores summarise pre-existing knowledge of diet-disease relationships, they are considered as less detailed indicators to assess dietary quality which might result in misclassification of diets, and hence weakened associations.

Table 4 Dietary quality scores, as an application of the dietary guidelines, in relation to environmental sustainability for a descriptive analysis on environmentally sustainable diets.

Reference Country	Health considerations				Environmental considerations	
	Dietary data	Diet scores ^{a}	Nutritional indicators in diet scores	Health evaluation of whole diet based on	Food aggregation level ^{b}	Environmental indicator
Carvalho et al., 2013 [51] Brazil	Individual level 2-day 24-hour recalls (Health Survey for São Paulo, 2003 - 2007)	Brazilian Healthy Eating Index Revised	9 food groups: fruits (total and, whole), vegetables (total and, dark green/orange vegetables and legumes), grains (total and, whole), milk and dairy, meat and eggs and legumes, and oils 2 restricting nutrients: sodium and saturated fat 1 other component: energy from solid fat, added sugar and alcohol	Total energy intake Nutrient intake Food group intake	/	GHGE
Vieux et al., 2013 [37] France	Individual level 7-day diet record (Individual National Survey and Food Consumption, 2006 - 2007)	Energy density Mean Adequacy Ratio Mean Excess Ratio	Total Energy and diet weigh 20 key nutrients: protein, fibre, retinol equivalents, vitamin B1, B2, B3, B6, B12, C, E, D, calcium, potassium, iron, magnesium, zinc, copper, iodine and selenium. 3 restricting nutrients: saturated fat, sodium and free sugars Total energy intake Total diet weight	Total energy intake Total diet weight Nutrient intake	391 items	GHGE
Masset et al., 2014 [38] France	Individual level 7-day diet record (Individual National Survey and Food Consumption, 2006 – 2007)	PANDiet score	20 key nutrients; protein, carbohydrate, fat, poly-unsaturated fat, fibre, vitamins A, B1, B3, B6, B9, B12, C, D and E, minerals calcium, magnesium, zinc, phosphorous, potassium and iron 3 restricting nutrients: saturated fat, cholesterol and sodium	Total energy intake Total diet weight Food group intake	391 items	GHGE ^{c}

Reference Country	Health considerations				Environmental considerations	
	Dietary data	Diet scores [a]	Nutritional indicators in diet scores	Health evaluation of whole diet based on	Food aggregation level [b]	Environmental indicator
Van Dooren et al., 2014 [40] and Van Dooren et al., 2014 [41] The Netherlands	Individual level 2-day diet record (Dutch National Food Consumption Survey, 1998)	Health score	Total energy 2 key nutrients: total fat and fibre 4 restricting nutrients: total fat, saturated fat, trans-fat, free sugars and sodium 3 food groups: vegetables, fruit and, fish	Total energy intake Food group intake	206 items	GHGE Land use [d]
Monsivais et al., 2015 [57] United Kingdom	Individual level FFQ (130-item, semi-quantitative)	DASH score	7 food groups: fruits, vegetables, nuts and legumes, whole grains, low-fat dairy, red and processed meat, and foods high in added sugar 1 restricting nutrient: sodium	Total energy intake	94 commodities	GHGE
Röös et al., 2015 [39] Sweden	Individual level 4-day diet record (Riskmaten, 2012)	Nutrient-Rich Diet 9.3 NRD 11.4 NRD 10.3	9 – 11 key nutrients: protein, fibre, vitamin A, C, E, calcium, iron, magnesium, potassium, (11.4: +vitamin D and folate; 10..3:+vitamin D and , folate - fibre) 3 – 4 restricting nutrients: SFA, added sugar, sodium (11.4: +phosphorus)	Total energy intake Nutrient intake	90 items	Climate change Land use Biodiversity damage potential

Abbreviations: GHGE, greenhouse gas emission.

[a] Diet scores are used to subdivide the population into groups of nutritional quality (e.g. Vieux et al., 2013 [37]; created four classes of nutritional quality in which a high-nutritional-quality diet was defined as having a Mean Adequacy Ratio score above the median, a Mean Excess Ratio score below the median and an Energy Density score below the median, Monsivais et al., 2015 [57]; quintiles of DASH scores, Masset et al., 2014 [38]; 2 groups by median split of PANDiet score).

Diet score are also used for comparison of different dietary scenarios (e.g. Carvalho et al., 2013 [51]; moderate meat consumption pattern with excessive meat consumption patterns (having a red and processed meat intake higher that World Cancer Research Fund maximum recommended intake of red and processed meat of 500 g/week (≈ 71.4 g/d), Röös et al., 2015 [24]; current diet with the Swedish Nordic recommended diet and the low carbohydrate - high fat diet applying energy-equivalent scenarios, Van Dooren et al., 2014 [40] and Van Dooren et al., 2014 [41]; current diet with recommended Dutch diet, semi-vegetarian, traditional vegetarian, vegan, Mediterranean, New Nordic diet, historical low lands and optimised low lands).

[b] Food aggregation level; the number of food items or commodities (depending on author's terminology) for which environmental sustainability data of food intake was available.

[c] GHGE median cut-off point to define a lower vs a higher carbon diet, and then in combination with the higher quality diet (PANDiet above median) the more sustainable diet in this populations has been identified.

[d] GHGE and land use are incorporated into a composite sustainability score, that is used for the comparison of different dietary scenarios.

(B3) Diet modelling techniques

Integrating the health aspect into environmental sciences in a more advanced way involves the application of mathematical modelling techniques, which allows for the design of optimised diets on multiple diet-related factors. Eight studies used mathematical modelling techniques, including quadratic modelling [27, 43], smooth nonlinear programming [46] and linear programming [44, 45, 52, 53, 56] to address the question "What would be the food composition of a diet when aiming at the optimisation of multiple diet-related factors?" (Table 5). These studies all aim at optimising the food composition of the diet based on objectives for health and environmental sustainability, while minimising the deviation from the habitual food composition of the current diet regardless of the modelling techniques and mathematical assumptions.

In diet modelling, nutritional constraints are used to ensure nutritional adequacy, and are built upon the physiological nutrient requirements often with the addition of a few food-based dietary guidelines (e.g. on fruit and vegetables, and fish). Additional constraints are added to the model to derive diets that are acceptable to consumers; these acceptability constraints are based on habitual food preferences, and therefore intend to minimise the deviation from the current diet. More specifically, constraints on the food quantity force the model to choose for standard useable portion sizes, and force the model to either select food items that would not have been selected because of high environmental sustainability or low nutritional values, or restrict the maximum quantity of food items that would have been selected otherwise [44, 45, 56]. Instead, constraints on food popularity force the model to minimise the deviations from the current diet [27, 45, 52, 53], whereby popularity is based on either the percentage of the population consuming a particular food item [45] or an arbitrary penalty score for any change from the current diet [27, 52, 53].

All these modelling techniques describe the optimised diet output in the format of a list of food items that can be consumed in a specified quantity, and it has been demonstrated that from such a list a seven-day week menu based on three meals a day and in-between snacks can be created while still maintaining dietary preferences (e.g. traditional meal compositions such as milk and breakfast cereals, meat and vegetables and potatoes, etc.) [44, 72]. However, the output of the diet model is highly dependent on the availability of an appropriate database, thus bridging dietary composition data with diet-related environmental sustainability data. Also, the acceptability constraints have a major influence on the output of the diet model, resulting in a sub-optimised, but more realistic diet in accordance with the current diet.

Table 5 Diet modelling using mathematical programming techniques for the design of optimised diets for health and environmental sustainability.

Reference Country	Health considerations in the diet modelling				Environmental considerations in the diet modelling	
	Dietary data	Nutritional constraints using dietary guidelines (i.e. Recommended Dietary Allowance)	Acceptability constraints with reference to the current diet	Health evaluation of whole diet based on	Food aggregation level [a]	Environmental indicator
Arnoult et al., 2010 [43] United Kingdom	Individual level 2-week diet record (Expenditure and Food Survey, 2003 – 2004)	UK Department of Health 12 nutrients 1 food group	Yes; similar energy and alcohol intake as current diet	Food group	293 items	Land use [b]
Macdiarmid et al., 2012 [44] United Kingdom	Individual level 7-day diet record (UK National Diet and Nutrition Survey, 2000 – 2001)	UK dietary guidelines for an adult women total energy 12 nutrients 3 food groups	No and Yes; food quantity limits for each food group [c]	Food group Energy Macronutrients Micronutrients	82 groups	GHGE, to be minimised
Thompson et al., 2013 [45] France Spain Sweden	Individual level 7-day diet record (INCA 2, France, 2007) 3-day diet record (ENIDE, Spain, 2013) 4-day diet record (Riskmaten, Sweden, 1997 - 1998)	Dietary guidelines from the French Agency for food, Food circle with Swedish Nutrition Recommendations Objectified	Yes; food quantity limits[c] and food popularity [d]	Food group Energy Macronutrients Micronutrients	68 items for France, 277 for Spain, and 88 for Sweden	GHGE, to be reduced by 25%
Wilson et al., 2013 [56] [e] New Zealand	Individual level 24-hour recalls and questionnaire (New Zealand Adult Nutrition Survey, 2008 – 2009)	New Zealand dietary recommendations for men total energy intake 14 nutrients	Yes; daily maximum limits for flour, pasta and oats, total vegetable intake and added salt	Food group Energy Macronutrients Micronutrients	76 items	GHGE, to be minimised

	Health considerations in the diet modelling				Environmental considerations in the diet modelling	
Reference Country	Dietary data	Nutritional constraints using dietary guidelines (i.e. Recommended Dietary Allowance)	Acceptability constraints with reference to the current diet	Health evaluation of whole diet based on	Food aggregation level [a]	Environmental indicator
Jalava et al., 2014 [27] [f] 176 countries	Population level Per country annual food supply data (FAOSTAT 2013)	County-specific dietary guidelines for total energy intake WHO dietary guidelines for macronutrient intake, and fruit and vegetables	Yes, food popularity using a penalty score for any deviation from the original diet	Macronutrients	13 groups	Consumptive water use at the global level [b]
Tyszler et al., 2014 [52] [g] The Netherlands	Individual level 2-day 24-hour recalls (Dutch National Food Consumption Survey, 2007 – 2010)	Dutch dietary guidelines for a non-active adult women total energy all macronutrients all micronutrients amino acids 2 food groups	Yes; food popularity including portion size by using a penalty score for each change in serving size [g]	Food group	207 items	pReCiPe, including GHGE, fossil energy use and land use, to be reduced by 30%
Green et al., 2015 [46] United Kingdom	Individual level 4-day diet record (UK National Diet and Nutrition Survey, 2010 – 2011)	WHO dietary guidelines 10 nutrients	Yes; similar energy intake as current diet and similar amount of liquids as current diet	Food group	42 groups	GHGE, to be gradually reduced by 10% [i]
Van Dooren et al., 2015 [53] The Netherlands	Individual level 2-day 24-hour recalls (Dutch National Food Consumption Survey, 2007 – 2010)	Dutch dietary guidelines total energy all macronutrients all micronutrients 1 food group	Yes; food popularity including portion size by using a penalty score for each change in serving size [g]	Food group Energy Macronutrients Micronutrients	206 items	GHGE, to be reduced by 20%

Abbreviations: GHGE, greenhouse gas emission.

[a] Food aggregation level; the number of food items or groups (depending on author's terminology) for which environmental sustainability data of food intake was available.

[b] Diet was optimised in view of dietary recommendations only using quadratic programming; the environmental impact was not considered during the modelling, but estimated afterwards for the optimised diet model.

[c] Food quantity limits (i.e. upper and/or lower bounds) were set for each group to give standard usable portion sizes (i.e. in whole units or in units in which it is sold).

[d] For France, acceptability constraints on food quantity for each food item included a minimum value equal to the 5th percentile of consumption observed in the population (non-consumers included) and a maximum value equal to the 95th percentile of consumption observed in the population (non-consumers excluded), to ensure that the number of daily portions is acceptable to the consumers. For Spain and Sweden, bounds were based on food popularity including minimum portion sizes. Food popularity (that is related to cultural preferences) was based on the current consumption as observed in the dietary surveys, and expressed as the percentage of the populating consuming a particular food item. This resulting in the following acceptability constraints: (1) amounts consumed in a particular food group should at least be 60 – 80% of the habitual consumption; (2) popular food (eaten by at least 50% of the population) could be increased by up to four times, but not decreased by 30% of the habitual consumption; (3) unpopular foods (eaten by less than 25% of the population) were limited to no more than twice the habitual consumption; and (4) other foods could be increased up to three times the habitual consumption.

[e] Additional diet models were optimised to meet nutrient requirements and (1) minimise costs, (2) minimise costs and GHGE, (3) be relatively healthy; Mediterranean- and Asian-style, and (4) include 'more familiar New Zealand meals'.

[f] Diet was initially optimised in view of dietary recommendations only, thereafter additional diet models were optimised using quadratic programming to meet nutritional constraints along with a forced reduction on the animal-based products, in particular including limits on the protein intake from all animal products and from meat starting from a limit to 50% and 16.7% respectively, and gradually reducing these to zero.

[g] Additional diet models were optimised to (1) meet nutritional constraints only, and along with forced reduction on animal-based products (2) excluding meat, (3) excluding meat and fish, and (4) excluding meat, fish, dairy and eggs.

[h] Penalty score; any change in servings size as compared to the current diet contributes to an arbitrary penalty score with a penalty contribution that is food and direction dependent.

[i] Diet was initially optimised in view of dietary recommendations only using smooth nonlinear programming, thereafter additional diet models were optimised in view of environmental concerns, in particular a gradual reduction by 10% of GHGE.

An approach evaluating the diet-related health impact: diet-related health impact analyses

Diet-related health impact analysis in environmental sciences addresses the question "What would be the change in health impact based on nutrient adequacy and/or health-disease outcomes when individuals adopt a more environmentally sustainable diet?" Seven studies quantified the diet-related health impact of diets differing in environmental sustainability, either directly by observing nutrient adequacy or chronic disease risk as outcomes [54, 60] or indirectly by modelling the expected health impact [31, 32, 47-49] (Table 6). The direct approach was used by one cross-sectional survey which assessed nutrient adequacy using data from the Dutch National Food Consumption Survey including 3819 subjects aged 7 – 69 years [54], and by one prospective cohort study which investigated total mortality risk using data from the EPIC-NL including 35,057 adults with a median follow-up of 16 years [60]. For the indirect approach, five studies did not actually observe nutrient adequacy or risk reductions as outcomes, but they modelled the expected diet-related health impact of the more environmentally sustainable diet based on risk ratios obtained from meta-analysis on diet-disease associations [31, 32, 47-49].

This approach of linking diet-related health/disease outcomes to environmental sustainability might be considered as suitable evidence to influence food choices and food production, since nutrient adequacy and diet-related health/disease outcomes are predictive for the future healthiness of dietary change. The healthiness of food products has been recognised as an important determinant of food choice, apart from taste and price, whereas sustainability motives are currently not considered substantial influential factors [63, 73-75].

Table 6 Diet-related health impact analyses of environmentally sustainable diets.

Reference Country	Health considerations				Environmental considerations	
	Dietary data	Dietary counterfactuals	Dietary exposure	Measure of health impact including the health-disease outcomes under study	Food aggregation level [a]	Environmental indicator
Friel et al., 2009 [49] United Kingdom Brazil	Individual level 4/7-day diet record (UK National Diet and Nutrition Surveys, 1998, 2000 and 2003) 1-day 24-hour recall (Sao Paulo The Household Health Survey, 2006)	30% decrease in the consumption of animal-based products	Decreased intake in saturated fat with increase in poly-unsaturated fat	Disability-Adjusted Life Years (DALYs) Years of Life Lost (YLL) for ischemic heart disease	/	Livestock production [b]
Aston et al., 2012 [47] United Kingdom	Individual level 7-day diet record (UK National Diet and Nutrition Survey, 2000 – 2001)	Counterfactual dietary distribution in which the proportion of vegetarians is doubled and all the non-vegetarians adopt a dietary pattern similar to that of the lowest red and processed meat consumers.	Decreased intake of red and processed meat	Potential impact fractions [c] for coronary heart disease, diabetes mellitus and colorectal cancers	45 categories	GHGE
Scarborough et al., 2012 [31] United Kingdom	Household level Per household 2-week food purchases (Family Food Survey, 2008)	– 50% decrease in the consumption of all meat and dairy products – A shift from red to white meat – A 50% decrease in white meat products	Decreased intake of meat and/or dairy , and an iso-caloric increased intake of fruit and vegetables, and cereals	Total deaths delayed or averted in the UK under each dietary counterfactual using the DIETRON model [d]	256 categories	GHGE

	Health considerations				Environmental considerations	
Reference Country	Dietary data	Dietary counterfactuals	Dietary exposure	Measure of health impact including the health-disease outcomes under study	Food aggregation level [a]	Environmental indicator
Briggs et al., 2013 [32] United Kingdom	Household level Per household 2-week food purchases (Living Costs and Food Survey , 2010)	Tax scenarios: a tax of £2.72/tonneCO2e/100 g product applied to all food and drink groups with GHGE above average Tax and subsidy scenario: including subsidies for food groups with GHGE below average	Decreased intake of food items with GHGE above average, and an increased intake of food items with GHGE below average	Total death delayed or averted in the UK under each dietary counterfactual using the DIETRON model [d]	256 categories	GHGE
Milner et al., 2015 [48] United Kingdom	Individual level 4-day diet record (UK National Diet and Nutrition Survey, 2010)	Optimised diet to achieve WHO guidelines with no GHGE reduction target and with a 10-60% reduction target [46]	Decreased intake of red and processed meat, and an increased intake of fruit and non-starchy vegetables	Years of Life Lost (YLL) for coronary heart disease, stroke, type 2 diabetes, cancers of the mouth/pharynx/larynx, oesophagus, lung, stomach and colon/rectum	42 groups	GHGE
Temme et al., 2015 [54] The Netherlands	Individual level 2-day 24-hour recalls (Dutch National Food Consumption Survey, 2007 - 2010)	Population stratification by environmental sustainability (i.e. diets of low, intermediate or high environmental load)	Dietary intake by diets of low, intermediate or high environmental load	Descriptive comparison of the food intake, energy intake and nutrient intake	254 items	GHGE

Reference Country	Health considerations				Environmental considerations	
	Dietary data	Dietary counterfactuals	Dietary exposure	Measure of health impact including the health-disease outcomes under study	Food aggregation level [a]	Environmental indicator
Biesbroek et al., 2014 [60] [e] The Netherlands	Individual level EPIC-NL FFQ (178-item, semi-quantitative, 1993 - 1997)	Population stratification by environmental sustainability (i.e. quartiles) Meat-substitution diets; one-third reduction in meat intake (35g) of the average daily meat intake (105g) [f]	Environmental sustainability, or replacement option	Crude and adjusted hazard ratios (for age, sex and energy intake) using cox proportional hazard models for all-cause mortality Cause-specific mortality (including cancer, cardiovascular diseases, respiratory diseases and other causes)	254 items	GHGE Land use

Abbreviations: GHGE, greenhouse gas emission.

[a] Food aggregation level; the number of food items or groups (depending on author's terminology) for which environmental sustainability data of food intake was available.

[b] A 30% decrease in livestock production is assumed to result in a reduction of equal size in the consumption of animal-based products, and thus a decrease in the dietary intake of saturated fat.

[c] Potential impact fraction was calculated as the difference between current aggregate risk and aggregate risk under counterfactual divided by current aggregate risk, and represents the proportion/percentage of disease in the population that can be attributed to the current diet, and therefore could potentially have been avoided under the counterfactual diet.

[d] The DIETRON model included the intake of total energy, fruit, vegetables, fibre, total fat, mono-and poly unsaturated, saturated and trans fatty acids, dietary cholesterol and salt as dietary input to estimate the link between food consumption and mortality using age-sex-specific relative risk estimates from meta-analyses.

[e] The analysis of the health impact (i.e. mortality survival analysis) was based on data from 35,057 subjects included in EPIC-NL, a prospective cohort study with a median follow-up of 15.9 years. The main aim was to investigate the relation between diet-related sustainability and mortality outcomes either by population stratification for the environmental indicators (e.g. GHGE and land use) and by meat-substitution scenarios.

[f] In the meat-substitution scenario, the replacement of meat was compensated by means of food weight and the plant-based meat-substitutes were potatoes, total vegetables, total fruit/nuts/seeds, pasta/rice/couscous, cheese, milk-based desserts or fish, representing acceptable alternatives for meat because these food are consumed in significant amounts in the Dutch diet and can replace meat in a hot meal. The reduction in all-cause mortality risk and environmental impact was estimated separately per meat-substitution option and for an option with no replacement.

METHODOLOGICAL CONSIDERATIONS

The design of optimised sustainable diets should take into account certain methodological considerations as presented below. First, the current diet needs to be linked to health and environmental sustainability, whereby this link depends on the assessment method of the current diet. Second, the indicators of ‘health’ and ‘environmental sustainability’ must be well-defined to support the design of sustainable diets. Third, sustainable diets incorporates more than only health and environmental sustainability, and thus future steps have to be taken to identify the social, ethical [76] and economic [77] indicators related to a sustainable diet, such as the cultural acceptance of a diet, the biodiversity, animal health and welfare, the production of economically fair products that are accessible and affordable for people at all times, etc.

Food availability or food intake –
How to connect health with environmental sustainability?

The assessment of the current diet can be based on either food availability related to food production and expenditure, or actual food intake closely related to food consumption and thus the health aspect of the diet. The main questions related to designing sustainable diets are “How to connect health with environmental sustainability?” and “What is the influence of the assessment method?”

The quantification of diet-related environmental sustainability should be preferably based on food availability estimates rather than on actual food intake data. The reason for this is that food availability estimates represent the food supply/production or food expenditure/purchases at the national or at the household level, and thus include food losses at production level and food wastages at consumption level. For example, data on the per capita food supply obtained from the Food Balance Sheets (FBS) of the FAO reflect the quantity of food products that are produced, used for trade, adjusted for stock changes and non-nutritional use, and expressed in primary equivalents (primary food commodities) per capita per day [78], whereas data on the households’ consumption expenditure obtained from the Household Budget Surveys (HBSs) reflect the quantity of food products that enters the households [79]. However, food availability estimates have little connection to the individual dietary pattern and thereby its diet-health relationship, as noticed in the limited health evaluation of the whole diet in studies using population or household measurement level.

In contrast, an individual's diet that is obtained from individual-level food intake assessment methods enables a strong connection with individuals' diet-related factors (e.g. age, sex, socio-economic status) and corresponding health aspects (e.g. nutrient adequacy and/or diet-related health/disease outcomes) [80], but has a less strong connection with the estimation of environmental sustainability (e.g. indicators are typically only available for primary food commodities up to the regional distribution centre). When using individual-level food intake assessment, some underlying methodological issues should be taken into account for assessing the health aspect of a diet at population level, in particular the representativeness of the individual's diet and the sample's representativeness for the population [80]. National survey methods, e.g. diet records and 24-hour recalls, are suitable methods to assess the intake of an unlimited number of food items, consumed by an individual over one or more days, with portion sizes and preparation practices, and hereby describing habitual intakes at population level, but not linking this with diet-related health/disease outcomes within individuals. An FFQ that focusses on ranking individuals according to their usual food intake by capturing the intake of food items over a designated time period (e.g. usually varying from the last month to the last year) from a finite list have been commonly used to assess the association between dietary intake and health/disease outcomes in large epidemiological studies. When aiming at estimating the environmental sustainability related to food consumption, the answer on the question which dietary assessment method to use depends on the desired link with health and the desired level of food aggregation, which is not yet available for sustainability indicators, on the level of (all) individual food items.

In short, this discrepancy in measurement/aggregation level forms a methodological barrier in connecting both health and environmental sustainability aspects of a diet. Based on the literature review, when aiming at designing sustainable diets, dietary data collected at the individual level might be considered as the preferred measurement level. The main reason for the selection of this measurement level is the possibility for monitoring health in terms of foods and nutrients, without directly hampering the linkage with environmental sustainability indicators. Foods are the common denominator regardless of the higher aggregation level of sustainability indicators and their conversion into primary commodities [81].

FUTURE PERSPECTIVES

In a complex field that has emerged from different scientific disciplines, clear definitions of ‘health’ and ‘environmental sustainability’ are essential. Health can be defined on the basis of nutrients and foods; the former using dietary reference values related to physiological needs for healthy growing and ageing [82], and the latter using food-based dietary guidelines related to health-disease outcomes [83]. A further issue in this is that nutrient-based and food-based dietary guidelines differ between countries, and that they are based on population averages with average energy requirements, whereas physiological nutrient needs vary considerably because of body size, physical activity and phase of the life cycle. Expressing nutritional requirements and intakes in terms of nutrient densities might be helpful to independently address food composition and energy intake [84]. However, when designing an optimised sustainable diet, both facets of nutritional health should be taken into account, i.e. the essential nutrients that are consumed in insufficient amounts or in excess at population level (nutritional adequacy), and the important acceptable foods for maintaining nutrient intake and promoting health (food-based dietary guidelines).

With regard to environmental sustainability, the quantification of this is still in its infancy and driven by present knowhow and available measurement equipment. This often results in focussing on the environmental impact of greenhouse gas emissions and land use, while omitting the broader perspective that also includes natural resource use and biodiversity, amongst others. Because this emphasis on greenhouse gas emissions and land use was included specifically in our search terms, this may have influenced the number of papers within the five approaches identified, but the range of approaches is likely to be covered. Also, the environmental assessment is often restricted to the system boundaries of the lifecycle assessment, which in theory cycles from farmer production to final consumption and disposal, but in practice usually stops at the distribution centre or even at the farm gate; thus many studies do address food availability on the basis of food production and/or food purchase data, i.e. addressing food that is produced and/or entering the households, thereby ignoring inedible parts and food waste[85]. Future research is therefore needed to develop quantitative methods for assessing the full picture of diet-related environmental sustainability indicators.

CONCLUSION

In operationalising the health aspect of an environmentally sustainable diet, the first priority will be to define which research questions to address and the second will be to ascertain an appropriate match in the measurement level of health and environmental sustainability. The research questions determine whether to apply a descriptive or an analytical outline. The descriptive outline refers to the comparison of different diets based on dietary guidelines, dietary quality scores and diet-related health-impact analysis, while the analytical outline refers to the design of alternative diets based on food item replacement and diet modelling techniques. Therefore, in the context of operationalising the health aspect when designing sustainable diets, diet modelling might be considered as the preferred approach since it captures the complexity of the diet as a whole. Hence, there is a need for individual-level dietary data related to the food consumption with regard to food and nutrient intakes. It is important to recognise that the concept of sustainable diets is used across multiple fields, and not only includes food and nutrition as such, but also the environment, agriculture, animal sciences, social and economic sciences which need to be taken into account when designing sustainable diets for the future.

An avenue for future research in designing sustainable diets: the SHARP diet

In the context of developing a future vision for designing optimised sustainable diets, the broader concept of sustainable diets as defined by the FAO [10] should be considered when aiming at diet optimisation in a multi-dimensional way. We, therefore, propose the concept of a diet that is SHARP: environmentally Sustainable (S), Healthy (H), Affordable (A; accessible for consumers yet also supporting the agriculture food sector), Reliable (R; stable in their supply and safe) and Preferable (P; consistent with cultural norms and food preferences). This SHARP diet would be in line with the wider definition of sustainability by including both its social, ecological and economic dimensions. This requires further exploration of mapping these diet-related dimensions into objectives/constraints for the diet model that aims at an optimised sustainable diet for all diet-related sustainability perspectives.

Diet modelling might be the preferred approach to analyse current and design future diets as multiple diet-related aspects (e.g. health, environmental sustainability, affordability, accessibility and acceptability) can be taken into account simultaneously. The output of the diet model (i.e. food list with specified quantities) is highly dependent on the constraints included and the diet-related sustainability data available. As different parameter settings for these constraints might have major effects, the robustness of such diet models need attention, especially with respect to trade-off between conflicting objectives and exploring adaptiveness to future changes in environmental sustainability options (e.g. improved food production processes), food consumption patterns (e.g. innovative new food products) and/or other diet-related factors (e.g. accessibility and affordability). A major challenge with analysing potential trade-offs to identify preferred scenarios is, however, to fully understand the interaction across all indicators of a sustainable diet within the different socio-economic and environmental contexts [86]. Importantly, the output of the diet model should not be viewed as achieving one optimum, but rather a set of preferred dietary options dependent on the optimisation aims of the different stakeholders (e.g. consumers, agricultural sectors, food industries, politicians).

Financial support

Funding was obtained from the Dutch Dairy Association (NZO), the European Union’s H2020 Programme (Grant Agreement number 633692, SUSFANS); preparatory work was funded by the Graduate School VLAG, Wageningen.

Conflict of interest

The authors have no personal or financial conflicts of interest.

Acknowledgements

The authors acknowledge prof Toon van Hooijdonk (Food Quality and Design, Wageningen University; Friesland Campina, Amersfoort, The Netherlands) for interesting academic partners and food industries in joint research into healthy, sustainable and consumer-friendly diets

REFERENCES

1. Tilman D, Balzer C, Hill J, Befort BL: **Global food demand and the sustainable intensification of agriculture**. *Proc Natl Acad Sci U S A* 2011, **108**(50):20260-20264.
2. Vermeulen SJ, Campbell BM, Ingram JSI: **Climate Change and Food Systems**. *Annu Rev Environ Resour* 2012, **37**:195.
3. Alexandratos N, Bruinsma J: **World agriculture towards 2030/2050: the 2012 revision**. In.: ESA Working paper; 2012.
4. Godfray H, Beddington J, Crute I, Haddad L, Lawrence D, Muir J, Pretty J, Robinson S, Thomas S, Toulmin C: **Food security: the challenge of feeding 9 billion people**. *Science* 2010, **327**:812 - 818.
5. Maynard LA: **An adequate diet**. *JAMA* 1959, **170**(4):457-458.
6. WHO (World Health Organisation): **Diet, nutrition and the prevention of chronic diseases**. In: *World Health Organ Tech Rep Ser.* vol. 916; 2003.
7. Garnett T: **Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)?** *Food Policy* 2011, **36**:S23-S32.
8. Hallström E, Carlsson-Kanyama A, Börjesson P: **Environmental impact of dietary change: a systematic review**. *J Clean Prod* 2015, **91**(0):1-11.
9. Craig WJ, Mangels AR: **Position of the American Dietetic Association: vegetarian diets**. *J Am Diet Assoc* 2009, **109**(7):1266-1282.
10. Burlingame B, Dernini S: **Biodiversity and sustainable diets united against hunger 3–5 November 2010 FAO Headquarters, Rome**. In.; 2012.
11. Alder J, Barling D, Dugan P, Herren H, Josupeit H, Lang T, Lele U, McClennen C, Murphy-Bokem D, Scherr S: **Avoiding future famines: strengthening the ecological foundation of food security through sustainable food systems**. 2012.
12. Eshel G, Martin PA: **Diet, Energy, and Global Warming**. *Earth Interact* 2006, **10**(9):1-17.
13. Baroni L, Cenci L, Tettamanti M, Berati M: **Evaluating the environmental impact of various dietary patterns combined with different food production systems**. *Eur J Clin Nutr* 2007, **61**(2):279-286.
14. Stehfest E, Bouwman L, van Vuuren D, den Elzen M, Eickhout B, Kabat P: **Climate benefits of changing diet**. *Clim Chang* 2009, **95**:83 - 102.
15. Westhoek H, Lesschen JP, Rood T, Wagner S, De Marco A, Murphy-Bokern D, Leip A, van Grinsven H, Sutton MA, Oenema O: **Food choices, health and environment: Effects of cutting Europe's meat and dairy intake**. *Glob Environ Chang* 2014, **26**(0):196-205.
16. Gerbens-Leenes W, Nonhebel S: **Food and land use. The influence of consumption patterns on the use of agricultural resources**. *Appetite* 2005, **45**(1):24-31.
17. Buzby J, Wells H, Vocke G: **Possible implications for U.S. agriculture from adoption of select dietary guidelines.** In: *Economic Research Service.* Washington: USDA; 2006.
18. Tukker A, Goldbohm RA, de Koning A, Verheijden M, Kleijn R, Wolf O, Perez-Dominguez I, Rueda-Cantuche JM: **Environmental impacts of changes to healthier diets in Europe**. *Ecol Econ* 2011, **70**(10):1776-1788.
19. Wolf O, Pérez-Domínguez I, Rueda-Cantuche JM, Tukker A, Kleijn R, de Koning A, Bausch-Goldbohm S, Verheijden M: **Do healthy diets in Europe matter to the environment? A quantitative analysis**. *J Policy Model* 2011, **33**(1):8-28.
20. Capone R, Iannetta M, Bilali HE, Colonna N, Debs P, Dernini S, Maiani G, Intorre F, Polito A, Turrini A *et al*: **A Preliminary Assessment of the Environmental Sustainability of the Current Italian**

Dietary Pattern: Water Footprint Related to Food Consumption. *J Food Nutr Res* 2013, **1**(4):59-67.

21. Sáez-Almendros S, Obrador B, Bach-Faig A, Serra-Majem L: **Environmental footprints of Mediterranean versus Western dietary patterns: beyond the health benefits of the Mediterranean diet**. *Environ Health* 2013, **12**(118.10):1186.
22. Saxe H, Larsen TM, Mogensen L: **The global warming potential of two healthy Nordic diets compared with the average Danish diet**. *Clim Chang* 2013, **116**(2):249-262.
23. Vanham D: **The water footprint of Austria for different diets**. *Water Sci Technol* 2013, **67**(4):824–830.
24. Vanham D, Mekonnen MM, Hoekstra AY: **The water footprint of the EU for different diets**. *Ecol Indic* 2013, **32**(0):1-8.
25. Heller MC, Keoleian GA: **Greenhouse gas emissions of the US diet: aligning nutritional recommendations with environmental concerns**. In: *9th International Conference LCA of Foods: 2014; San Francisco, USA*; 2014.
26. Heller MC, Keoleian GA: **Greenhouse gas emission estimates of US dietary choices and food loss**. *J Ind Ecol* 2014.
27. Jalava M, Kummu M, Porkka M, Siebert S, Varis O: **Diet change—a solution to reduce water use?** *Environ Res Lett* 2014, **9**(7):074016.
28. Collins A, Fairchild R: **Sustainable Food Consumption at a Sub-national Level: An Ecological Footprint, Nutritional and Economic Analysis**. *J Environ Pol Plan* 2007, **9**(1):5-30.
29. Friel S, Barosh LJ, Lawrence M: **Towards healthy and sustainable food consumption: An Australian case study**. *Public Health Nutri* 2013, **17**(05):1156-1166.
30. Pairotti MB, Cerutti AK, Martini F, Vesce E, Padovan D, Beltramo R: **Energy consumption and GHG emission of the Mediterranean diet: a systemic assessment using a hybrid LCA-IO method**. *J Clean Prod* 2015, **103**:507-516.
31. Scarborough P, Allender S, Clarke D, Wickramasinghe K, Rayner M: **Modelling the health impact of environmentally sustainable dietary scenarios in the UK**. *Eur J Clin Nutr* 2012, **66**(6):710-715.
32. Briggs A, Kehlbacher A, Tiffin R, Garnett T, Rayner M, Scarborough P: **Assessing the impact on chronic disease of incorporating the societal cost of greenhouse gases into the price of food: an econometric and comparative risk assessment modelling study**. *BMJ open* 2013, **3**(10):e003543.
33. Berners-Lee M, Hoolohan C, Cammack H, Hewitt CN: **The relative greenhouse gas impacts of realistic dietary choices**. *Energy Policy* 2012, **43**:184-190.
34. Hoolohan C, Berners-Lee M, McKinstry-West J, Hewitt CN: **Mitigating the greenhouse gas emissions embodied in food through realistic consumer choices**. *Energy Policy* 2013, **63**:1065-1074.
35. Vieux F, Darmon N, Touazi D, Soler LG: **Greenhouse gas emissions of self-selected individual diets in France: Changing the diet structure or consuming less?** *Ecological Economics* 2012, **75**(0):91-101.
36. Werner LB, Flysjo A, Tholstrup T: **Greenhouse gas emissions of realistic dietary choices in Denmark: the carbon footprint and nutritional value of dairy products**. *Food Nutr Res* 2014, **58**.
37. Vieux F, Soler LG, Touazi D, Darmon N: **High nutritional quality is not associated with low greenhouse gas emissions in self-selected diets of French adults**. *Am J Clin Nutr* 2013, **97**(3):569-583.

38. Masset G, Vieux F, Verger EO, Soler LG, Touazi D, Darmon N: **Reducing energy intake and energy density for a sustainable diet: a study based on self-selected diets in French adults**. *Am J Clin Nutr* 2014, **99**(6):1460-1469.
39. Roos E, Karlsson H, Witthoft C, Sundberg C: **Evaluating the sustainability of diets-combining environmental and nutritional aspects**. *Environmental Science & Policy* 2015, **47**:157-166.
40. van Dooren C, Marinussen M, Blonk H, Aiking H, Vellinga P: **Exploring dietary guidelines based on ecological and nutritional values: A comparison of six dietary patterns**. *Food Policy* 2014, **44**:36-46.
41. Van Dooren C, Aiking H: **Defining a nutritionally healthy, environmentally friendly, and culturally acceptable Low Lands Diet**. In: *9th International Conference LCA of Foods: 2014; San Francisco, USA*; 2014.
42. Germani A, Vitiello V, Giusti AM, Pinto A, Donini LM, del Balzo V: **Environmental and economic sustainability of the Mediterranean Diet**. *Int J Food Sci Nutr* 2014, **65**(8):1008-1012.
43. Arnoult MH, Jones PJ, Tranter RB, Tiffin R, Traill WB, Tzanopoulos J: **Modelling the likely impact of healthy eating guidelines on agricultural production and land use in England and Wales**. *Land Use Policy* 2010, **27**(4):1046-1055.
44. Macdiarmid JI, Kyle J, Horgan GW, Loe J, Fyfe C, Johnstone A, McNeill G: **Sustainable diets for the future: Can we contribute to reducing greenhouse gas emissions by eating a healthy diet?** *Am J Clin Nutr* 2012, **96**(3):632-639.
45. Thompson S, Gower R, Darmon N, Vieux F, Murphy-Bokern D, Maillot M: **A balance of healthy and sustainable food choices for France, Spain and Sweden**. In. Godalming, United Kingdom: WWF-UK; 2013.
46. Green R, Milner J, Dangour AD, Haines A, Chalabi Z, Markandya A, Spadaro J, Wilkinson P: **The potential to reduce greenhouse gas emissions in the UK through healthy and realistic dietary change**. *Climatic Change* 2015, **129**(1-2):253-265.
47. Aston LM, Smith JN, Powles JW: **Impact of a reduced red and processed meat dietary pattern on disease risks and greenhouse gas emissions in the UK: a modelling study**. *BMJ open* 2012, **2**(5).
48. Milner J, Green R, Dangour AD, Haines A, Chalabi Z, Spadaro J, Markandya A, Wilkinson P: **Health effects of adopting low greenhouse gas emission diets in the UK**. *BMJ open* 2015, **5**(4).
49. Friel S, Dangour AD, Garnett T, Lock K, Chalabi Z, Roberts I, Butler A, Butler CD, Waage J, McMichael AJ *et al*: **Health and Climate Change 4 Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture**. *Lancet* 2009, **374**(9706):2016-2025.
50. Temme EH, van der Voet H, Thissen JT, Verkaik-Kloosterman J, van Donkersgoed G, Nonhebel S: **Replacement of meat and dairy by plant-derived foods: estimated effects on land use, iron and SFA intakes in young Dutch adult females**. *Public Health Nutr* 2013, **16**(10):1900-1907.
51. Carvalho AMd, César CLG, Fisberg RM, Marchioni DML: **Excessive meat consumption in Brazil: diet quality and environmental impacts**. *Public Health Nutr* 2013, **16**(10):1893-1899.
52. Tyszler M, Kramer G, Blonk H: **Just eating healthier is not enoug: studying the environmental impact of different diet scenarios for the Netherlands by linear programming**. In: *9th International Conference LCA of Foods: 2014; San Francisco, USA*; 2014.
53. van Dooren C, Tyszler M, Kramer G, Aiking H: **Combining Low Price, Low Climate Impact and High Nutritional Value in One Shopping Basket through Diet Optimization by Linear Programming**. *Sustainability* 2015, **7**(9):12837.
54. Temme EH, Toxopeus IB, Kramer GF, Brosens MC, Drijvers JM, Tyszler M, Ocke MC: **Greenhouse gas emission of diets in the Netherlands and associations with food, energy and macronutrient intakes**. *Public Health Nutr* 2015, **18**(13):2433-2445.

55. Hendrie GA, Ridoutt BG, Wiedmann TO, Noakes M: **Greenhouse gas emissions and the Australian Diet—comparing dietary recommendations with average intakes**. *Nutrients* 2014, **6**(1):289-303.

56. Wilson N, Nghiem N, Mhurchu C, Eyles H, Baker M, Blakely T: **Foods and dietary patterns that are healthy, low-cost, and environmentally sustainable: a case study of optimization modeling for New Zealand**. *PLoS One* 2013, **121**(21):2271 - 2283.

57. Monsivais P, Scarborough P, Lloyd T, Mizdrak A, Luben R, Mulligan AA, Wareham NJ, Woodcock J: **Greater accordance with the Dietary Approaches to Stop Hypertension dietary pattern is associated with lower diet-related greenhouse gas production but higher dietary costs in the United Kingdom**. *Am J Clin Nutr* 2015, **102**(1):138-145.

58. Meier T, Christen O: **Environmental impacts of dietary recommendations and dietary styles: Germany as an example**. *Environ Sci Technol* 2013, **47**(2):877-888.

59. Meier T, Christen O, Semler E, Jahreis G, Voget-Kleschin L, Schrode A, Artmann M: **Balancing virtual land imports by a shift in the diet. Using a land balance approach to assess the sustainability of food consumption. Germany as an example**. *Appetite* 2014, **74**:20-34.

60. Biesbroek S, Bueno-de-Mesquita H, Peeters P, Verschuren W, van der Schouw Y, Kramer G, Tyszler M, Temme E: **Reducing our environmental footprint and improving our health: greenhouse gas emission and land use of usual diet and mortality in EPIC-NL: a prospective cohort study**. *Environmental Health* 2014, **13**(1):27.

61. de Bakker E, Dagevos H: **Reducing meat consumption in today’s consumer society: questioning the citizen-consumer gap**. *J Agr Environ Ethic* 2012, **25**(6):877-894.

62. de Boer J, Schösler H, Aiking H: **“Meatless days” or “less but better”? Exploring strategies to adapt Western meat consumption to health and sustainability challenges**. *Appetite* 2014, **76**:120-128.

63. Verain MC, Dagevos H, Antonides G: **Sustainable food consumption. Product choice or curtailment?** *Appetite* 2015, **91**:375-384.

64. WHO (World Health Organisation): **World health statistics 2010**. In.: World Health Organization; 2010.

65. Mensink GB, Fletcher R, Gurinovic M, Huybrechts I, Lafay L, Serra-Majem L, Szponar L, Tetens I, Verkaik-Kloosterman J, Baka A *et al*: **Mapping low intake of micronutrients across Europe**. *Br J Nutr* 2013, **110**(4):755-773.

66. Health Council of the Netherlands: **Guidelines for a Healthy Diet: The Ecological Perspective**. In. The Hague: Health Council of the Netherlands; 2011.

67. Reynolds CJ, Buckley JD, Weinstein P, Boland J: **Are the dietary guidelines for meat, fat, fruit and vegetable consumption appropriate for environmental sustainability? A review of the literature**. *Nutrients* 2014, **6**(6):2251-2265.

68. Hutton T: **Sodium technological functions of salt in the manufacturing of food and drink products**. *Brit Food J* 2002, **104**(2):126-152.

69. Wirt A, Collins CE: **Diet quality–what is it and does it matter?** *Public Health Nutr* 2009, **12**(12):2473-2492.

70. Drewnowski A, Fulgoni V, 3rd: **Nutrient profiling of foods: creating a nutrient-rich food index**. *Nutr Rev* 2008, **66**(1):23-39.

71. Van Kernebeek HRJ, Oosting SJ, Feskens EJM, Gerber PJ, De Boer IJM: **The effect of nutritional quality on comparing environmental impacts of human diets**. *Journal of Cleaner Production* 2014, **73**(0):88-99.

72. Macdiarmid J, Kyle J, Horgan G, Loe J, Fyfe C, Johnstone A, McNeill G: **Livewell: a balance of healthy and sustainable food choices. WWF-UK**. In.; 2011.
73. Roininen K, Lähteenmäki L, Tuorila H: **Quantification of consumer attitudes to health and hedonic characteristics of foods**. *Appetite* 1999, **33**(1):71-88.
74. Verbeke W: **Impact of communication on consumers' food choices**. *Proc Nutr Soc* 2008, **67**(03):281-288.
75. Grunert KG, Hieke S, Wills J: **Sustainability labels on food products: Consumer motivation, understanding and use**. *Food Policy* 2014, **44**:177-189.
76. Coff C, Korthals M, Barling D: **Ethical traceability and informed food choice**. In: *Ethical traceability and communicating food.* Springer; 2008: 1-18.
77. Oosterveer P, Sonnenfeld DA: **Food, globalization and sustainability**: Routledge; 2012.
78. **Supply Utilization accounts and Food Balance Sheets - background information for your better understanding** [http://www.fao.org/economic/the-statistics-division-ess/methodology/methodology-systems/supply-utilization-accounts-and-food-balance-sheets-background-information-for-your-better-understanding/en/]
79. Trichopoulou A: **Monitoring food intake in Europe: a food data bank based on household budget surveys**. *Eur J Clin Nutr* 1992, **46**(5):S3-S8.
80. Thompson FE, Subar AF, Coulston A, Boushey C: **Dietary assessment methodology**. *Nutrition in the Prevention and Treatment of Disease* 2008, **2**:3-39.
81. Herforth A, Frongillo EA, Sassi F, Mclean MS, Arabi M, Tirado C, Remans R, Mantilla G, Thomson M, Pingali P: **Toward an integrated approach to nutritional quality, environmental sustainability, and economic viability: research and measurement gaps**. *Ann N Y Acad Sci* 2014, **1332**(1):1-21.
82. EFSA (European Food Safety Authority): **Panel (EFSA Panel on Dietetic Products, Nutrition and Allergies), 2010. Scientific Opinion on principles for deriving and applying Dietary Reference Values**. *EFSA Journal 2010* 2010, **8**(3):1458
83. WHO (world Health Organisation): **Food-based dietary guidelines in the WHO European Region**. 2003.
84. Backstrand JR: **Quantitative approaches to nutrient density for public health nutrition**. *Public Health Nutr* 2003, **6**(08):829-837.
85. Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S: **Recent developments in life cycle assessment**. *J Environ Manage* 2009, **91**(1):1-21.
86. Lock K, Smith RD, Dangour AD, Keogh-Brown M, Pigatto G, Hawkes C, Fisberg RM, Chalabi Z: **Health, agricultural, and economic effects of adoption of healthy diet recommendations**. *The Lancet* 2010, **376**(9753):1699-1709.

CHAPTER 3

FFQ versus repeated 24-hour recalls for estimating diet-related environmental impact

Elly Mertens

Anneleen Kuijsten

Johanna M Geleijnse

Hendriek Boshuizen

Edith JM Feskens

Pieter van 't Veer

Published in: Nutrition Journal 2019;18(1):2

ABSTRACT

Background There is an increasing interest in estimating environmental impact of individuals' diets by using individual-level food consumption data. However, like assessment of nutrient intakes, these data are prone to substantial measurement errors dependent on the method of dietary assessment, and this often result in attenuation of associations.

Purpose To investigate the performance of a food frequency questionnaire (FFQ) for estimating the environmental impact of the diet as compared to independent 24-hour recalls (24hR), and to study the association between environmental impact and dietary quality for the FFQ and 24hR.

Methods We analysed cross-sectional data from 1,169 men and women, aged 20-76 years, who participated in the NQplus study, the Netherlands. They completed a 216-item FFQ and two replicates of web-based 24hR. Life cycle assessments of 207 food products were used to calculate greenhouse gas emissions, fossil energy and land use, summarised into an aggregated score, pReCiPe. Validity of the FFQ was evaluated against 24hRs using correlation coefficients and attenuation coefficients. Associations with dietary quality were based on Dutch Healthy Diet 15-index (DHD15-index) and Nutrient Rich Diet score (NRD9.3).

Results For pReCiPe, correlation coefficient between FFQ and 24hR was 0.33 when adjusted for covariates age, gender and BMI, and increased to 0.76 when de-attenuated for within-subject variation in the 24hR. Energy-adjustment slightly reduced these correlations (r=0.71 for residuals of observed values and 0.59 for residuals of density values). Covariate-adjusted attenuation coefficient for the FFQ was 0.56 (λ_1=0.56 and λ_1=0.65 for observed and density residuals), slightly lower than without covariate adjustment. Diet-related environmental impact was inversely associated with the food-based DHD15-index for both FFQ and 24hR, while associations with the nutrient-based NRD9.3 were inconsistent.

Conclusion The FFQ slightly underestimated environmental impact when compared to 24hR. Associations with dietary quality are highly dependent on the diet score used, and less dependent on the method of dietary assessment.

BACKGROUND

Climate change has led to an increased interest in shifting towards environmentally-friendly food consumption patterns. Several studies have estimated the environmental impact related to dietary intake [1, 2]. This, however, is very challenging due to e.g.: high diversity in food products, their production practices, as well as inconsistencies in life cycle assessment (LCA) methods, including data availability and quality [3, 4]. On top of these, assessment of diet-related environmental impact depends on the method of dietary assessment, ranging from per capita food availability at the national level to food consumption at the individual level [5].

Assessment of the diet-related environmental impact was initially studied in the production domain dealing with a limited number of primary agricultural commodities of basic food items, using data on food availability, i.e. apparent food consumption data, defined as production – exports + imports, sourced from Eurostat and FAO databases. With the increasing availability of LCA data on single food products, it is now possible to study diet-related environmental impact in the consumer domain using food consumption data collected at the individual level. Moreover, individual-level dietary assessment allows combining environmental impact of the diet with other diet-related aspects, like dietary quality, acceptability of the diet, etc. [6]. So far, the few studies that have addressed this association with dietary quality used a multiple-day diet record [7-10] or a food frequency questionnaire (FFQ) [11, 12], but produced no clear results. Studies using diet records most often found that diet-related environmental impact was not associated with dietary quality [7-10], while an inverse association was reported in studies using FFQ [11, 12]. However, evaluation studies have shown that FFQs are subject to large between-person errors and introduce attenuation in associations with nutritional health outcomes [13, 14]. Moreover, as compared to 24hRs, FFQs are likely to perform less well for environmental impact as they purposively aggregate and incorporate food items that differentiate diets with respect to dietary quality rather than environmental impact. Until now, little is known about the potential influence of the method of dietary assessment on properly estimating diet-related environmental impact and its association with dietary quality.

Literature has acknowledged that all reported dietary intake values are prone to substantial measurement errors, both systematic, including intake-related and person-specific bias, and random errors, that often results in attenuation of the association [15]. In order to correct associations for dietary measurement error, a regression calibration approach, as introduced by Rosner et al. [16], is commonly used, which calculates attenuation coefficients in order to adjust for the bias caused by measurement error. Correct application of the regression calibration, however, is not guaranteed without a reference instrument that is unbiased and has errors independent of true exposure and independent of errors in dietary-reports [15, 17].

In the present study, we first evaluated the FFQ as a method to estimate environmental impact of individuals' diets as compared to the 24hR as the individual-level and detailed reference method of dietary assessment. Second, we studied the association between food-based and nutrient-based diet scores based on 24hR and environmental impact based on either 24hR or FFQ with adjustment for random and systematic errors in assessment.

METHODS

Study population

The present study was conducted with data obtained from the Nutrition Questionnaires plus (NQplus) study, conducted in Wageningen and its surroundings, the Netherlands [18, 19]. Initially, 2,048 men and women, aged 20-70 years were recruited between 2011 and 2013. Subjects filled out an FFQ, general and health questionnaires, and underwent physical examinations at baseline, and multiple web-based recalls 24hRs were administered. Frequency of sampling 24hRs was not identical for each subject. Recall days were randomly selected and scheduled across the first year of the study with at least 40 days in between each other. Of the NQplus study population, a total of 1,653 subjects completed one FFQ at a baseline and a total of 1,430 subjects completed two replicates of a web-based 24hR spaced over one-to-five month period. We excluded 185 subjects with misreporting for the FFQ, and 37 subjects with misreporting for the 24hR. A total of 1,169 subjects completed both an FFQ and two replicates of the 24hR, and remained for analysis (Figure 1). The NQplus study was approved by the ethics committee of Wageningen University and conducted according to the Declaration of Helsinki, and all subjects provided their written informed consent.

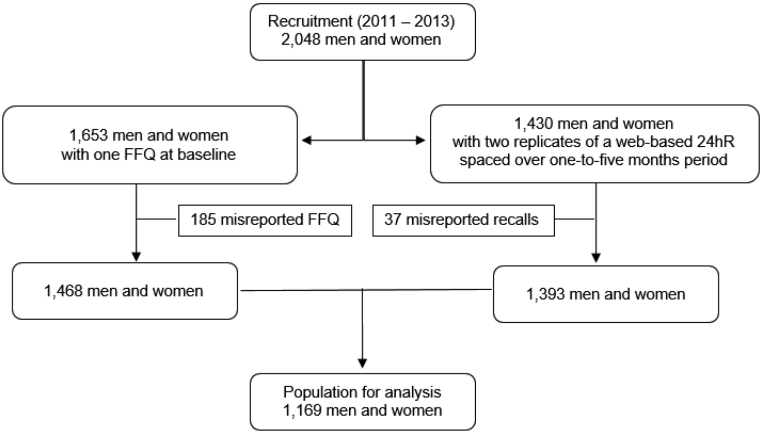


Figure 1 Flow diagram of subjects through the study

Methods of dietary assessment

The 24hR was a self-administered web-based highly-standardised version using the five-step multiple pass method, a validated technique to increase the accuracy of recalls [20]. Recall dates were randomly selected and scheduled evenly across the year and days of the week. For each subject, we included two recalls spaced over a one to five months period, resulting in 2,338 recalls. Daily energy and nutrient intakes were calculated by multiplying the intake of food items with their nutrient content using the Dutch food composition table of 2011 [21].

The FFQ was developed to assess habitual intake, and consisted of 216 food items with questions on frequency and consumed amounts with a one-month reference period. This self-administered semi-quantitative FFQ was validated for energy intake [22], macronutrients, dietary fibre and selected micronutrients [23].

Estimating diet-related environmental impact

Environmental impact was calculated based on LCA data from Blonk Consultants, available for 207 food products commonly consumed in the Dutch diet (Blonk Consultants data set version 2016) [24]. LCA were from cradle to grave, and included production, processing, packaging, transport, storage, preparation, cooking, avoidable waste and unavoidable food waste (inedible parts) at home, and waste incineration. Greenhouse gas emission (GHGE; in kilogram CO_2-equivalents (kg CO_2e)/day) covers carbon dioxide (CO_2) emissions through the use of fossil fuels, methane (CH_4) released during rearing of cattle and cultivation of certain crops, and nitrous oxide (N_2O) released from fertilizers, manure and ploughing of grassland. Fossil energy use (FE, in Mega Joules(MJ)/day) covers the resources containing hydrocarbons needed for the production of food, and land use (LU, in m^2*year/day) the surface needed for the production of food during a certain period of time. Environmental impact of the diet was reported for each impact category individually (i.e. GHGE, FE and LU), and aggregated - weighing their relative importance - into a single measure of environmental impacts, i.e. pReCiPe based on the principles of the ReCiPe method [25], calculated as

$$pReCiPe = 0.0459 * GHGE + 0.0025 * FE + 0.0439 * LU$$

where GHGE is greenhouse gas emissions in kilogram CO_2 equivalents, FE fossil energy use in mega joules, LU land use in m^2*year, and weighing values were obtained using a panel approach, then characterised and normalised using the year 2000 as reference year, and information was gathered for the European situation, as specified by the authors.

These LCA data were linked to food consumption data of the 24hRs and FFQ to calculate individual daily diet-related environmental impact using coding of the Dutch food composition table. For the 24hR, of the 1,264 food products consumed in this cohort, 1,198 (95%) food products were linked to LCA data either by direct matching or extrapolation. There was a direct match on food code for 203 (16%) food products consumed in this cohort, which covered 50% of total food weight intake, excluding beverages, and 53% of total energy intake. Extrapolations were made to other food products consumed according to the 24hR based on similarities in type of food product (11%) or production method (56%), and based on ingredient composition by using standard recipes for composite foods (12%). For the FFQ, the 216 FFQ-items were disaggregated into 1,159 food products with different contribution percentages based on Dutch dietary survey data, coded by the Dutch food composition table, and subsequently matched with LCA data on their food code. When LCA data were not available for all food products within an FFQ-item (n = 135), we scaled the food products with LCA data in such a way that the FFQ-item was 100% represented by those food products, while accounting for their contribution percentage. LCA data were available for 167 FFQ-items covering 89% of the total food weight and 86% of the total energy intake. Remaining FFQ-items (n=49) received an extrapolated value based on similarities in type of food product, production method and ingredient composition.

Estimating dietary quality

Dietary estimates of the 24hR were analysed for their dietary quality using a diet score based on food groups, i.e. the Dutch Healthy Diet Index 2015 (DHD15-index) [26], and one based on nutrients, i.e. the Nutrient Rich Diet score (NRD9.3) [10, 27]. DHD15-index consists of fifteen food groups included the Dutch food-based dietary guidelines of 2015: vegetables, fruit, wholegrain products, legumes, nuts, dairy, fish, tea, fats and oils, filtered coffee, red meat, processed meat, sweetened beverages and fruit juices, alcohol, and salt. A proportional score between 0 and 10 was assigned to all other food groups, and the final score was the mean of all food groups and ranged from 0 (minimal adherence) to 10 (maximal adherence). NRD9.3 was based on the principles of the Nutrient Rich Food Index, NRF9.3 [28, 29]. This NRF9.3 algorithm is the unweighted sum of percentage daily values (DVs) for nine nutrients to encourage (protein, dietary fibre, calcium, iron, potassium, magnesium, and vitamin A, C and E) minus the sum of percentage maximum recommended values for three nutrients to limit (saturated fat, added sugar, and sodium), calculated per 100 kcal and capped at 100%DV. We expressed nutrient intakes relative to a daily energy intake of 2,000 kcal to obtain a daily nutrient density score.

Covariates

Data were collected on age (years), sex, educational level (low: no, lower or lower vocational education; intermediate: intermediate vocational; and high: higher vocational or university), smoking status (never/former/current) by means of questionnaires. Physical activity was assessed using the Short QUestionnaire to Asses Health enhancing physical activity (SQUASH) [30], and was categorised according to the average time spent per week doing commuting, leisure-time and household activities, and activities at work (Metabolic Equivalent of Task (MET) in minutes per week); low: <500; moderate: 500 ≤ MET< 1000; high: MET ≥ 1000). Body weight was measured by a trained research assistant without shoes and heavy clothing and with empty pockets on a digital scale (SECA 877; SECA Corp.), and height was measured without shoes using a stadiometer (SECA 213; SECA Corp.). Body Mass Index (BMI) was calculated as body weight (kg) divided by height squared (m^2).

Measurement Error Model

It was assumed that estimates obtained from 24hRs were the best available standards to approximate true diet-related environmental impact, as no independent reference methods are available [31, 32]. In contrast, in the FFQ, constant bias at the group level, intake-related bias and person-specific bias were assumed to be present. The measurement error model was specified as:

24-hour recall (R): $R = T + e_R$ (1)

FFQ (Q): $Q = A_Q + B_Q\,T + q\ + e_Q$

where T is the true (unknown) intake, e the within-person random error, and A the overall constant bias at group level, B the intake-related bias and q the person-specific bias for the FFQ. By this model, it was assumed that estimates from two replicates of the 24hRs are statistically independent and contains no intake-related bias and no person-specific bias [33].

Statistical methods

To evaluate the performance of the FFQ versus the 24hR, linear mixed models with a random intercept for subjects were applied to account for the two replicates of the 24hRs per subject. Attenuation coefficient was estimated as the slope in the linear regression of the reference method (i.e. 24hR) on the FFQ through the following linear mixed model:

$$R_{ij} = \lambda_0 + \lambda_1 Q_i + u_i + e_{ij} \quad (2)$$

where R_{ij} is the j^{th} observation of the recall for the i^{th} individual, Q_i the FFQ-report of that individual, u_j the random intercept for that individual and e_{ij} the random within-person variation, λ_0 is the method-specific intercept and λ_1 the attenuation coefficient. The random terms were assumed to be independent, normally distributed with mean zero and variances $\sigma^2(u)$ and $\sigma^2(e)$. Correlation coefficients between FFQ and the average of two 24hRs were estimated as Pearson correlations, without and with adjustment for covariates age, gender and BMI. To account for within-subject variation in the 24hR, correlation coefficients were de-attenuated by dividing by the square root of the intra-class correlation coefficient (ICC) of the replicates of the 24hR; ICC was calculated as the variance in random intercept divided by the total variance obtained from a mixed model without Q as covariate under the assumption of no person-specific bias [34].

In the analysis of diet associations, e.g.: impact vs quality, covariate adjustment is essential for the internal study validity, hence the usual covariates age (continuous), gender (men/women), and BMI (continuous) were included in the calibration equation [31]. In addition, stratified analyses were performed for men and women separately (results in Supplementary Tables 1 and 2). Specific attention was paid to energy intake as a key covariate in diet analyses, using linear regression of diet-related environmental impact on energy-intake [35]; the latter was done for both observed values and densities, i.e. observed values divided by total energy intake, and standardised to 2,000 kcal. Densities and residuals were calculated for each method of dietary assessment using estimates as measured by that method of dietary assessment.

To illustrate the possible influence of the method of dietary assessment, we analysed the association between dietary quality and diet-related environmental impact by linear regression analyses with adjustments for age, gender, BMI, and energy intake. Dietary quality was assessed by the food-based DHD15-index and the nutrient-based NRD9.3 both based on the 24hR as the alleged gold standard reference. When the (explanatory) diet-related environmental impact variables were derived from the 24hR the associations with diet scores were corrected for within-subject variation using Best Linear Unbiased Predictions (BLUPs) from a mixed model without Q as covariate [36]. When the diet-related environmental impact variables were based on the FFQ, the association with dietary quality was calibrated using a mixed model accounting for random effects (i.e. the predicted values from equation 2 with covariates added). All statistical analyses were performed using SAS version 9.3 (SAS Institute, Inc.).

RESULTS

Mean age of the population was 53 (SD 12) years and mean BMI was 25.6 (SD 3.7) kg/m^2 (Table 1). More than 60% of the population completed a level of higher education, less than 35% had a high level of physical activity and less than 10% was current smoker. Approximately half of the population (48%) were women, who were on average younger, had a lower BMI, a lower level of physical activity, and a lower energy intake than men. Mean diet scores, measured by 24hR, were 4.9 (SD 1.0) for DHD15-index and 440 (SD 91) for NRD9.3; with the diets of women having a higher dietary quality (respectively 5.3 vs 4.6, and 409 vs 474). Measured by two replicates of the 24hR, mean (SD) estimated crude environmental impact of the diet was 3.6 (SD 1.5) kg CO2e/d for GHGE, 31.1 (SD 9.2) MJ/d for FE, and 4.2 (SD 1.8) m^2*year/d for LU; summarised in a pReCiPe of 0.43 (SD 0.16), with the diets of women having a lower environmental impact (pReCiPe of 0.39 versus 0.46).

Meat, dairy, and beverage consumption contributed the most to the environmental impact, irrespective of the method of dietary assessment (meat 29% of total daily dietary pReCiPe, dairy 16% and beverages 15% according to 24hR, and with similar values for the FFQ) (Table 2). Impacts of type of meat, however, differed by method of dietary assessment with for the FFQ a higher contribution to pReCiPe and its components from non-processed meat and a lower contribution from processed meat (18% vs 9%) as compared to the 24hR (15% vs 14%); consistent with reported intake differences. In addition, reported intakes of dairy and plant-based foods, like potatoes, bread, vegetables, legumes and fruit, were in general higher for the FFQ than for the 24hR. Contribution of the different food groups to daily diet-related environmental impact was dependent on the environmental impact measures for some food groups; meat had a higher share in total daily dietary GHGE and LU than in FE, while the opposite was seen for plant-based foods, fish and beverages.

Table 1 General characteristics of the NQplus study (n=1,169)[a]

	Total (n=1,169)		Men (n=606)		Women (n=563)	
Age, years	53.2	(11.5)	55.6	(10.7)	50.6	(11.7)
BMI, kg/m^2 [b]	25.6	(3.7)	26.2	(3.3)	24.9	(3.9)
Education level [c]						
Low	67	(6%)	46	(7%)	21	(4%)
Intermediate	343	(29%)	162	(27%)	181	(32%)
High	757	(65%)	397	(66%)	360	(64%)
Physical activity						
Low	539	(46%)	249	(41%)	290	(51%)
Moderate	224	(19%)	114	(19%)	110	(20%)
High	406	(35%)	243	(40%)	163	(29%)
Smoking status [d]						
Never	587	(53%)	263	(45%)	324	(61%)
Former	435	(39%)	259	(45%)	176	(33%)
Current	90	(8%)	56	(10%)	34	(6%)
Energy intake, kcal/d [e]	2012	(583)	2200	(617)	1808	(466)
DHD15-index [e]	4.92	(1.00)	4.61	(0.94)	5.29	(0.96)
NRD9.3 [e]	500	(72)	493	(71)	507	(73)
GHGE, kgCO$_2$e/d [e]	3.64	(1.46)	3.94	(1.60)	3.32	(1.20)
FE, MJ/d [e]	31.10	(9.20)	33.36	(9.83)	28.66	(7.77)
LU, m^2*year/d [e]	4.15	(1.82)	4.57	(1.99)	3.71	(1.51)
pReCiPe [e]	0.43	(0.16)	0.46	(0.18)	0.39	(0.14)

Abbreviations: DHD15-index, Dutch Healthy Diet Index 15; NRD9.3, Nutrient Rich Diet score 9.3;GHGE, greenhouse gas emissions; FE, fossil energy use; LU, land use; pReCiPe, a weighted summary score for GHGE, FE, and LU.

[a] Values are expressed as mean (standard deviations), numbers and percentages. Comparisons between men and women were tested by independent samples t-test for continuous variables and chi-square test for categorical variables. All characteristics above were statistically significant using P-value below 0.05. [b] Data were available for 1,168 subjects, i.e. 605 men and 563 women. [c] Data were available for 1,167 subjects, i.e. 605 men and 562 women. [d] Data were available for 1,112 subjects, i.e. 578 men and 534 women. [e] Dietary estimates were crude values based on two 24-hour recalls.

Table 2 Contribution of the different food groups to daily intake and environmental impact in the NQplus Study, using two replicates of the 24-hour recall and an FFQ.

	24-hour Recall						FFQ					
Food groups	g/d (%)	E%d (%)	GHGE (%)	FE (%)	LU (%)	pReCiPe (%)	g/d (%)	E%d (%)	GHGE (%)	FE (%)	LU (%)	pReCiPe (%)
Potatoes	2.5	4.1	1.7	3.0	2.1	2.1	3.3	3.9	2.0	3.5	2.5	2.5
Cereals,cereal products												
Bread products	5.2	18.1	3.7	5.5	4.4	4.3	5.5	15.2	3.4	5.1	4.3	4.1
Cake, Biscuits	1.5	7.4	2.6	2.8	3.1	2.9	1.5	6.2	2.1	2.5	2.9	2.5
Pasta,rice,couscous	2.0	5.4	1.8	1.8	2.9	2.3	3.0	5.5	2.7	2.2	3.7	3.1
Vegetables	5.1	1.9	5.1	8.0	1.9	4.3	6.9	2.3	5.4	9.1	2.0	4.6
Legumes	0.2	0.4	0.2	0.4	0.2	0.3	0.6	0.7	0.6	0.9	0.4	0.6
Fruit	5.7	5.1	3.8	5.1	1.9	3.3	8.0	5.4	4.9	6.7	2.4	4.2
Nuts and seeds	0.4	3.3	0.6	0.6	2.3	1.4	0.6	4.4	0.9	0.9	3.3	1.9
Dairy												
Cheese	1.2	5.8	8.7	4.7	5.6	6.6	1.3	4.8	8.4	4.5	5.3	6.4
Milk[a]	6.1	4.2	5.9	4.9	4.0	4.9	7.8	4.1	6.8	5.5	4.5	5.6
Milk-based desserts[b]	4.4	4.7	5.4	4.3	3.3	4.3	5.4	4.8	5.8	4.7	3.5	4.6
Meat												
Non-processed[c]	1.4	3.1	15.7	9.4	16.9	15.0	1.6	2.8	18.6	9.8	20.5	17.8
Processed[d]	1.7	5.5	14.9	8.8	14.3	13.6	1.4	3.7	9.5	6.2	8.8	8.6
Fish	0.7	1.7	2.9	4.9	1.1	2.5	0.7	1.2	3.0	5.1	0.6	2.3
Eggs	0.5	1.0	1.3	1.5	1.6	1.5	0.6	0.9	1.4	1.6	1.7	1.6
Vegetarian products												
Soy drink, desserts[e]	0.1	0.1	0.0	0.1	0.1	0.0	0.3	0.2	0.1	0.1	0.1	0.1
Meat replacers	0.2	0.3	0.2	0.3	0.2	0.2	0.2	0.3	0.3	0.4	0.3	0.3
Fats, Oils, Sauces	1.1	6.4	2.5	2.2	4.3	3.2	1.8	10.1	3.2	3.3	7.4	5.0
Sugar, Sweets[f]	0.9	5.6	1.1	1.7	1.3	1.3	1.8	7.5	3.4	2.6	3.5	3.3
Snacks	0.5	2.7	1.5	1.7	1.8	1.7	1.3	5.7	2.9	3.4	4.4	3.6
Soup,Composite dishes	4.0	4.4	7.8	7.3	12.3	9.6	2.7	3.3	3.1	1.8	3.7	3.3
Beverages												
Non-alcoholic	48.0	2.8	7.9	13.6	8.3	9.1	40.0	4.7	9.9	16.4	13.3	12.5
Alcoholic	6.2	5.6	4.5	7.3	6.0	5.6	3.7	2.2	1.6	2.6	1.0	1.5

Abbreviations: DHD15, Dutch Healthy Diet Index 15; NRD7.3, Nutrient Rich Diet score 7.3; GHGE, greenhouse gas emissions; FE, fossil energy use; LU, land use; pReCiPe, a weighted summary score for GHGE, FE, and LU

[a] milk: milk, milk beverages (chocolate milk) and coffee milk [b] milk-based desserts: all kind of yoghurts, creams, and milk-based puddings and dessert [c] non-processed meat: beef, pork, and chicken [d] processed meat: meat products as sandwich filling, ham, ready-to-eat minced meat, sausages, organ meat and miscellaneous types [e] soy drinks, desserts: soy-based drinks, yoghurts, puddings and creams [f] Sugar, sweets: sugar, candy, sweet and savoury sandwich filling like jams, honey, chocolate spread, peanut butter.

Table 3 shows the diet-related environmental impact according to the FFQ and the 24hR as well as the ICC for the latter. Observed values for FFQ and 24hR were similar for protein, and environmental indicators (<5% difference), but energy intake was overestimated by the FFQ (6%). After energy-adjustment, we observed underestimated values for protein intake (6%) and for diet-related environmental impact measures (7-10%) by the FFQ. ICC for replicates of the 24hR were low (≤ 0.30) for all variables under study; they were slightly lower for observed residuals (0.12-0.22) than for observed values (0.17-0.28) and density residuals (0.19-0.30). Thus, most of the observed variation was due to within-person variation, such as day-to-day variability, rather than between-person variation.

The crude correlation coefficient between FFQ and 24hR was 0.46 for protein, and ranged from 0.35 for GHGE to 0.45 for FE, but weakened after covariate adjustment. When accounting for random error in the 24hR, the correlation coefficient was 0.75 for protein, and ranged from 0.66 for GHGE to 0.76 for pReCiPe, as shown by the de-attenuated correlation coefficient. After adjustment for energy, de-attenuated correlation coefficients were similar when using observed residuals, but they were lower when using density residuals, except for protein.

Estimated attenuation coefficients, as displayed by the regression slopes λ_1, were all below one, pointing to a flattened slope phenomenon in associations when using the FFQ. This attenuation appeared to be more severe with the inclusion of the covariates age, gender and BMI in the measurement error model for all variables under study (attenuation coefficients were lower). Covariate-adjusted attenuation coefficient for observed values was 0.51 for protein, and ranged from 0.53 for GHGE to 0.57 for FE. Energy-adjustment by the residual method of observed values showed similar attenuation coefficients as with non-energy-adjusted values; and for density residuals, the fully-adjusted attenuation coefficients tended to be higher, i.e. attenuation was lower than for the non-energy adjusted values, but less marked for protein and GHGE (with attenuation coefficient of 0.54 for protein and from 0.57 for GHGE to 0.69 for FE).

Table 3 Diet-related environmental impact according to the food frequency questionnaire (FFQ) and two replicates of the 24-hour recall (24hR, with intra-class correlation coefficient) and group level bias, with correlation between the methods (crude, adjusted, de-attenuated) and attenuation coefficient (crude, adjusted) for observed and energy-adjusted values standardised to a 2,000 kcal diet [a].

	FFQ	2 replicates of 24hR			Correlation coefficient (24hR with FFQ)			Attenuation coefficient λ_1	
Dietary variables	Mean (SD)	Mean (SD)	%bias	ICC	Crude (95%CI)	Adjusted[b](95%CI)	De-attenuated(95%CI)	Crude (SE)	Adjusted[b] (SE)
Observed values									
Energy, kcal/d	2139 (532)	2012 (583)	6.3	0.31	0.47 (0.43; 0.52)	0.38 (0.33; 0.43)	0.68 (0.59; 0.77)	0.52 (0.03)	0.42 (0.03)
Protein, g/d	77.6 (18.5)	78.2 (23.5)	-0.8	0.27	0.46 (0.41; 0.50)	0.39 (0.34; 0.44)	0.75 (0.65; 0.84)	0.58 (0.03)	0.51 (0.04)
GHGE, $kgCO_2e/d$	3.50 (0.87)	3.64 (1.46)	-3.8	0.21	0.35 (0.30; 0.40)	0.30 (0.25; 0.35)	0.66 (0.54; 0.77)	0.59 (0.05)	0.53 (0.05)
FE, MJ/d	30.19 (6.71)	31.10 (9.20)	-2.9	0.28	0.45 (0.40; 0.49)	0.40 (0.35;0.44)	0.75 (0.66; 0.84)	0.62 (0.04)	0.57 (0.04)
LU, m^2*year/d	4.01 (1.08)	4.15 (1.82)	-3.4	0.17	0.37 (0.32; 0.42)	0.31 (0.26; 0.36)	0.75 (0.62; 0.87)	0.63 (0.05)	0.56 (0.05)
pReCiPe	0.41 (0.10)	0.43 (0.16)	-4.7	0.19	0.39 (0.34; 0.43)	0.33 (0.28; 0.38)	0.76 (0.64; 0.87)	0.62 (0.04)	0.56 (0.05)
Energy-adjusted values by regression residuals of observed values on energy(observed residuals)									
Protein, g/d	73.5 (10.3)	77.9 (14.2)	-5.6	0.20	0.35 (0.30; 0.40)	0.33 (0.28; 0.38)	0.75 (0.63; 0.86)	0.49 (0.04)	0.46 (0.04)
GHGE, $kgCO_2e/d$	3.33 (0.61)	3.63 (1.24)	-8.3	0.12	0.26 (0.20; 0.31)	0.23 (0.17; 0.28)	0.66 (0.50; 0.81)	0.52 (0.06)	0.48 (0.06)
FE, MJ/d	28.82 (4.21)	30.98 (6.77)	-7.0	0.22	0.39 (0.34; 0.43)	0.35 (0.30; 0.40)	0.76 (0.65; 0.86)	0.62 (0.04)	0.59 (0.05)
LU, m^2*year/d	3.80 (0.71)	4.14 (1.56)	-8.2	0.13	0.30 (0.24; 0.35)	0.27 (0.21; 0.32)	0.73 (0.58; 0.88)	0.65 (0.06)	0.60 (0.06)
pReCiPe,	0.39 (0.07)	0.43 (0.14)	-9.3	0.14	0.30 (0.24; 0.35)	0.26 (0.21; 0.32)	0.71 (0.57; 0.85)	0.61 (0.06)	0.56 (0.06)
Energy-adjusted values by regression residuals of densities on energy (density residuals)									
Protein density, %	14.9 (2.0)	15.9 (3.1)	-6.3	0.20	0.37 (0.31; 0.41)	0.35 (0.29; 0.40)	0.78 (0.66; 0.89)	0.57 (0.04)	0.54 (0.04)
GHGEdensity,$kgCO_2e/d$	3.38 (0.60)	3.73 (1.30)	-9.4	0.19	0.28 (0.23; 0.33)	0.25 (0.20; 0.30)	0.59 (0.46; 0.71)	0.61 (0.06)	0.57 (0.06)
FE density, MJ/d	29.31 (4.09)	32.14 (7.62)	-8.8	0.30	0.39 (0.34; 0.44)	0.36 (0.31; 0.41)	0.66 (0.56; 0.74)	0.73 (0.05)	0.69 (0.05)
LU density, m^2*year/d	3.83 (0.70)	4.24 (1.72)	-9.7	0.21	0.30 (0.24; 0.35)	0.27 (0.21; 0.32)	0.59 (0.47; 0.71)	0.73 (0.07)	0.67 (0.07)
pReCiPe density	0.40 (0.06)	0.44 (0.15)	-9.1	0.22	0.31 (0.26; 0.36)	0.28 (0.22; 0.33)	0.59 (0.48; 0.71)	0.70 (0.06)	0.65 (0.07)

ICC, intra class correlation coefficient; GHGE, greenhouse gas emissions; FE, fossil energy use; LU, land use; pReCiPe, a weighted summary score for GHGE, FE, and LU; % bias, group-level bias calculated as (mean intake FFQ /mean intake 24hR)x100; 100; correlation coefficient (95%CI) estimated as the Pearson correlation coefficient; de-attenuated correlation coefficient (95%CI) estimated as the Pearson correlation coefficient/$\sqrt{ICC_{24hR}}$; Attenuation coefficient λ_1 (SE) estimated as the slope in the linear regression of the 24hR on the FFQ using linear mixed models to account for within-person day-to-day variability.

[a] Mean values with their standard deviations, correlation coefficient with its 95% confidence intervals, attenuation coefficient with its standard error.

[b] Adjusted for age, gender and BMI.

In stratified analysis, patterns of results for group-mean bias, correlation coefficients, and attenuation coefficients were generally similar for men and women (Supplementary Tables 1 and 2). Estimated correlation coefficients and attenuation coefficients for observed values did not change with covariate adjustment; indicating that gender explained most of the variation in this population. However, when using energy-adjusted values, as compared to non-energy-adjusted values, attenuation coefficients appeared to be higher for density residuals, and this was more marked in women than in men.

Table 4 shows the association between dietary quality (DHD15-index and NRD9.3) and diet-related environmental impact using observed and de-attenuated 24hR-values, and observed and calibrated FFQ-values, for different methods of energy adjustment. Regression coefficients represent the percentage change in diet score per unit increase in diet-related environmental impact. Diet-related environmental impact was significantly inversely associated with the food-based DHD15-index, for all environmental impact measures, and for all methods of dietary assessment. Compared to de-attenuated 24hR-values, regression coefficients using FFQ-values as observed were weakened, and became closer when calibrated FFQ-values were used. For the nutrient-based NRD9.3, no statistically significant associations were observed for summary score pReCiPe and its components GHGE and LU, but a positive significant association was observed for FE. Using de-attenuated 24hR-values showed a negative association for LU, while using FFQ-values as observed showed a positive association and calibration could only repair this when using energy-adjusted values. Considering the method of energy adjustment, for both DHD15-index and NRD9.3, associations based on de-attenuated 24hR-values were stronger for observed residuals than for observed values with inclusion of energy in the multivariate model, but were weaker for density residuals.

Table 4 Regression coefficients (with 95% confidence intervals)[a] for dietary quality, measured by food-based DHD15 -index and nutrient-based NRD9.3, and diet-related environmental impact, measured by GHGE, FE, LU, and pReCiPe, using observed and de-attenuated 24-hour recall (24hR)-values, and observed and calibrated FFQ-values, for different methods of energy adjustment in the total population.

Response variables	**DHD15-index (based on 2 replicates of 24hR)**						**NRD9.3 (based on 2 replicates of 24hR)**					
Explanatory variables	Observed values		Observed residuals		Density residuals		Observed values		Observed residuals		Density residuals	
	β	(95%CI)	β	(95%CI)	β	(95%CI)	β	(95%CI)	β	(95%CI)	β	(95%CI)
GHGE, per 1 kgCO2e/d												
24hR as observed	-3.3	(-4.1; -2.4)	-3.3	(-4.1; -2.4)	-2.7	(-3.5; -1.8)	-0.2	(-0.9; 0.6)	-0.2	(-0.9; 0.6)	-0.4	(-1.1; 0.3)
De-attenuated 24hR	-11.3	(-14.1; -8.4)	-14.5	(-18.0; -10.9)	-8.3	(-10.8; -5.8)	-0.5	(-3.1; 2.0)	-0.7	(-4.0; 2.7)	-1.2	(-3.3; 1.0)
FFQ as observed	-3.9	(-5.7; -2.0)	-3.9	(-5.7; -2.0)	-3.9	(-5.8; -2.0)	1.0	(-0.5; 2.5)	1.0	(-0.5; 2.5)	1.1	(-0.5; 2.6)
Calibrated FFQ	-8.3	(-10.8; -5.8)	-10.8	(-13.6; -8.0)	-7.7	(-9.8; -5.5)	0.9	(-1.2; 3.2)	0.8	(-1.7; 3.4)	-0.1	(-2.0; 1.8)
FE, per 5 MJ/d												
24hR as observed	-1.3	(-2.1; -0.5)	-1.3	(-2.1; -0.5)	-0.8	(-1.6; -0.1)	1.3	(0.7; 2.0)	1.3	(0.7; 2.0)	0.7	(0.1; 1.3)
De-attenuated 24hR	-2.9	(-4.8; -1.1)	-3.6	(-5.8; -1.3)	-1.8	(-3.4; -0.2)	3.1	(1.5; 4.6)	2.3	(1.9; 5.7)	1.5	(0.2; 2.7)
FFQ as observed	-1.7	(-3.1; -0.3)	-1.7	(-3.1; -0.3)	-1.6	(-3.0; -0.2)	2.3	(1.2; 3.4)	2.3	(1.2; 3.4)	2.4	(1.2; 3.5)
Calibrated FFQ	-2.5	(-4.3; -0.8)	-3.1	(-5.0; -1.3)	-1.9	(-3.3; -0.5)	3.6	(2.1; 5.0)	3.8	(2.3; 5.4)	2.1	(0.9; 3.3)
LU, per 1 m^2*year/d												
24hR as observed	-3.2	(-3.9; -2.5)	-3.2	(-3.9; -2.5)	-2.6	(-3.2; -2.0)	-0.6	(-1.2; -0.1)	-0.6	(-1.2; -0.1)	-0.9	(-1.4; -0.4)
De-attenuated 24hR	-10.4	(-12.5; -8.3)	-13.2	(-15.8; -10.6)	-7.4	(-9.1; -5.6)	-2.1	(-4.0; -0.2)	-2.7	(-5.1; -0.3)	-2.6	(-4.1; -1.1)
FFQ as observed	-6.3	(-7.8; -4.7)	-6.3	(-7.8; -4.7)	-6.2	(-7.7; -4.7)	0.2	(-1.1; 1.5)	0.2	(-1.1; 1.5)	0.1	(-1.2; 1.4)
Calibrated FFQ	-9.6	(-11.4; -7.7)	-11.4	(-13.3; -9.4)	-8.0	(-9.4; -6.4)	-0.8	(-2.4; 0.9)	-0.9	(-2.7; 0.9)	-1.7	(-3.0; -0.4)
pReCiPe, per 0.1												
24hR as observed	-3.3	(-4.1; -2.5)	-3.3	(-4.1; -2.5)	-2.6	(-3.3; -1.9)	-0.3	(-0.9; 0.4)	-0.3	(-0.9; 0.4)	-0.6	(-1.2; 0.0)
De-attenuated 24hR	-10.0	(-12.3; -7.7)	-12.9	(-15.7; -9.9)	-7.1	(-9.1; -5.2)	-0.8	(-2.9; 1.2)	-1.1	(-3.7; 1.6)	-1.6	(-3.3; 0.0)
FFQ as observed	-5.1	(-6.8; -3.4)	-5.1	(-6.8; -3.4)	-5.1	(-10.3; -5.1)	0.9	(-0.5; 2.3)	0.9	(-0.5; 2.3)	0.9	(-0.5; 2.4)
Calibrated FFQ	-8.6	(-10.7; -6.5)	-10.6	(-12.8; -8.3)	-7.3	(-9.0; -5.5)	0.5	(-1.3; 2.4)	0.4	(-1.6; 2.5)	-0.6	(-2.1; 0.9)

Abbreviations: DHD15-index, Dutch Healthy Diet Index 15; NRD9.3, Nutrient Rich Diet score 9.3; GHGE, greenhouse gas emissions; FE, fossil energy use; LU, land use; pReCiPe, a weighted summary score for GHGE, FE, and LU. De-attenuated 24hR-values estimated using the method of Best Linear Unbiased Prediction (BLUP) to correct for random error. Calibrated FFQ values calculated as the predicted values from a mixed model with FFQ-values, age, gender and BMI as covariates, accounting for random effects.

[a] Regression coefficients represent the percentage change in diet score per unit increase in diet-related environmental impact, and are adjusted for energy intake (continuous and using estimates as measured by that method of dietary assessment), age (continuous), gender (men/women), and BMI (continuous).

DISCUSSION

Group-mean differences between FFQ and the reference 24hR were small (<5%) for absolute values of GHGE, FE, LU and pReCiPe. Covariate-adjusted de-attenuated correlation coefficients between FFQ and 24hR were around 0.70, and attenuation coefficients were around 0.55 for observed values on diet-related environmental impact measures. When we studied the association between environmental impact and dietary quality, an inverse association was observed when dietary quality was assessed using a food-based score (DHD15-index), but inconsistent and weak associations were seen when using a nutrient-based score (NRD9.3).

To the best of our knowledge, this is the first calibration study on diet-related environmental impact measures comparing the environmental impact obtained from FFQ with that of the 24hR. The latter was used as reference instrument since no truly gold standard exist. As a means for comparison, we calculated correlation coefficients and attenuation factors for protein intake as this is a widely studied nutrient in dietary validation studies. Correlation coefficients and attenuation coefficients for intake of energy and protein are in line with earlier calibration studies [33, 37]. In the present study, the unadjusted correlation coefficient for protein was 0.46 (men: 0.41; women: 0.38), and the unadjusted attenuation coefficient for protein intake was 0.58 (men; 0.54; women. 0.48). Pooled analysis of protein intake in eight European validation studies within the European Prospective Investigation into Cancer [37] reported correlation coefficients between FFQ and 24hR varying between 0.35 and 0.67, and attenuation coefficients for the FFQ on 24hR between 0.26 and 0.63. In the US, the Observing Protein and Energy Nutrition (OPEN) study [33] reported correlation coefficients of 0.31 for men and 0.33 for women and attenuation coefficients of 0.53 for men and 0.70 for women. Thus, as compared to protein, correlation coefficients between these two methods tended to be slightly lower for all diet-derived measures of environmental impact, whereas attenuation coefficients were slightly higher, especially for FE and LU. As there was a strong correlation between measure of environmental impact and protein intake (correlation coefficients between 0.6 – 0.9), results might to some extent be affected by protein-poor food sources that contributed to diet-related environmental impact with their intake and contribution highly varying by the method of dietary assessment.

Changes in dietary intake are generally based on iso-caloric exchanges of foods, hence the need to keep energy intake constant when comparing diets between groups. Previous studies on the measurement error structure of self-reported protein intake have noted that the attenuation is less severe when energy intake is taken into account by either regression of protein intake on energy intake (protein residuals) or by the density method (dividing energy from protein intake by energy) [13, 33]. Our analysis shows that the same holds for diet-derived measures of environmental impact, with less attenuation for density residuals than for observed residuals. This is in line with the results of Table 4: regression coefficients using observed FFQ-values were closer to those using de-attenuated 24hR-vales for densities residuals than for observed residuals. Measurement errors in the assessment of environmental impact are strongly correlated with errors in the measurement of total energy intake, and this appeared to be more marked for observed residuals, as shown by the lower ICC. This finding further supports the importance for using energy-adjusted intakes in nutritional epidemiology, however caution must be applied for their interpretation, as has been discussed previously [35]. Diet-related environmental impact is preferably expressed in relative values (i.e.: impact per 2,000kcal) rather than absolute values, because of the application of densities in public health recommendations. Individuals and populations can reduce their diet-related environmental impact per kcal consumed by replacing the intake of specific foods by environmental-friendly alternatives, thus by changing diet composition rather than total energy intake, unless physical activity and body weight have been changed substantially. Total energy intake is however strongly positively related to diet-related environmental impact as observed, which are absolute impact levels important in environmental sciences, hence the need for using density residuals.

In our study, the assessment of environmental sustainability of the diet was restricted by the availability of LCA data from 207 food products, resulting in an imprecise estimation of the environmental impact of the diet for both FFQ and 24hR. In addition, methods of dietary assessment to date have been developed to monitor food and nutrient intakes, without considering sustainable dietary practices, such as food origin, packaging and preparation methods, transport, storage, food waste, etc. Our results, however, show that the measurement errors for LCA-based environmental impact measures are of similar size as protein intake, which is at the better end of the range of errors in assessment of food and nutrient intake [33, 37, 38]. This was not hypothesized a priori. Nutrient-based selection of food items does not necessarily capture the variation for diet-related environmental impact measures, but apparently it does for the 24hR and FFQ in this study. This suggests that errors in classification (foods vs grouped items), portions size (specific vs standard) and frequency (FFQ only) largely explain the differences between the 24hR and FFQ, and eventually result in similar errors for estimated daily nutrient intake and environmental impact. Still, 24hRs (and diet records) provide more objective data on dietary practices, and for some food products packaging and preparation methods might by this time be recorded dependent on the dietary knowledge level and cooking skills of the subject. Provided that LCA data are more widely available for all kind of food products, these open-ended methods of dietary assessment that consider both healthy and environmental dietary practices would perform much better as compared to the FFQ, unless specifically designed for assessing environmental impact.

The secondary aim of this paper was to investigate the association between dietary quality (DHD15-index and NRD9.3) and environmental impact of the diet (24hR-based or FFQ-based). Dietary quality was used as independent variable using the 24hR, and measures of environmental impact as dependent variable using both methods of dietary assessment (24hR and FFQ) without and with accounting for measurement error. Differences in regression coefficients can therefore be attributed to the ability of the 24hR versus FFQ to assess associations with environmental impact. Our results show that quality of the food pattern (DHD15-index in our case) is similarly related to all environmental impact measures under study, and more environmentally-friendly diets (lower value) tend to score better on food-based dietary quality (hence a negative regression coefficient); this is irrespective of the environmental impact measures. However, when nutrient quality of the diet (NRD9.3 in our case) is considered, the results differ by environmental impact measure and whether 24hR or FFQ was used as the method of dietary assessment.

In the detail for NRD9.3, we showed that nutrient quality tended to be positively associated with diet-related GHGE and FE; but inversely with diet-related LU. The reason for these apparently conflicting findings is likely attributable to the contribution of different food groups to daily diet-related environmental impact and nutrient intake. The positive association for diet-related FE with NRD9.3 is likely to be driven by food sources such as fish, bread, fruit and vegetables that have a higher contribution to total-diet related FE as compared to GHGE and LU (Table 2). Moreover, these foods have a high nutrient density contributing to high intakes of dietary fibre, potassium, magnesium, iron, vitamin C, E, and low intakes of sodium, added sugar and saturated fat. In contrast, the inverse association for LU is likely to be driven by the low contribution of fruit and vegetables to diet-related LU as compared to GHGE and FE (Table 2). This inverse association between LU and NRD9.3 was seen when using a 24hR, but not when using an FFQ; which might be explained by the higher intakes of fruit and vegetables observed in the FFQ. As the abovementioned foods played a less important role in the DHD15-index (only four out of fifteen components), an inverse association with diet-related environmental impact was found for this food-based diet score.

Our results are supported by previous studies that also showed inverse associations between diet-related GHGE and the food-based scores [11, 12, 39], whereas studies using nutrient-based scores showed no clear associations [7, 8, 40]. This discrepancy between results for food-based scores and nutrient-based scores may be explained by the different components included in the scores [41, 42]: food-based DHD15-index is conceptually related to food-based dietary guidelines and easily captures intakes of nutrient-dense plant-based foods versus animal-based foods; while the nutrient-based NRD9.3 evaluates dietary quality based on nutrient intake relative to nutritional requirements irrespective of the food sources. A sole focus on food-based approaches to a healthy and environmentally-friendly diet may therefore not capture the full spectrum of nutritional risks and may incorrectly lump all sustainability indicators together. Research is still needed to identify appropriate diet scores, differentially weighing various aspects of healthy and environmentally-friendly diets [43].

CONCLUSION

In conclusion, estimations of the environmental impact of the diet are dependent of the method of dietary assessment; the FFQ slightly underestimated environmental impact when compared with the 24hR. Using energy-adjusted values resulted in a higher group mean bias and a lower correlation between FFQ and 24hR, but there was less attenuation. Correlation coefficients and attenuation coefficients for environmental impact measures behaved in a similar way as for protein intake, this suggests that our findings and conclusions related to covariate- and energy-adjustment can be extended to other dietary factors. Moreover, de-attenuation of the 24hR and calibration of the FFQ to 24hR increases the strength of the associations between dietary quality and diet-related environmental impact. Higher dietary quality was associated with improved environmental impact for food-based scores, but no clear associations for nutrient-based scores. It is therefore important to include nutrient-based approaches, next to food-based approaches, to prevent that the transition to environmentally-friendly diets negatively affects nutritional status of the population.

Funding

Financial support for this original contribution was obtained from funding from the European Union’s H2020 Programme under Grant Agreement number 633692 (SUSFANS: Metrics, models and foresight for European sustainable food and nutrition security), from TiFN under Project Agreement number 15SD01 (SHARP-BASIC), from ZonMw under Grant Agreement number 91110030 (Nutrition Questionnaires plus study).

REFERENCES

1. Auestad N, Fulgoni VL, 3rd: **What Current Literature Tells Us about Sustainable Diets: Emerging Research Linking Dietary Patterns, Environmental Sustainability, and Economics**. *Adv Nutr* 2015, **6**(1):19-36.
2. Hallström E, Carlsson-Kanyama A, Börjesson P: **Environmental impact of dietary change: a systematic review**. *J Clean Prod* 2015, **91**(0):1-11.
3. Jones AD, Hoey L, Blesh J, Miller L, Green A, Shapiro LF: **A Systematic Review of the Measurement of Sustainable Diets**. *Adv Nutr* 2016, **7**(4):641-664.
4. Nemecek T, Jungbluth N, i Canals LM, Schenck R: **Environmental impacts of food consumption and nutrition: where are we and what is next?** *The International Journal of Life Cycle Assessment* 2016, **21**(5):607-620.
5. Heller MC, Keoleian GA, Willett WC: **Toward a life cycle-based, diet-level framework for food environmental impact and nutritional quality assessment: a critical review**. *Environ Sci Technol* 2013, **47**(22):12632-12647.
6. Perignon M, Vieux F, Soler L-G, Masset G, Darmon N: **Improving diet sustainability through evolution of food choices: review of epidemiological studies on the environmental impact of diets**. *Nutr Rev* 2017, **75**(1):2-17.
7. Clerfeuille E, Vieux F, Lluch A, Darmon N, Rolf-Pedersen N: **Assessing the construct validity of five nutrient profiling systems using diet modeling with linear programming**. *Eur J Clin Nutr* 2013, **67**(9):1003-1005.
8. Masset G, Vieux F, Verger EO, Soler LG, Touazi D, Darmon N: **Reducing energy intake and energy density for a sustainable diet: a study based on self-selected diets in French adults**. *Am J Clin Nutr* 2014, **99**(6):1460-1469.
9. van Dooren C, Marinussen M, Blonk H, Aiking H, Vellinga P: **Exploring dietary guidelines based on ecological and nutritional values: A comparison of six dietary patterns**. *Food Policy* 2014, **44**:36-46.
10. Roos E, Karlsson H, Witthoft C, Sundberg C: **Evaluating the sustainability of diets-combining environmental and nutritional aspects**. *Environmental Science & Policy* 2015, **47**:157-166.
11. Monsivais P, Scarborough P, Lloyd T, Mizdrak A, Luben R, Mulligan AA, Wareham NJ, Woodcock J: **Greater accordance with the Dietary Approaches to Stop Hypertension dietary pattern is associated with lower diet-related greenhouse gas production but higher dietary costs in the United Kingdom**. *Am J Clin Nutr* 2015, **102**(1):138-145.
12. Biesbroek S, Verschuren WM, Boer JM, van de Kamp ME, van der Schouw YT, Geelen A, Looman M, Temme EH: **Does a better adherence to dietary guidelines reduce mortality risk and environmental impact in the Dutch sub-cohort of the European Prospective Investigation into Cancer and Nutrition?** *British Journal of Nutrition* 2017, **118**(1):69-80.
13. Freedman LS, Schatzkin A, Midthune D, Kipnis V: **Dealing with dietary measurement error in nutritional cohort studies**. *Journal of the National Cancer Institute* 2011, **103**(14):1086-1092.
14. Schatzkin A, Kipnis V, Carroll RJ, Midthune D, Subar AF, Bingham S, Schoeller DA, Troiano RP, Freedman LS: **A comparison of a food frequency questionnaire with a 24-hour recall for use in an epidemiological cohort study: results from the biomarker-based Observing Protein and Energy Nutrition (OPEN) study**. *International journal of epidemiology* 2003, **32**(6):1054-1062.
15. Kipnis V, Carroll RJ, Freedman LS, Li L: **Implications of a new dietary measurement error model for estimation of relative risk: application to four calibration studies**. *American Journal of Epidemiology* 1999, **150**(6):642-651.
16. Rosner B, Spiegelman D, Willett W: **Correction of logistic regression relative risk estimates and confidence intervals for random within-person measurement error**. *American journal of epidemiology* 1992, **136**(11):1400-1413.

17. Kipnis V, Midthune D, Freedman LS, Bingham S, Schatzkin A, Subar A, Carroll RJ: **Empirical evidence of correlated biases in dietary assessment instruments and its implications**. *American journal of epidemiology* 2001, **153**(4):394-403.
18. van Lee L, Feskens EJ, Meijboom S, van Huysduynen EJH, van't Veer P, de Vries JH, Geelen A: **Evaluation of a screener to assess diet quality in the Netherlands**. *British Journal of Nutrition* 2016, **115**(3):517-526.
19. Brouwer-Brolsma EM, van Lee L, Streppel MT, Sluik D, van de Wiel AM, de Vries JHM, Geelen A, Feskens EJM: **Nutrition Questionnaires plus (NQplus) study, a prospective study on dietary determinants and cardiometabolic health in Dutch adults**. *BMJ open* 2018, **8**(7).
20. Moshfegh AJ, Rhodes DG, Baer DJ, Murayi T, Clemens JC, Rumpler WV, Paul DR, Sebastian RS, Kuczynski KJ, Ingwersen LA: **The US Department of Agriculture Automated Multiple-Pass Method reduces bias in the collection of energy intakes**. *The American journal of clinical nutrition* 2008, **88**(2):324-332.
21. NEVO-tabel: **Nederlands Voedingsstoffen-tabel (NEVO-tabel) 2011 (Dutch Food Composition Table 2011) version 3**. In. Bilthoven, the Netherlands: RIVM/Dutch Nutrition Centre; 2011.
22. Siebelink E, Geelen A, de Vries JH: **Self-reported energy intake by FFQ compared with actual energy intake to maintain body weight in 516 adults**. *British journal of nutrition* 2011, **106**(2):274-281.
23. Streppel MT, de Vries JH, Meijboom S, Beekman M, de Craen AJ, Slagboom PE, Feskens EJ: **Relative validity of the food frequency questionnaire used to assess dietary intake in the Leiden Longevity Study**. *Nutrition journal* 2013, **12**(1):75.
24. Blonk H, Ponsioen T, Kool A, et al.: **The Agri-Footprint Method. Methodological LCA Framework, Assumptions and Applied Data.** In. Edited by Gouda: Blonk Milieu Advies; 2011.
25. Goedkoop M, Heijungs R, De Schryver A, Struijs J, van Zelm R: **ReCiPe 2008. A LCA method which comprises harmonised category indicators at the midpoint and the endpoint level; Report 1 Characterisation**. In.; 2013.
26. Looman M, Feskens EJ, de Rijk M, Meijboom S, Biesbroek S, Temme EH, de Vries J, Geelen A: **Development and evaluation of the Dutch Healthy Diet index 2015**. *Public Health Nutrition* 2017:1-11.
27. Van Kernebeek HRJ, Oosting SJ, Feskens EJM, Gerber PJ, De Boer IJM: **The effect of nutritional quality on comparing environmental impacts of human diets**. *Journal of Cleaner Production* 2014, **73**(0):88-99.
28. Drewnowski A: **Defining nutrient density: development and validation of the nutrient rich foods index**. *J Am Coll Nutr* 2009, **28**(4):421s-426s.
29. Fulgoni VL, 3rd, Keast DR, Drewnowski A: **Development and validation of the nutrient-rich foods index: a tool to measure nutritional quality of foods**. *J Nutr* 2009, **139**(8):1549-1554.
30. Wendel-Vos GC, Schuit AJ, Saris WH, Kromhout D: **Reproducibility and relative validity of the short questionnaire to assess health-enhancing physical activity**. *Journal of clinical epidemiology* 2003, **56**(12):1163-1169.
31. Freedman LS, Commins JM, Willett W, Tinker LF, Spiegelman D, Rhodes D, Potischman N, Neuhouser ML, Moshfegh AJ, Kipnis V: **Evaluation of the 24-Hour Recall as a Reference Instrument for Calibrating Other Self-Report Instruments in Nutritional Cohort Studies: Evidence From the Validation Studies Pooling Project**. *American Journal of Epidemiology* 2017:1-10.
32. Park Y, Dodd KW, Kipnis V, Thompson FE, Potischman N, Schoeller DA, Baer DJ, Midthune D, Troiano RP, Bowles H *et al*: **Comparison of self-reported dietary intakes from the Automated Self-Administered 24-h recall, 4-d food records, and food-frequency questionnaires against recovery biomarkers**. *Am J Clin Nutr* 2018, **107**(1):80-93.

33. Kipnis V, Subar AF, Midthune D, Freedman LS, Ballard-Barbash R, Troiano RP, Bingham S, Schoeller DA, Schatzkin A, Carroll RJ: **Structure of dietary measurement error: results of the OPEN biomarker study**. *American journal of epidemiology* 2003, **158**(1):14-21.
34. Donner A: **A Review of Inference Procedures for the Intraclass Correlation Coefficient in the One-Way Random Effects Model**. *International Statistical Review / Revue Internationale de Statistique* 1986, **54**(1):67-82.
35. Willett WC, Howe GR, Kushi LH: **Adjustment for total energy intake in epidemiologic studies**. *The American journal of clinical nutrition* 1997, **65**(4):1220S-1228S.
36. Singer JM, Stanek EJ, Lencina VB, González LM, Li W, San Martino S: **Prediction with measurement errors in finite populations**. *Statistics & probability letters* 2012, **82**(2):332-339.
37. Freedman LS, Commins JM, Moler JE, Arab L, Baer DJ, Kipnis V, Midthune D, Moshfegh AJ, Neuhouser ML, Prentice RL: **Pooled results from 5 validation studies of dietary self-report instruments using recovery biomarkers for energy and protein intake**. *American journal of epidemiology* 2014, **180**(2):172-188.
38. Kynast-Wolf G, Becker N, Kroke A, Brandstetter BR, Wahrendorf J, Boeing H: **Linear regression calibration: theoretical framework and empirical results in EPIC, Germany**. *Annals of nutrition & metabolism* 2002, **46**(1):2-8.
39. Murakami K, Livingstone MBE: **Greenhouse gas emissions of self-selected diets in the UK and their association with diet quality: is energy under-reporting a problem?** *Nutr J* 2018, **17**(1):27.
40. Walker C, Gibney ER, Hellweg S: **Comparison of Environmental Impact and Nutritional Quality among a European Sample Population - findings from the Food4Me study**. *Scientific reports* 2018, **8**(1):2330.
41. Kant AK: **Indexes of overall diet quality: a review**. *J Am Diet Assoc* 1996, **96**(8):785-791.
42. Arvaniti F, Panagiotakos DB: **Healthy indexes in public health practice and research: a review**. *Critical reviews in food science and nutrition* 2008, **48**(4):317-327.
43. van Dooren C, Douma A, Aiking H, Vellinga P: **Proposing a Novel Index Reflecting Both Climate Impact and Nutritional Impact of Food Products**. *Ecological Economics* 2017, **131**:389-398.

SUPPLEMENTARY MATERIALS

Supplementary Table 1 Diet-related environmental impact according to the food frequency questionnaire (FFQ) and two replicates of the 24-hour recall (24hR, with intra-class correlation coefficient) and group level bias, with correlation between the methods (crude, adjusted, de-attenuated) and attenuation coefficient (crude, adjusted) for observed and energy-adjusted values standardised to a 2,000 kcal diet in men [a].

	FFQ	**2 replicates of 24hR**			**Correlation coefficient (24hR with FFQ)**			**Attenuation coefficient λ_1**	
Dietary variables	Mean (SD)	Mean (SD)	%bias	ICC	Crude (95%CI)	Adjusted[b](95%CI)	De-attenuated(95%CI)	Crude (SE)	Adjusted[b] (SE)
Observed values									
Energy, kcal/d	2348 (534)	2200 (617)	6.7	0.31	0.42 (0.35; 0.48)	0.39 (0.32; 0.45)	0.69 (0.57; 0.81)	0.49 (0.04)	0.45 (0.04)
Protein, g/d	83.8 (18.8)	84.9 (24.8)	-1.3	0.27	0.41 (0.34; 0.47)	0.39 (0.32; 0.45)	0.74 (0.61; 0.87)	0.54 (0.05)	0.51 (0.05)
GHGE, $kgCO_2e/d$	3.77 (0.88)	3.94 (1.60)	-4.3	0.18	0.28 (0.21; 0.35)	0.27 (0.20; 0.34)	0.64 (0.46; 0.81)	0.51 (0.07)	0.50 (0.07)
FE, MJ/d	32.40 (6.89)	33.36 (9.83)	-2.9	0.28	0.40 (0.33; 0.47)	0.40 (0.33; 0.46)	0.75 (0.61; 0.87)	0.57 (0.05)	0.57 (0.05)
LU, m^2*year/d	4.38 (1.06)	4.57 (1.99)	-4.2	0.18	0.29 (0.21; 0.36)	0.28 (0.20; 0.35)	0.67 (0.49; 0.84)	0.54 (0.07)	0.52 (0.07)
pReCiPe	0.45 (0.10)	0.46 (0.18)	-2.2	0.19	0.31 (0.23; 0.38)	0.30 (0.22; 0.37)	0.68 (0.51; 0.84)	0.54 (0.07)	0.53 (0.07)
Energy-adjusted values by regression residuals of observed values on energy(observed residuals)									
Protein, g/d	73.8 (11.0)	78.6 (15.1)	-6.1	0.19	0.41 (0.34; 0.47)	0.31 (0.23; 0.38)	0.70 (0.53; 0.86)	0.44 (0.05)	0.42 (0.05)
GHGE, $kgCO_2e/d$	3.37 (0.64)	3.69 (1.40)	-8.7	0.12	0.28 (0.21; 0.35)	0.21 (0.13; 0.29)	0.61 (0.39; 0.82)	0.51 (0.09)	0.48 (0.09)
FE, MJ/d	28.93 (4.35)	31.23 (7.19)	-7.4	0.20	0.38 (0.31; 0.44)	0.36 (0.28; 0.42)	0.80 (0.64; 0.95)	0.62 (0.06)	0.61 (0.07)
LU, m^2*year/d	3.88 (0.72)	4.26 (1.74)	-8.9	0.12	0.26 (0.19; 0.33)	0.24 (0.16; 0.32)	0.69 (0.47; 0.90)	0.63 (0.09)	0.60 (0.10)
pReCiPe,	0.40 (0.07)	0.43 (0.15)	-7.0	0.13	0.27 (0.19; 0.34)	0.25 (0.17; 0.32)	0.68 (0.47; 0.88)	0.56 (0.09)	0.57 (0.09)
Energy-adjusted values by regression residuals of densities on energy (density residuals)									
Protein density, %	14.8 (1.9)	16.0 (2.85)	-7.5	0.18	0.32 (0.25; 0.39)	0.31 (0.23; 0.38)	0.73 (0.55; 0.89)	0.48 (0.06)	0.46 (0.06)
GHGEdensity,$kgCO_2e/d$	3.39 (0.55)	3.75 (1.28)	-9.6	0.16	0.25 (0.17; 0.32)	0.22 (0.15; 0.30)	0.57 (0.37; 0.75)	0.57 (0.09)	0.53 (0.09)
FE density, MJ/d	29.10 (3.77)	32.07 (6.63)	-9.3	0.21	0.39 (0.32; 0.46)	0.37 (0.30; 0.44)	0.80 (0.65; 0.94)	0.69 (0.07)	0.66 (0.07)
LU density, m^2*year/d	3.90 (0.65)	4.33 (1.62)	-9.9	0.13	0.27 (0.19; 0.34)	0.24 (0.17; 0.32)	0.67 (0.46; 0.88)	0.66 (0.10)	0.62 (0.10)
pReCiPe density	0.40 (0.06)	0.44 (0.14)	-9.1	0.17	0.28 (0.20; 0.35)	0.26 (0.18; 0.33)	0.63 (0.44; 0.81)	0.65 (0.09)	0.61 (0.09)

ICC, intra class correlation coefficient; GHGE, greenhouse gas emissions; FE, fossil energy use; LU, land use; pReCiPe, a weighted summary score for GHGE, FE, and LU; % bias, group-level bias calculated as (mean intake FFQ /mean intake 24hR)x100; 100; correlation coefficient (95%CI) estimated as the Pearson correlation coefficient; de-attenuated correlation coefficient (95%CI) estimated as the Pearson correlation coefficient/$\sqrt{ICC_{24hR}}$; Attenuation coefficient λ_1 (SE) estimated as the slope in the linear regression of the 24hR on the FFQ using linear mixed models to account for within-person day-to-day variability.

[a] Mean values with their standard deviations, correlation coefficient with its 95% confidence intervals, attenuation coefficient with its standard error.

[b] Adjusted for age and BMI.

Supplementary Table 2 Diet-related environmental impact according to the food frequency questionnaire (FFQ) and two replicates of the 24-hour recall (24hR, with intra-class correlation coefficient) and group level bias, with correlation between the methods (crude, adjusted, de-attenuated) and attenuation coefficient (crude, adjusted) for observed and energy-adjusted values standardised to a 2,000 kcal diet in women [a] .

	FFQ	**2 replicates of 24hR**			**Correlation coefficient (24hR with FFQ)**			**Attenuation coefficient λ_1**	
Dietary variables	Mean (SD)	Mean (SD)	%bias	ICC	Crude (95%CI)	Adjusted[b](95%CI)	De-attenuated(95%CI)	Crude (SE)	Adjusted[b] (SE)
Observed values									
Energy, kcal/d	1915 (431)	1808 (466)	5.9	0.29	0.34 (0.27; 0.41)	0.35 (0.27; 0.42)	0.64 (0.50; 0.77)	0.37 (0.04)	0.37 (0.04)
Protein, g/d	70.9 (15.6)	71.0 (19.7)	-0.1	0.27	0.38 (0.31; 0.45)	0.38 (0.31; 0.45)	0.74 (0.60; 0.87)	0.48 (0.05)	0.49 (0.05)
GHGE, $kgCO_2e/d$	3.20 (0.76)	3.32 (1.20)	-3.6	0.14	0.35 (0.28; 0.42)	0.35 (0.27; 0.42)	0.92 (0.72; 1.11)	0.55 (0.06)	0.56 (0.07)
FE, MJ/d	27.81 (5.62)	28.66 (7.77)	-3.0	0.27	0.39 (0.32; 0.46)	0.39 (0.32; 0.46)	0.75 (0.61; 0.88)	0.54 (0.05)	0.56 (0.06)
LU, m^2*year/d	3.60 (0.94)	3.71 (1.51)	-3.0	0.17	0.37 (0.30; 0.44)	0.36 (0.29; 0.43)	0.88 (0.70; 1.05)	0.60 (0.06)	0.60 (0.07)
pReCiPe	0.37 (0.09)	0.39 (0.14)	-5.1	0.18	0.38 (0.30; 0.44)	0.37 (0.29; 0.44)	0.88 (0.70; 1.04)	0.58 (0.06)	0.59 (0.06)
Energy-adjusted values by regression residuals of observed values on energy(observed residuals)									
Protein, g/d	73.3 (9.5)	77.1 (13.1)	-4.9	0.21	0.38 (0.31; 0.45)	0.37 (0.30; 0.44)	0.67 (0.51; 0.82)	0.56 (0.05)	0.52 (0.06)
GHGE, $kgCO_2e/d$	3.30 (0.59)	3.58 (1.04)	-7.8	0.11	0.35 (0.28; 0.42)	0.26 (0.18; 0.33)	0.76 (0.53; 0.99)	0.52 (0.07)	0.47 (0.08)
FE, MJ/d	28.58 (4.03)	30.57 (6.27)	-6.5	0.24	0.40 (0.33; 0.46)	0.35 (0.28; 0.42)	0.71 (0.56; 0.86)	0.62 (0.06)	0.57 (0.06)
LU, m^2*year/d	3.73 (0.69)	4.01 (1.34)	-7.0	0.15	0.34 (0.26; 0.41)	0.31 (0.23; 0.38)	0.80 (0.60; 0.99)	0.66 (0.08)	0.61 (0.08)
pReCiPe,	0.39 (0.06)	0.42 (0.12)	-7.1	0.15	0.34 (0.26; 0.41)	0.30 (0.22; 0.37)	0.77 (0.57; 0.96)	0.61 (0.07)	0.56 (0.08)
Energy-adjusted values by regression residuals of densities on energy (density residuals)									
Protein density, %	14.8 (2.0)	15.7 (3.3)	-5.7	0.21	0.40 (0.33; 0.47)	0.37 (0.30; 0.44)	0.82 (0.66; 0.97)	0.66 (0.06)	0.62 (0.07)
GHGEdensity,$kgCO_2e/d$	3.35 (0.64)	3.67 (1.31)	-8.7	0.21	0.31 (0.24; 0.39)	0.28 (0.20; 0.35)	0.61 (0.44; 0.78)	0.65 (0.08)	0.60 (0.09)
FE density, MJ/d	29.11 (4.35)	31.65 (8.47)	-8.0	0.35	0.39 (0.32; 0.46)	0.35 (0.27; 0.42)	0.59 (0.46; 0.70)	0.76 (0.08)	0.71 (0.08)
LU density, m^2*year/d	3.77 (0.75)	4.10 (1.81)	-8.0	0.27	0.32 (0.24; 0.39)	0.29 (0.21; 0.36)	0.55 (0.40; 0.69)	0.77 (0.10)	0.71 (0.10)
pReCiPe density	0.39 (0.07)	0.43 (0.15)	-9.3	0.29	0.34 (0.26; 0.41)	0.30 (0.22; 0.37)	0.56 (0.41; 0.69)	0.75 (0.09)	0.69 (0.09)

ICC, intra class correlation coefficient; GHGE, greenhouse gas emissions; FE, fossil energy use; LU, land use; pReCiPe, a weighted summary score for GHGE, FE, and LU; % bias, group-level bias calculated as (mean intake FFQ /mean intake 24hR)x100; 100; correlation coefficient (95%CI) estimated as the Pearson correlation coefficient; de-attenuated correlation coefficient (95%CI) estimated as the Pearson correlation coefficient/$\sqrt{ICC_{24hR}}$; Attenuation coefficient λ_1 (SE) estimated as the slope in the linear regression of the 24hR on the FFQ using linear mixed models to account for within-person day-to-day variability.

[a] Mean values with their standard deviations, correlation coefficient with its 95% confidence intervals, attenuation coefficient with its standard error.

[b] Adjusted for age and BMI.

PART II

Health and environmental sustainability of European diets

CHAPTER 4

Geographic and socioeconomic diversity of food and nutrient intakes: a comparison of four European countries

Elly Mertens
Anneleen Kuijsten
Marcela Dofková
Lorenza Mistura
Laura D'Addezio
Aida Turrini
Carine Dubuisson
Sandra Favret
Sabrina Havard
Ellen Trolle
Pieter van 't Veer
Johanna M Geleijnse

Published in: European Journal of Nutrition 2019;58(4):1475-1493

ABSTRACT

Purpose Public health policies and actions increasingly acknowledge the climate burden of food consumption. The aim of this study is to describe dietary intakes across four European countries, as baseline for further research towards healthier and environmentally-friendlier diets for Europe.

Methods Individual-level dietary intake data in adults were obtained from nationally-representative surveys from Denmark and France using a seven-day diet record, Italy using a three-day diet record, and Czech Republic using two replicates of a 24-hour recall. Energy-standardised food and nutrient intakes were calculated for each subject from the mean of two randomly selected days.

Results There was clear geographical variability, with a between-country range for mean fruit intake from 118 to 199 g/day, for vegetables from 95 to 239 g/day, for fish from 12 to 45 g/day, for dairy from 129 to 302 g/day, for sweet beverages from 48 to 224 ml/day, and for alcohol from 8 to 15 g/d, with higher intakes in Italy for fruit, vegetables and fish, and in Denmark for dairy, sweet beverages and alcohol. In all countries, intakes were low for legumes (< 20 g/day), and nuts and seeds (< 5 g/day), but high for red and processed meat (> 80 g/day). Within countries, food intakes also varied by socio-economic factors like age, gender, and educational level, but less pronounced by anthropometric factors like overweight status. For nutrients, intakes were low for dietary fibre (15.8 – 19.4 g/d) and vitamin D (2.4 – 3.0 μg/d) in all countries, for potassium (2288 – 2938 mg/d) and magnesium (268 – 285 mg/d) except in Denmark, for vitamin E in Denmark (6.7 mg/d), and for folate in Czech Republic (212 μg/d).

Conclusion There is considerable variation in food and nutrient intakes across Europe, not only between, but also within countries. Individual-level dietary data provide insight into the heterogeneity of dietary habits beyond per capita food supply data, and this is crucial to balancing healthy and environmentally-friendly diets for European citizens.

INTRODUCTION

Poor dietary habits are the second-leading risk factor for deaths and disability-adjusted life-years (DALYs) globally, accounting for 10.3 million deaths and 229.1 million DALYs in 2016 [1]. Low intakes of whole grains, fruit and vegetables, and nuts and seeds, and high intakes of alcohol and sodium ranked among the leading risk factors for early death and disability in European populations. However, as westernisation of diets progressed, diets high in red and processed meat, followed by diets high in sugar-sweetened beverages and low in milk are becoming a growing public health concern.

Dietary patterns are shaped by cultural, environmental, technological and economic factors, and they have become more similar over time owing to a general rise in living standards and globalisation of the food sector [2, 3]. Also in Europe there is a growing similarity of diets, in which traditional diets of Northern and Mediterranean countries are converging towards a more Western diet, viewed by the increased share of fruit and vegetables in Northern countries and the increased share of animal-based products in Mediterranean countries [4-6]. Increase in animal-based products and excessive caloric intake have been thought as a key factor in nutrition transition, which warrants the need for public health action to promote healthier food patterns consistent with traditional cultural preferences, hence the development of food-based dietary guidelines.

Food-based dietary guidelines are evidence-based integrated messages aimed at the general population for maintaining health and the prevention of non-communicable diseases [7, 8]. Promoting the intake of whole grains, fruit and vegetables, low-fat dairy and fish, and limiting the intake of red and processed meat, sugar-sweetened food products, alcohol and salt is covered by most national food-based dietary guidelines [9], although recommended quantities may differ. Monitoring food consumption patterns and assessing adherence to dietary guidelines in a nationally representative sample is especially regarded as a key instrument for evaluating the effectiveness of public health action towards a healthier diet.

In recent years, public health policies and actions have increasingly acknowledged the climate burden of food production and consumption, hence the need to address the food-climate connection, as outlined in the SUSFANS project (Metrics, Models and Foresight for European SUStainable Food And Nutrition Security) [10]. Production and technological changes in the food system will however not be sustainable without a change in food consumption patterns. The SUSFANS project, therefore, elaborates on the status-quo of diets and the design of optimised diets that are environmentally Sustainable, Healthy, Affordable, Reliable and Preferred (SHARP). This paper is a first step to study European food consumption patterns in terms of food groups and nutrients using national dietary survey data carried out at the individual level in four countries. Intakes of food groups and nutrients were compared with current food-based dietary guidelines and nutrient reference values, overall and in relevant population subgroups.

POPULATIONS AND METHODS

Data sources

Individual-level dietary intake data from national dietary surveys representative for different European regions, i.e. Denmark (Scandinavia) [11], Czech Republic (Central East Europe) [12], Italy (Mediterranean) [13] and France (Western Europe) [14], were collated for adult population aged ≥ 18 years within the SUSFANS project [10]. These four countries were chosen to capture the wide range of foods and agricultural commodities, including their extreme intakes, that are incorporated in the diverse European food consumption patterns.

Survey characteristics

Survey characteristics are shown in Table 1. National representativeness was ensured by using random sampling based on civil registration systems in Denmark [11], national census data in Czech Republic [12] and France [14], and national census data with telephone books in Italy [13] that served as sampling frame, and followed by appropriate weighing for socio-demographic parameters, as applied in Denmark [11, 15] and France [14]. Surveys were organised throughout the whole year, covering the four seasons of the year, and have dietary data on week- and weekend-days.

Table 1 Dietary surveys in four European countries, i.e. Denmark, Czech Republic, Italy and France, including adult population only.

	Denmark	Czech Republic	Italy	France
Survey characteristics, including adult population only				
Survey, year	The Danish National Survey on Diet and Physical Activity 2005-08 National Food Institute, Technical University of Denmark (DTU)	Czech National Food Consumption Survey 2003-04 (SISP04) National Institute of Public Health	Italian National Food Consumption Survey INRAN-SCAI 2005-06 National institute for Research on Food and Nutrition	Individual and National Study on Food Consumption INCA-2 2006-07 Agence Française de Sécurité Sanitaires des Aliments (AFSSA)
Population	18 – 75 years	18 – 90 years	18 – 98 years	18 – 79 years
Method of dietary assessment [a]	7-day diet record on consecutive days	24-hour recall on two non-consecutive days	3-day diet record on consecutive days	7-day diet record on consecutive days
Baseline characteristics of the study sample, including adult population only, n (%)				
Sample size (response rate)	2,025 (54%)	1,869 (54%)	2,831 (33%)	2,624 (60%)
Age, 18 – 64 years	1,739 (85.9%)	1,666 (89.1%)	2,313 (81.7%)	2,276 (86.7%)
Gender, men	777 (44.7%)	793 (47.6%)	1,068 (46.2%)	936 (41.1%)
Educational level, low	248 (14.2%)	345 (20.7%)	692 (31.7%)	1,039 (45.8%)
Overweight status, BMI≥25	739 (43.2%)	864 (51.9%)	828 (35.8%)	871 (38.7%)

Abbreviation: BMI, Body Mass Index [a] Included in the present study were for Czech Republic both days, for Denmark and France two randomly selected days, and for Italy the first and the last day of the national dietary survey.

Method of dietary assessment

In the four study countries, dietary intake was assessed over two to seven 24-hour periods, either consecutively for three to seven days using a diet record, as applied in Denmark, Italy and France [11, 13, 14], or non-consecutively spaced over a three to five months sampling period using two replicates of 24-hour recall, as applied in Czech Republic [12]. In the present analyses, dietary intake from two random days has been reported. To this end, two non-consecutive days were sampled in Denmark, Italy and France, whereas all available days were used in Czech Republic.

Food and nutrient intakes

Intakes of food groups and nutrients were calculated for each subject from the mean of the selected two days, and were standardised for energy using the density method. Densities were calculated as the absolute value divided by total energy intake, and multiplied by 2,000 kcal. Harmonised food groups, including similar foods, have been elaborated using the 'Exposure Hierarchy' of the food classification and description system FoodEx2 developed and revised in 2015 by the European Food Safety Authority (EFSA) [16, 17]. A main challenge to encounter when grouping the foods was the level of food disaggregation; disaggregation of foods into ingredients was only considered as necessary for composite/prepared foods provided that the food itself was not included in FoodEx2, but its ingredients are. Nutrient intakes were calculated from dietary sources only, i.e. excluding dietary supplements, using country-specific food composition tables [18-24]. Intakes of added sugar, plant and animal protein were calculated based on food selection. Added sugar was defined as the total sugar intake minus sugars naturally occurring in fruits, vegetables and dairy. Plant protein was defined as protein derived from cereals, legumes, nuts and seeds, and others (including potatoes, vegetables, fruits, etc.). Animal protein was defined as protein derived from meat and meat products, fish and fish products, egg and egg products, milk and milk products (including cream, cheese and butter). None of the data excluded under- and over-reporting, however misreporting was identified using Goldberg equation [25] and adopted by Black [26] (Supplementary Table 1).

Dietary quality

Foods

To evaluate European populations' energy-standardised food group intakes, references values were set for the food groups that are important for disease risk reduction based on an inventory of the current food-based dietary guidelines of European countries. Minimum values were set for foods that are beneficial for health, such as fruits and vegetables, and maximum values for foods that are unfavourable for health, such as red and processed meat (see Box 1). Reference values were derived using the 2015 Dutch food-based dietary guidelines [8] as reference point, complemented by the food-based dietary guidelines of the four countries [27-30] in which the less restrictive reference values were chosen (Supplementary Methods).

Box 1 A set of food-based dietary guidelines for European countries, including their exposure definition and reference values, developed for the SUSFANS project.

	Exposure definition	Reference values [a]
Foods to increase		
Fruit	All kind of fruits (including fresh, dried, tinned or canned fruit products, but excluding fruit juice)	≥ 200 g/day
Vegetables	All kind of vegetables (including fresh, dried, tinned or canned vegetable products, but excluding potatoes, vegetable juices and vegetables from soup, sauces and ready-to-eat products)	≥ 200 g/day
Legumes	Kidney beans, pinto beans, white beans, black beans, garbanzo beans (chickpeas), lima beans, split peas, lentils, and edamame (green soybeans)	≥ 135 g/week (≥ 19 g/day)
Nuts and seeds	Walnuts, almonds, hazel, cashew, pistachio, macadamia, Brazil, pecan, pine nuts, flax seeds, sesame seeds, sunflower seeds, pumpkin seeds, poppy seeds, and peanut	≥ 15 g/day
Dairy products	Food products produced from the milk of mammals, including milk, yoghurt, fresh uncured cheese, quark, custard, milk puddings, excluding cheese and butter	≥ 300 g/day
Fish	All kind of fish and fish products	≥ 150 g/week (≥ 21 g/day)
Foods to decrease		
Red and processed meat	Red meat: all mammalian muscle meat, including beef, veal, pork, lamb, mutton, horse and goat, excluding rabbit; Processed meat: meat transformed through salting, curing, fermentations, smoking or other processed to enhance flavour or improve preservation (e.g. meat as sandwich filling, ready-to-eat minced meat, sausages, etc.)	≤ 500 g/week (≤ 71 g/day)
Cheese	All types of cheese formed by coagulation of milk protein casein	≤ 150 g/week (≤ 21 g/day)
Sugar-sweetened beverages	Cold beverages with added sugars (sucrose, fructose or glucose), for example fruit juices/nectars, soft drinks, ice teas, drinks with added sugars	≤ 500 ml/week (≤ 71 ml/day)
Alcohol (Ethanol)	Ethanol content calculated from all kind of alcoholic beverages	≤ 10 g/day
Foods to replace [b]		
Whole grains	Whole grains (bran, germ and endosperm in their natural proportion) from cereals, pasta, bread, breakfast cereals and other grain sources.	Replace refined by whole grains
White meat	Meat from all kind of poultry, including rabbit meat.	Replace red and processed meat by white meat
Soft margarines and oils	Soft margarine: soft-solid fats made from vegetables oils; Oils: liquid fats at room temperature derived from plants or fish	Replace butter and hard margarines by soft margarines and oils

[a] Reference values were derived from current food-based dietary guidelines, using the 2015 Dutch food-based dietary guidelines [8] as reference point, complemented by the food-based dietary guidelines of the four countries [27-30] in which the less restrictive reference values was chosen (Quantitative guideline).

[b] 'Foods to replace' represent food groups for insufficient convincing evidence was available to set a fixed cut-off point, however replacement of those food products by a healthier alternative is recommended (Qualitative guideline).

Nutrients

To evaluate European populations' energy-standardised nutrient intakes, nutrient density of the diet was quantified using Nutrient Rich Diet (NRD) score [31, 32], i.e. overall summary estimate of nutrient intakes based on the principles of the Nutrient Rich Food Index [33, 34]. The NRD algorithm was calculated as:

$$NRD\ X.Y = \sum_{i}^{i=X} \frac{Q_{nutrient\ i}}{DRV\ i} * 100 - \sum_{j}^{j=Y} \frac{Q_{nutrient\ j}}{MRV\ j} * 100$$

where X is the number of qualifying nutrients, Y is the number of disqualifying nutrients, Q nutrient i or j is the average daily intake of nutrient i or j, DRV is the Dietary Reference Value of qualifying nutrient i and MRV j is the Maximum Recommended Value of the nutrient to limit j. DRVs are defined using reference values from EFSA [35], i.e. Average Requirement (AR), and Adequate Intake (AI) if AR cannot be set, and MRVs using reference values of World Health Organisation [36, 37] and Food and Agriculture Organisation [38].

In the present analyses, NRD9.3 and NRD15.3 were used. The NRD9.3, including nine nutrients for which intake should be promoted (protein, dietary fibre, calcium, iron, potassium, magnesium, and vitamin A, C and E) and three nutrients for which intake should be limited (saturated fat (SFA), added sugar, and sodium), standardised for 2,000 kcal/d diet and capped nutrient intake at 100% of DRV was primarily chosen, based on its validation among US populations [33, 34]. To capture more nutrients that are potentially relevant for European populations, we also used its extended version, i.e. NRD15.3 that additionally included mono-unsaturated fatty acids, zinc, vitamin D and B-vitamins (B1, B2, B12, folate), but excluded magnesium. A sub-score on the intake of qualifying nutrients is represented in NRD9 and NRD15, and that of disqualifying nutrients in NRDX.3, while the total score, i.e. NRD9.3 and NRD15.3, is a combination of both.

Estimating the dietary quality of European population diets

Percentages of the population that adhere to food-based dietary guidelines and percentages of the population with inadequate nutrient intakes were estimated using the AR cut-point method [39], without correction for within subject variability. This percentage would be interpreted as proxy figures for adherence and inadequacy, because of different survey's methodologies. When the DRV of the nutrient under study was defined as an AI (dietary fibre, potassium, magnesium, vitamin D, E and B12), this percentage of populations with intake below AI was only applicable for comparison between countries and population subgroups. Dietary intakes were characterised in the overall country-specific population of adults aged ≥ 18 years and in relevant population subgroups by age, gender, educational level, and overweight status. Subgroups by age included younger and middle-aged adults (18 – 64 years) and elderly (≥ 65 years). Younger and middle-aged adult populations were additionally stratified by gender, educational level using three categories, i.e. primary or lower secondary degree ('low'), higher secondary degree ('intermediate') and university or post-university degree ('high'), and overweight status using two categories, i.e. BMI < 25 and ≥ 25 kg/m^2.

As the information available consisted only of summarised data (i.e. mean and standard deviation of the energy-standardised dietary intake under study and sample size), analysis of variance test was performed to check whether there were differences in mean intake of food groups and nutrients between countries and within countries by population subgroups of age, gender, educational level and overweight status. Bonferroni post hoc test was used for multiple comparisons. A two sided p-value below 0.0001 was considered as statistically significant. Statistical analyses were performed with SAS version 9.3 (SAS Institute Inc.).

RESULTS

Baseline characteristics

Age and gender distribution were comparable between countries, with 80 – 90% of the population aged 18 – 64 years and 40 – 48% being men. Distribution of educational level varied markedly between countries; a low proportion of low-educated subjects in Denmark (15%) and a high proportion in France (46%); but proportion of the high-educated subjects was the lowest in Czech Republic (8%) and varied between 23 – 33% for Denmark, Italy and France. Approximately half of the Czech population (52%) was overweight, BMI ≥ 25 kg/m^2, whereas overweight in Denmark (44%), France (39%) and Italy (36%) was less prevalent.

Foods

Table 2 shows the energy-standardised intakes of food groups and general adherence to food-based dietary guidelines in four European adult populations, aged ≥ 18 years. Stratified intakes by age, gender, educational level and overweight status are shown in Table 3.

Foods to increase

Mean fruit and vegetable intake varied significantly between countries with lower intakes for Czech Republic (118 and 95 g/d respectively) and higher intakes for Italy (199 and 239 g/d respectively), and varied in the same direction between men and women within all four countries showing higher intakes for women. Higher fruit intake was also observed in all four countries for the elderly and for subjects with a higher educational level, but no differences by overweight status. Vegetable intake tended to be higher among elderly in Denmark and France, among higher educated subjects in Denmark and Czech Republic, and among overweight subjects in Italy and France. Mean intakes of legumes (6.5 – 16.7 g/d), and nuts and seeds (0.5 – 2.6 g/d) were generally low in all countries. Mean intake of dairy was higher in Denmark (302 g/d), while fish was higher in Italy (44.6 g/d) and France (34.4 g/d).

Foods to decrease

Mean intake of red and processed meat was generally high in all countries (84 – 94 g/d). Within-countries, red and processed meat intake was lower for the elderly and women in all four countries, and except in Italy for the higher educated subjects, and in Czech Republic and France for the non-overweight. Alcohol intake varied between countries with lower intakes in Italy (8.2 g/d) and higher intakes for Denmark (14.6 g/d), and varied within countries in the same direction by gender and overweight status with lower intakes for women and the non-overweight. Alcohol intake also tended to be lower for the young and middle-aged adults, except in Czech Republic where intake is lower for the elderly. For the higher-educated subjects, alcohol intake tended to be lower in Czech Republic and Italy, but higher in Denmark and France.

Table 2 Energy-standardised food group intakes and adherence to food-based dietary guidelines in four European populations, aged ≥ 18 years[ab].

	cut-offs	Denmark (n=2,025)			Czech Republic (n=1,869)			Italy (n=2,831)			France (n=2,624)		
		Mean	P50(P25;P75)	%adh	Mean	P50(P25;P75)	%adh	Mean	P50(P25;P75)	%adh	Mean	P50(P25;P75)	%adh
Foods to increase													
Fruit, g/d	≥200	174*	133(36.0; 255)	35%	118*	83(12.0; 171)	20%	199*	163(76; 275)	40%	140*	95(0.0; 210)	26%
Vegetables, g/d	≥200	147*	112(63; 184)	21%	95*	74(39.0; 127)	10%	239*	206(138; 300)	53%	187*	157(84; 254)	37%
Legumes. g/d	≥19	6.5	1.6(0.0; 6.7)	10%	7.5	0.0(0.0; 3.0)	12%	11.0	0.0(0.0; 2.4)	19%	16.5*	0.0(0.0; 0.8)	18%
Nuts and seeds, g/d	≥15	2.2	0.0(0.0; 0.0)	5%	2.6	0.0(0.0; 0.0)	7%	0.5*	0.0(0.0; 0.0)	1%	1.7	0.0(0.0; 0.0)	3%
Dairy products, g/d	≥300	302*	248(113; 422)	41%	134	94(31.0;192)	12%	129	116(8.0; 20)	8%	199*	152(55; 290)	24%
Fish, g/d	≥21	18.0	5.5(0.0; 24.1)	28%	11.7	0.0(0.0;0.0)	17%	44.6*	6.5(0.0;77)	42%	34.3*	4.3(0.0; 54)	43%
Foods to decrease													
Red and processed meat, g/d	≤71	94	85(51; 127)	39%	88	82(46.0; 125)	42%	84	77(39.2; 119)	51%	93	82(40.5; 133)	43%
Cheese, g/d	≤21	29.3	24.3(11.3;42.0)	44%	20.9*	13.2(0.0; 33.0)	63%	53*	47.2(16.2; 76)	28%	30.1	24.0(2.9; 45.6)	46%
Sweet beverages [c], ml/d	≤71	224*	127(0.0; 305)	40%	108	0.0(0.0; 144)	63%	47.5*	0.0(0.0; 65)	76%	121	6.0(0.0; 171)	56%
Alcohol (ethanol), g/d	≤10	14.6*	7.3(0.0; 22.6)	56%	10.3	4.4(0.0; 16.0)	66%	8.2	0.1(0.0; 13.7)	67%	9.3	0.1(0.0; 14.5)	67%
Foods to replace													
Cereals, total, g/d	-	26.1*	16.9(6.7; 35.0)	-	48.2	32.5(11.0; 72)	-	46.6	38.3(0.6; 73)	-	38.8*	16.05(0.0; 57)	-
Cereals, wholegrains, g/d	-	0.4	0.0(0.0; 0.0)	-	0.1	0.0(0.0; 0.0)	-	0.8	0.0(0.0; 0.0)	-	1.8	0.0(0.0; 0.0)	-
Pasta, total, g/d	-	5.2*	0.0(0.0; 1.2)	-	39.9*	13.6(0.0; 66)	-	52*	48.4(29.8; 82)	-	10.3*	0.0(0.0; 0.0)	-
Pasta, wholegrains, g/d	-	-	-	-	0.0*	0.0(0.0; 0.0)	-	0.3*	0.0(0.0; 0.0)	-	9.8*	0.0(0.0; 0.0)	-
Bread, total, g/d	-	149*	140(94; 194)	-	122*	118(83; 157)	-	109*	103(60; 151)	-	98*	92(51; 139)	-
Bread, wholegrains, g/d	-	52*	44.3(22.4; 72)	-	7.9*	0.0(0.0; 0.0)	-	41.4*	0.0(0.0; 70)	-	16.3*	0.0(0.0; 6.1)	-
Breakfast cereals, total, g/d	-	11.8*	0.6(0.0; 18.0)	-	2.9	0.0(0.0; 0.0)	-	1.5	0.0(0.0; 0.0)	-	5.3*	0.0(0.0; 0.0)	-
Breakfastcereals,wholegrains,g/d	-	9.3*	0.0(0.0; 12.1)	-	1.9*	0.0(0.0; 0.0)	-	0.5*	0.0(0.0; 0.0)	-	3.4*	0.0(0.0; 0.0)	-
Red meat, g/d	-	66*	57.1(28.3; 93)	-	34.0*	28.4(0.0; 55)	-	58	53(0.0; 89)	-	58	45.6(0.0; 91)	-
Processed meat, g/d	-	27.3	19.4(7.1; 37.2)	-	54*	44.5(14.0; 80)	-	25.5	19.4(0.0; 38.9)	-	34.7*	22.6(0.0; 54)	-
White meat, g/d	-	21.3	1.6(0.0; 29.9)	-	22.5	0.0(0.0; 41.0)	-	23.5	0.0(0.0;44.9)	-	31.5*	0.0(0.0; 52)	-
Butter, hard margarines, g/d	-	24.8*	22.7(13.5;33.8)	-	17.6*	15.5(7.0; 25.0)	-	2.8*	0.0(0.0; 3.8)	-	16.3*	13.7(5.8; 24.0)	-
Soft margarines, oils, g/d	-	1.9*	0.0(0.0; 1.5)	-	15.0*	13.1(7.0; 21.0)	-	34.8*	34.0(26.3;42.7)	-	11.2*	7.4(0.4; 17.3)	-

[a] Intake of food groups are standardised to a 2,000 kcal/d diet. [b] %adherence represents a proxy for the percentage of the population that adhere to food-based dietary guidelines.

[c] sweet beverages instead of sugar-sweetened beverages due to a lack of detailed data on beverages.

* Bonferroni $p < 0.0001$ test comparison for intake that was significantly different from all other three countries under study.

Table 3 Energy-standardised food group intakes and the adherence to their corresponding food-based dietary guidelines in four European populations in subgroups by age, gender, educational level, and overweight status: main findings [ab]

	Cut-offs	Subgroups by age						p-value
		Younger and middle-aged adults			Elderly,≥ 65 years			
		Mean	P50 (P25;P75)	%adh	Mean	P50 (P25;P75)	%adh	
Denmark			(n = 1,739)			(n = 286)		
Fruit, g/d	≥200	171	126 (32.2;251)	34%	197	159 (81; 281)	40%	0.011
Vegetables, g/d	≥200	151	114 (64; 189)	22%	119	98 (54; 167)	16%	<.0001
Legumes, g/d	≥19	6.6	1.8 (0.0; 7.1)	10%	5.3	0.9 (0.0; 4.6)	10%	<.0001
Red and processed meat, g/d	≤ 71	95	87 (52; 128)	38%	83	73 (41.5;108)	48%	0.001
Alcohol, g/d	≤10	13.8	6.4 (0.0; 21.5)	58%	20.5	15.0 (1.7; 29.8)	40%	<.0001
Czech Republic			(n = 1,666)			(n = 203)		
Fruit, g/d	≥200	115	79 (10.0;167)	19%	143	118 (38.7;218)	28%	0.006
Vegetables, g/d	≥200	95	75 (39.3;128)	10%	94	70 (39.4;122)	8%	0.874
Legumes, g/d	≥19	7.6	0.0 (0.0; 2.2)	11%	6.7	0.0 (0.0; 4.2)	13%	0.591
Red and processed meat, g/d	≤ 71	89	81 (44.8;125)	42%	83	79 (45.3;118)	42%	0.253
Alcohol, g/d	≤10	10.7	5.1 (0.0; 17.0)	65%	7.4	0.0 (0.0; 9.4)	77%	0.002
Italy			(n = 2,313)			(n = 518)		
Fruit, g/d	≥200	185	153 (67; 257)	37%	257	222 (125; 333)	54%	<.0001
Vegetables, g/d	≥200	238	205 (134; 299)	52%	241	215 (149; 307)	55%	0.680
Legumes, g/d	≥19	10.7	0.0 (0.0; 2.9)	19%	12.4	0.0 (0.0; 0. 0)	19%	0.194
Red and processed meat, g/d	≤ 71	85	77 (37.6;120)	65%	75	68 (31.6;111)	62%	0.015
Alcohol, g/d	≤10	7.8	0.1 (0.0; 12.7)	70%	10.0	2.6 (0.0; 16.5)	60%	0.0002
France			(n = 2,276)			(n = 348)		
Fruit, g/d	≥200	129	77 (0.0 ; 198)	23%	209	174 (77; 309)	42%	<.0001
Vegetables, g/d	≥200	182	152 (80; 248)	36%	219	196 (110; 293)	46%	<.0001
Legumes, g/d	≥19	15.9	0.0 (0.0 ; 0.8)	17%	20.9	0.0 (0.0; 5.3)	20%	0.040
Red and processed meat, g/d	≤ 71	94	84 (40.7;134)	43%	90	79 (37.8;133)	45%	0.316
Alcohol, g/d	≤10	9.0	0.0 (0.0; 13.8)	69%	11.2	5.2 (0.0; 18.2)	56%	0.008

	Cut-offs	Subgroups by gender [c]						p-value
		Men			Women			
		Mean	P50 (P25;P75)	%adh	Mean	P50 (P25;P75)	%adh	
Denmark								
Fruit, g/d	≥200	120	74 (0.5; 172)	21%	222	187 (74; 324)	47%	<.0001
Vegetables, g/d	≥200	117	95 (54; 146)	13%	185	141 (84; 231)	31%	<.0001
Legumes, g/d	≥19	5.9	1.3 (0.0; 5.6)	8%	7.3	2.2 (0.0; 8.6)	11%	<.0001
Red and processed meat, g/d	≤ 71	109	100 (66; 143)	29%	82	75 (43.3;114)	47%	<.0001
Alcohol, g/d	≤10	16.6	10.0 (0.0; 25.6)	50%	10.9	0.0 (0.0; 17.0)	66%	<.0001
Czech Republic			(n = 793)			(n = 873)		
Fruit, g/d	≥200	66	39 (0.7; 93)	6%	160	128 (51; 224)	31%	<.0001
Vegetables, g/d	≥200	78	61 (35.0;106)	5%	111	87 (46.0; 51)	14%	<.0001
Legumes, g/d	≥19	6.1	0.0 (0.0; 1.7)	10%	9.0	0.0 (0.0; 2.6)	12%	0.012
Red and processed meat, g/d	≤ 71	108	103 (69; 142)	27%	71	64 (28.4;103)	55%	<.0001
Alcohol, g/d	≤10	15.8	12.5 (1.2; 23.5)	47%	6.1	0.0 (0.0; 8.6)	81%	<.0001
Italy			(n = 1,068)			(n= 1,245)		
Fruit, g/d	≥200	153	125 (50.4;220)	28%	214	185 (88; 292)	45%	<.0001
Vegetables, g/d	≥200	222	190 (126; 282)	47%	252	156 (145; 317)	56%	<.0001
Legumes, g/d	≥19	10.1	0.0 (0.0; 3.9)	19%	11.3	27.1 (0.0; 2.3)	19%	0.265
Red and processed meat, g/d	≤ 71	88	81 (43.6;122)	65%	82	74 (32.7;119)	64%	<.0001
Alcohol, g/d	≤10	11.3	6.8 (0.0; 18.9)	57%	4.8	8.4 (0.0; 7.0)	80%	<.0001
France			(n = 936)			(n = 1,340)		
Fruit, g/d	≥200	103	65 (0.0; 154)	17%	148	103 (0.0; 219)	28%	<.0001
Vegetables, g/d	≥200	152	128 (65; 204)	26%	202	173 (95; 272)	45%	<.0001
Legumes, g/d	≥19	17.7	0.0 (0.0; 1.8)	19%	14.6	0.0 (0.0; 0.4)	16%	0.068
Red and processed meat, g/d	≤ 71	101	92 (49.8;143)	38%	88	77 (33.9;127)	47%	<.0001
Alcohol, g/d	≤10	13.5	6.6 (0.0; 21.1)	57%	5.8	0.0 (0.0; 7.3)	81%	<.0001

		Subgroups by educational level [c]												
		Low				Intermediate				High				p-
		Mean	P50	(P25;P75)	%adh	Mean	P50	(P25;P75)	%adh	Mean	P50	(P25;P75)	%adh	value [d]
Denmark			(n = 248)				(n = 943)				(n= 548)			
Fruit, g/d	≥200	152	94	(0.0;234)	29%	159	115	(30.4;233)	32%	214	167	(64;305)	42%	<.0001
Vegetables, g/d	≥200	126	96	(56;152)	16%	150	118	(63;185)	21%	184	137	(84;238)	32%	<.0001
Legumes, g/d	≥19	6.1	0.4	(0.0;6.7)	10%	6.5	1.6	(0.0;6.8)	10%	7.7	2.8	(0.0;7.8)	11%	<.0001
Red and processed meat, g/d	≤ 71	102	90	(58;143)	39%	99	92	(58;131)	33%	82	75	(44.5;111)	46%	<.0001
Alcohol, g/d	≤10	13.2	6.3	(0.0;21.4)	58%	13.7	6.0	(0.0;20.6)	59%	15.0	8.8	(0.0;24.5)	52%	0.226
Czech Republic			(n = 345)				(n = 1,194)				(n = 127)			
Fruit, g/d	≥200	89	61	(1.3;141)	11%	122	82	(13.4;173)	21%	121	96	(40.1;179)	20%	0.0004
Vegetables, g/d	≥200	90	71	(40.0;123)	8%	94	74	(37.0;126)	10%	120	85	(59;160)	15%	0.002
Legumes, g/d	≥19	8.9	0.0	(0.0;3.0)	12%	7.3	0.0	(0.0;2.0)	11%	7.3	0.0	(0.0;2.7)	11%	0.524
Red and processed meat, g/d	≤ 71	96	86	(47.4;134)	42%	88	82	(44.3;124)	41%	81	72	(43.4;117)	48%	0.035
Alcohol, g/d	≤10	11.7	5.0	(0.0;19.0)	61%	10.5	4.8	(0.0;16.3)	66%	10.1	7.7	(0.0;16.8)	61%	0.354
Italy			(n = 692)				(n = 985)				(n = 507)			
Fruit, g/d	≥200	182	155	(69;260)	38%	183	149	(65;250)	36%	206	169	(83;282)	41%	0.027
Vegetables, g/d	≥200	242	206	(137;296)	53%	238	205	(136;300)	52%	232	202	(129;287)	51%	0.534
Legumes, g/d	≥19	11.7	0.0	(0.0;4.1)	22%	10.7	0.0	(0.0;3.3)	19%	10.1	0.0	(0.0;4.5)	17%	0.560
Red and processed meat, g/d	≤ 71	88	81	(41.0;122)	65%	85	77	(37.5;119)	65%	83	77	(35.9;121)	65%	0.332
Alcohol, g/d	≤10	8.8	0.0	(0.0;15.3)	66%	7.1	0.1	(0.0; 11.9)	72%	7.4	0.2	(0.0;11.1)	74%	0.001
France			(n = 1,039)				(n = 495)				(n = 737)			
Fruit, g/d	≥200	125	76	(0.0;200)	24%	128	84	(0.0;195)	21%	137	95	(13.9;196)	23%	0.265
Vegetables, g/d	≥200	181	152	(77;248)	36%	179	144	(74;245)	33%	183	156	(87;249)	37%	0.892
Legumes, g/d	≥19	19.5	0.0	(0.0;1.3)	21%	13.2	0.0	(0.0;0.4)	15%	12.5	0.0	(0.0;0.5)	15%	0.0003
Red and processed meat, g/d	≤ 71	102	91	(48.7;144)	39%	90	79	(33.5;129)	44%	84	74	(33.9;123)	47%	<.0001
Alcohol, g/d	≤10	8.3	0.0	(0.0;11.8)	73%	9.4	0.2	(0.0;15.1)	66%	9.6	0.2	(0.0;15.5)	67%	0.135

	Cut-offs	BMI < 25 kg/m²			BMI ≥ 25 kg/m²			p-value
		Subgroup by overweight status [c]						
		Mean	P50 (P25;P75)	%adh	Mean	P50 (P25;P75)	%adh	
Denmark			(n = 972)			(n = 739)		
Fruit, g/d	≥200	167	124 (33.1;246)	34%	174	129 (23.5;255)	33%	0.382
Vegetables, g/d	≥200	154	118 (66;191)	23%	146	108 (63;182)	21%	0.072
Legumes, g/d	≥19	6.4	1.9 (0.0;6.9)	9%	6.9	1.5 (0.0;7.4)	11%	0.055
Red and processed meat, g/d	≤ 71	94	86 (52;126)	38%	99	90 (54;134)	37%	0.072
Alcohol, g/d	≤10	13.2	6.2 (0.0;20.5)	58%	14.5	6.7 (0.0;23.4)	57%	0.100
Czech Republic			(n = 802)			(n = 864)		
Fruit, g/d	≥200	112	79 (19.1;165)	19%	118	79 (5.9;168)	19%	0.371
Vegetables, g/d	≥200	96	77 (40.0;126)	10%	95	73 (37.8;128)	9%	0.807
Legumes, g/d	≥19	7.3	0.0 (0.0;2.3)	11%	7.9	0.0 (0.0;2.1)	11%	0.588
Red and processed meat, g/d	≤ 71	83	73 (40.0;121)	48%	94	88 (50.2;130)	37%	0.0002
Alcohol, g/d	≤10	10.4	4.5 (0.0;16.9)	65%	11.0	5.5 (0.0;16.9)	64%	0.402
Italy			(n = 1,484)			(n = 828)		
Fruit, g/d	≥200	185	155 (68;249)	37%	187	150 (68;272)	37%	0.788
Vegetables, g/d	≥200	229	200 (130;288)	50%	254	213 (144;323)	55%	0.0001
Legumes, g/d	≥19	10.5	0.0 (0.0;2.3)	19%	11.1	0.0 (0.0;4.2)	19%	0.592
Red and processed meat, g/d	≤ 71	84	77 (36.8;118)	65%	86	78 (39.2;124)	64%	0.433
Alcohol, g/d	≤10	6.8	0.0 (0.0;11.2)	73%	9.6	4.0 (0.0;15.9)	62%	<.0001
France			(n = 1,379)			(n = 871)		
Fruit, g/d	≥200	126	82 (0.0;191)	22%	134	89 (0.0;204)	24%	0.180
Vegetables, g/d	≥200	175	146 (75;242)	33%	188	158 (85;254)	39%	0.036
Legumes, g/d	≥19	16.3	0.0 (0.0;1.1)	19%	15.5	0.0 (0.0;0.5)	16%	0.645
Red and processed meat, g/d	≤ 71	89	78 (35.7;127)	44%	101	91 (48.7;145)	40%	0.0001
Alcohol, g/d	≤10	8.0	0.0 (0.0;12.1)	73%	10.6	0.1 (0.0;16.9)	64%	<.0001

Abbreviations: BMI, Body Mass Index;

[a] Intake of food groups are standardised to a 2,000 kcal/d diet. [b] %adherence represents a proxy for the percentage of the population that adhere to food-based dietary guidelines. [c] Younger and middle-aged adults, aged 18 – 64 years, were stratified by gender, educational level and overweight status. [d] P-value for the overall comparisons between population subgroups.

Foods to replace

Mean intakes of whole grains from cereals, pasta and bread were low in all countries, illustrated by the fraction of whole grains on total grains of ≤ 15% with one exception for wholegrain pasta in France. Although mean intake of total breakfast cereals per day was very low, the whole grain variants were primarily eaten. Intake of white meat was much lower than red and processed meat, in particular red and processed meat contributed to 70 – 80% of total meat intake comprising mainly of red meat in Denmark, Italy and France, and of processed meat in Czech Republic. Intakes of butter and hard margarines were only slightly higher than intakes of soft margarines and vegetable oils, except for Denmark where butter and hard margarines were predominantly chosen as fat source, and for Italy where vegetable oils were dominating.

Nutrients

Table 4 shows the energy-standardised nutrient intakes, their corresponding proxy prevalence figures for inadequate intakes, and the NRD scores in four European adult populations, aged ≥ 18 years. Low intakes were observed for dietary fibre (15.8 – 19.4 g/d) and vitamin D (2.4 – 3.0 µg/d) in all countries, and for potassium (2288 – 2939 mg/d), and magnesium (268 – 285 mg/d), except in Denmark. Intake of vitamin E was lower in Denmark (6.7 mg/d), and folate in Czech Republic (212 µg/d). Mean intakes were high for protein (67.1 – 83.5 g/d), and iron (9.1 – 12.4 mg/d) in all countries analysed. Remaining nutrients, including calcium, zinc, vitamin A, C, B1, B2, and B12, showed varying intake levels between countries. Of the three nutrients to limit, a large penalty was obtained from saturated fatty acids (11.1 – 15.1 E%) in all countries, and from estimated sodium intake (2797 – 4244 mg/d) except in Italy. Based on the NRD scores, it is apparent that the nutrient density of the diet was highest in Italy (NRD9.3 of 537, and NRD15.3 of 1051), followed by Denmark (NRD9.3 of 416, and NRD15.3 of 896) and France, and the lowest in Czech Republic (NRD9.3 of 327 and NRD15.3 of 787). Within countries, nutrient density of the diet tended to be higher for women in all four countries and for the higher-educated subject, except in Italy (Table 5).

Table 4 Energy-standardised nutrient intakes, prevalence of inadequate intake, and Nutrient Rich Diet scores in four European populations, aged ≥ 18 years [ab]

	DRV	Denmark (n=2,025)				Czech Republic (n=1,869)				Italy (n=2,831)				France (n=2,624)			
		Mean	P50	(P25;P75)	%<DRV	Mean	P50	(P25; P75)	%<DRV	Mean	P50	(P25; P75)	%<DRV	Mean	P50	(P25; P75)	%<DRV
Unstandardised energy intake, kcal/d	-	2264*	2155	(1681;2738)	-	2523*	2396	(1790;3106)	-	2119*	2057	(1666;2491)	-	1980*	1912	(1509;2390)	-
Qualifying nutrients																	
Protein, g/d	0.66 g/BW	68.7	67.6	(59.7;77.1)	16%	67.1	66.1	(59.1;73.8)	12%	79.0*	77.8	(70.5; 86.1)	1%	83.5*	81.4	(70.9; 93.4)	2.4%
Protein, E%	-	13.9	13.8	(12.4;15.2)	-	13.4	13.2	(11.8; 14.8)	-	15.6*	15.6	(14.1; 17.2)		16.7*	16.3	(14.2; 18.7)	
Animal protein, g/d	-	44.8*	43.2	(35.6;52.8)	-	38.8*	37.5	(30.1; 45.8)	-	48.6*	47.1	(38.9; 56.8)	-	[d]			
Plant protein, g/d	-	20.3*	20.2	(16.9;23.6)	-	23.9*	23.8	(20.1; 27.3)	-	30.3*	30.3	(26.5; 34)	-	[d]			
Dietary fibre, g/d [b]	25	19.4*	18.6	(14.5;23.2)	81%	15.8*	15.1	(12.7; 18.3)	96%	18.1*	17.0	(14.0; 21.0)	88%	16.6*	15.7	(12.3; 19.5)	91%
MUFA, g/d [b]	-	25.7*	25.5	(21.0;30.0)	-	32.0*	31.8	(27.8; 36.4)	-	39.0*	38.7	(33.5; 44.1)	-	29.7*	28.9	(24.0;34.2)	-
MUFA , E%	10-20 E%	11.7*	11.6	(9.5;13.6)	31%	14.4*	14.3	(12.5; 16.4)	8%	17.6*	17.4	(15.1; 19.9)	25%	13.4*	13.0	(10.8; 15.4)	23%
Calcium, mg/d	750	983*	928	(705;1189)	30%	660*	593	(424; 805)	69%	742*	708	(539; 897)	57%	899*	842	(649;1066)	38%
Iron, mg/d	M:6;F:7	9.1*	8.9	(7.7;10.2)	8%	10.6*	10.1	(8.5; 12.1)	4%	11.1*	10.5	(9.0; 12.3)	2%	12.4*	11.2	(9.4; 13.8)	2%
Potassium, mg/d [c]	3500	3143*	3073	(2514;3658)	69%	2288*	2199	(1895;2573)	96%	2938	2834	(2420;3326)	81%	2879	2763	(2326;3287)	82%
Magnesium, mg/d[c]	M:350;F:300	322*	315	(270;365)	54%	285	274	(241; 315)	75%	268*	254	(219 299)	80%	282	263	(230 ; 309)	77%
Zinc, mg/d	M:7.5; F:6.2	9.5*	9.3	(8.1;10.8)	10%	7.0*	6.7	(5.6; 8.0)	52%	11.0*	10.5	(9.1; 12.4)	3%	10.2*	9.6	(8.1;11.8)	9%
Vitamin A, µgRE/d	M:570;F490	1032*	851	(557;1242)	23%	692*	450	(315; 631)	62%	854*	635	(467; 924)	34%	1200*	822	(552;1279)	23%
Vitamin C, mg/d	M:90;F:80	102*	85	(57;131)	50%	78*	63	(37; 103)	65%	126*	103	(66; 159)	38%	91*	76	(46;119)	56%
Vitamin E, mg/d [c]	M:13; F:11	6.7*	6.1	(5.1;7.7)	95%	11.7*	11.1	(8.4;14.4)	56%	12.7*	11.8	(9.7; 14.1)	53%	10.6*	9.4	(6.9; 13.2)	66%
Vitamin D, µg/d [c]	15	3.0	1.9	(1.3;2.7)	97%	2.9	2.1	(1.4; 3.2)	99%	2.4	1.5	(1.0; 2.4)	99%	2.6	1.7	(1.0; 3.0)	99%
Vitamin B1, mg/d	0.6	1.1	1.1	(0.9;1.3)	3%	1.1	1.0	(0.9;1.2)	2%	1.10	0.9	(0.8; 1.1)	53%	1.20	1.1	(0.9; 1.3)	0%
Vitamin B2, mg/d	M:1.1; F:0.9	1.47*	1.38	(1.13;1.70)	20%	1.08*	0.99	(0.84;1.20)	65%	1.40*	1.3	(1.1; 1.6)	16%	1.80*	1.7	(1.4; 2.1)	8%
Vitamin B12, µg/d[c]	4	4.7	4.2	(3.1;5.6)	45%	4.4	3.4	(2.5; 4.8)	64%	6.1	4.1	(3.1; 5.8)	48%	5.6	4.0	(2.9; 5.8)	50%
Folate, µg DFE/d	250	293	268	(214;334)	41%	212*	182	(146; 242)	76%	350*	305	(254; 380)	23%	278	253	(203; 322)	49%

	MRV	Denmark (n=2,025)			Czech Republic (n=1,869)			Italy (n=2,831)			France (n=2,624)		
		Mean	P50 (P25;P75)	%>MRV	Mean	P50 (P25; P75)	%>MRV	Mean	P50 (P25; P75)	%>MRV	Mean	P50 (P25; P75)	%<MRV
Disqualifying nutrients													
SFA, g/d	-	30.4	30.2 (25.0;35.4)	-	30.6	30.4 (25.5;35.1)	-	24.6*	24.2 (20.3;28.3)	-	33.5*	33.4 (27.7;39.1)	-
SFA, E%/d [e]	< 10 E%	13.8	13.7 (11.3;16.1)	86%	13.8	13.7 (11.5;15.8)	80%	11.1*	10.9 (9.1; 12.7)	62%	15.1*	15.0 (12.5;17.6)	91%
Added sugar, g/d	-	43.2*	36.4 (21.3;57.2)	-	36.6	31.3 18.8; 50.6)	-	38.6	35.2 (21.1;52.5)	-	[d]		-
Added sugar, E%[e]	< 10 E%	8.8*	7.4 (4.3;11.6)	32%	7.3	6.3 (3.8; 10.1)	21%	7.7	7.0 (4.2; 10.5)	24%	[d]		[c]
Sodium, mg/d [e]	< 2400	3012*	2919 (2484;3439)	80%	4244*	4153 (3576;4800)	98%	1703*	1648 (1245;2076)	13%	2797*	2668 (2228;3223)	85%
Nutrient Rich Diet Scores													
Sub-score NRD9	-	765	775 (710;829)	-	715*	721 (643; 794)	-	781*	793 (730; 841)	-	759	767 (701; 826)	-
Sub-score NRD15	-	1245	1259 (1192;1310)	-	1175*	1182 (1097; 263)	-	1295*	1310 (1246;1356)	-	1250	1262 (1191;1324)	-
Sub-score NRDX.3	-	349*	346 (300;392)	-	388*	387 (347; 427)	-	244*	242 (215; 271)	-	[d]		-
Total score NRD9.3	-	416*	427 (334;507	-	327*	328 (256; 400)	-	537*	547 (482; 600)	-	[d]		-
Total score NRD15.3	-	896*	916 (823;992)	-	787*	791 (704; 875)	-	1051*	1062 997; 1115	-	[d]		-

Abbreviations: DRV, Dietary Reference Value; AR, Average Requirement; AI, Adequate Intake; RE, Retinol Equivalents; DFE, Dietary Folate Equivalents; E%, energy percentage; MUFA, mono-unsaturated fatty acids; SFA, saturated Fatty Acids; NRD, Nutrient Rich Diet scores, including their sub-scores.

[a] Intakes of nutrients are standardised to a 2,000 kcal/d diet. [b] %<AR represents a proxy for the percentage of the population that have an inadequate intake, i.e. intake lower than the dietary reference value. [c] Nutrients where AR cannot be set, hence AI is defined. [d] cannot be computed. [e] Percentages shown for SFA, added sugar and sodium reflect the proportion of the population that have an excessive intake, i.e. intake higher than the reference value (Maximum Recommend Value). * Bonferroni $p < 0.0001$ test comparison for intake that was significantly different from all other three countries under study.

Table 5 Nutrient density of the diet, using Nutrient Rich Diet 9.3 and 15.3, in four European populations in subgroups by age, gender, educational level and overweight status [a]

	Subgroups by age				
	Younger and middle-aged adults		Elderly,≥ 65 years		p-value
	Mean	P50 (P25; P75)	Mean	P50 (P25; P75)	
Denmark		(n = 1,739)		(n = 286)	
Sub-score NRD9	764	774 (708;829)	772	787 (721;833)	0.120
Sub-score NRD15	1243	1256 (1191;1308)	1256	1275 (1198;1325)	0.033
Sub-score NRDX.3	351	348 (301;395)	333	336 (291;382)	<.0001
Total score NRD9.3	413	424 (327;505)	439	424 (328;505)	0.001
Total score NRD15.3	892	913 (817;988)	923	940 (847;1010)	0.003
Czech Republic		(n = 1,666)		(n = 203)	
Sub-score NRD9	714	720 (641;793)	729	728 (666; 807)	0.037
Sub-score NRD15	1174	1182 (1092;1261)	1185	1181 (1114;1269)	0.208
Sub-score NRDX.3	387	385 (345; 427)	396	395 (360; 430)	0.053
Total score NRD9.3	327	327 (253; 400)	333	342 (270; 401)	0.456
Total score NRD15.3	787	790 (703; 876)	789	792 (711; 873)	0.830
Italy		(n = 2,313)		(n = 518)	
Sub-score NRD9	777	790 (725; 837)	796	805 (759; 852)	<.0001
Sub-score NRD15	1293	1307 (1240;1350)	1305	1321 (1272;1360)	0.003
Sub-score NRDX.3	245	243 (215; 271)	242	240 (213; 269)	0.464
Total score NRD9.3	533	541 (476; 598)	554	563 (509; 609)	<.0001
Total score NRD15.3	1048	1059 (991; 1115)	1064	1075 (1021;1122)	0.002
France		(n = 2,276)		(n = 348)	
Sub-score NRD9	754	762 (696; 821)	785	787 (743; 841)	<.0001
Sub-score NRD15	1244	1256 (1182;1319)	1278	1289 (1222;1346)	<.0001

	Subgroups by gender				
	Men		Women		p-value
	Mean	P50 (P25; P75)	Mean	P50 (P25; P75)	
Denmark		(n = 777)		(n=965)	
Sub-score NRD9	731	733 (679;786)	796	808 (758;853)	<.0001
Sub-score NRD15	1215	1227 (1162;1280)	1271	1284 (1226;1328)	<.0001
Sub-score NRDX.3	355	353 (309;400)	346	339 (297;388)	0.011
Total score NRD9.3	376	386 (295;456)	450	465 (388;537)	<.0001
Total score NRD15.3	860	876 (780;944)	925	944 (859;1021)	<.0001
Czech Republic		(n = 793)		(n = 873)	
Sub-score NRD9	659	656 (597; 719)	763	777 (713; 821)	<.0001
Sub-score NRD15	1119	1115 (1039;1197)	1223	1235 (1157;1297)	<.0001
Sub-score NRDX.3	375	377 (333; 417)	398	397 (358; 436)	<.0001
Total score NRD9.3	284	283 (216; 349)	366	373 (298; 440)	<.0001
Total score NRD15.3	744	744 (665; 821)	826	836 (751; 910)	<.0001
Italy		(n = 1,068)		(n= 1,245)	
Sub-score NRD9	747	754 (692; 806)	803	814 (764; 856)	<.0001
Sub-score NRD15	1264	1271 (1210;1330)	1317	1329 (1278;1367)	<.0001
Sub-score NRDX.3	242	240 (212; 271)	247	245 (219; 272)	0.004
Total score NRD9.3	505	513 (443; 572)	556	565 (509; 614)	<.0001
Total score NRD15.3	1022	1032 (959; 1091)	1070	1079 (1024;1127)	<.0001
France		(n = 936)		(n = 1,340)	
Sub-score NRD9	717	723 (668; 775)	788	799 (743; 846)	<.0001
Sub-score NRD15	1208	1219 (1147; 1284)	1278	1289 (1228; 1346)	<.0001

	Subgroups by educational level[b]						
	Low		Intermediate		High		p-value[c]
	Mean	P50 (P25; P75)	Mean	P50 (P25; P75)	Mean	P50 (P25; P75)	
Denmark		(n = 248)		(n = 943)		(n= 548)	
Sub-score NRD9	746	754 (690;814)	760	767 (705;826)	791	803 (743;844)	<.0001
Sub-score NRD15	1221	1236 (1165;1293)	1242	1254 (1193;1306)	1271	1282 (1224;1325)	<.0001
Sub-score NRDX.3	356	356 (305;404)	356	350 (304;401)	334	334 (291;370)	<.0001
Total score NRD9.3	390	404 (292;498)	405	414 (324;492)	456	459 (392;537)	<.0001
Total score NRD15.3	865	893 (767;978)	887	905 (817;978)	937	942 (869;1013)	<.0001
Czech Republic		(n = 345)		(n = 1,194)		(n = 127)	
Sub-score NRD9	695	684 (624; 780)	716	722 (644; 794)	740	744 (682; 802)	<.0001
Sub-score NRD15	1153	1149 (1060;1252)	1175	1181 (1098;1259)	1217	1238 (1149;1281)	<.0001
Sub-score NRDX.3	378	378 (339; 421)	390	387 (346; 430)	384	381 (348; 413)	0.007
Total score NRD9.3	317	307 (237; 387)	327	327 (254; 406)	356	360 (301; 403)	0.003
Total score NRD15.3	775	775 (681; 862)	785	789 (706; 874)	833	847 (771; 904)	<.0001
Italy		(n = 692)		(n = 985)		(n = 507)	
Sub-score NRD9	774	788 (718; 835)	776	789 (725; 834)	788	801 (734; 851)	0.005
Sub-score NRD15	1291	1309 (1234;1355)	1292	1304 (1242;1353)	1300	1316 (1249;1360)	0.140
Sub-score NRDX.3	240	240 (211; 267)	246	243 (217; 273)	249	246 (220; 276)	0.001
Total score NRD9.3	534	545 (478; 603)	530	536 (474; 593)	539	550 (480; 603)	0.158
Total score NRD15.3	1051	1065 (992; 1118)	1046	1056 (993; 1111)	1051	1064 (991; 1115)	0.439
France		(n = 1,039)		(n = 495)		(n = 737)	
Sub-score NRD9	749	760 (681; 822)	756	763 (702; 817)	761	764 (707; 825)	0.014
Sub-score NRD15	1237	1252 (1166;1319)	1247	1250 (1194; 1314)	1254	162 (1190;1326)	0.002

	Subgroup by overweight status [b]				
	BMI < 25 kg/m^2		BMI ≥ 25 kg/m^2		P-value
	Mean	P50 (P25; P75)	Mean	P50 (P25; P75)	
Denmark		(n = 972)		(n = 739)	
Sub-score NRD9	769	779 (717;829)	759	766 (702;831)	0.054
Sub-score NRD15	1250	1261 (1204;1308)	1237	1249 (1177;1309)	0.021
Sub-score NRDX.3	351	349 (305:392)	351	347 (295;398)	1.000
Total score NRD9.3	408	418 (316;511)	408	418 (316;511)	0.2448
Total score NRD15.3	887	908 (791;990)	887	907 (791;990)	0.165
Czech Republic		(n = 802)		(n = 864)	
Sub-score NRD9	719	725 (646; 795)	709	713 (633; 791)	0.036
Sub-score NRD15	1175	1186 (1097;1260)	1172	1178 (1091;1261)	0.605
Sub-score NRDX.3	389	390 (347; 430)	385	382 (343; 424)	0.196
Total score NRD9.3	330	329 (258; 400)	324	323 (248; 399)	0.260
Total score NRD15.3	786	791 (704; 876)	787	789 (703; 877)	0.872
Italy		(n = 1,484)		(n = 828)	
Sub-score NRD9	779	792 (728; 838)	775	788 (720; 836)	0.245
Sub-score NRD15	1294	1308 (1244;1355)	1291	1307 (1234;1354)	0.414
Sub-score NRDX.3	248	245 (219; 273)	240	237 (209; 268)	<.0001
Total score NRD9.3	531	539 (475; 598)	535	545 (476; 597)	0.289
Total score NRD15.3	1046	1058 (992; 1114)	1051	1064 (990; 1115)	0.206
France		(n = 1,379)		(n = 871)	
Sub-score NRD9	753	760 (696; 819)	758	766 (699; 827)	0.181
Sub-score NRD15	1242	1256 (1177; 1316)	1249	1258 (1191; 1329)	0.110

Abbreviations: BMI, Body Mass Index; NRD, Nutrient Rich Diet scores, including their sub-scores.

[a] For France, sub-score NRDX.3, total score NRD9.3 and 15.5 cannot be computed due to a lack of data on sugars. [b] Younger and middle-aged adults, aged 18 – 64 years, were stratified by gender, educational level and overweight status. [c] P-value for the overall comparisons between population subgroups.

DISCUSSION

In this study, we found that dietary intakes varied markedly across the four European countries, irrespective of energy intake. Within countries, food intakes also varied markedly by socio-economic factors like age, gender, and educational level, but less pronounced by anthropometric factors like overweight status. However, the set of food-based dietary guideline was not met by a large part of the population and/or population subgroup by age, gender, educational level or overweight status.

When describing food group intakes, mean daily intakes of fruit and vegetables, sweet beverages, and alcohol varied most between countries, showing higher intakes of fruit and vegetables, and lower intakes of sweet beverages and alcohol in Italy. In addition, we observed in Italy and France a similar vegetable intake among the different levels of education, whereas in Denmark and Czech Republic higher intake of vegetables was observed among higher-educated subjects; which is in line with previous studies conducted in European populations [40-42]. This region-dependent tendency might be attributed to the long-standing cultural tradition of using vegetables in the Mediterranean diet, as consumed in Italy and France, and is often easily recognisable by all layers of the population. However, a comparison of population subgroups within-countries is often closely related to dietary preferences, beliefs and practices of that particular consumer group. Higher intake of fish, nuts and seeds along with lower intake of red and processed meat are, for example, generally seen among women and higher-educated subjects, which might be driven by their health considerations and awareness of climate change [43].

When describing nutrient intakes summarised by the NRD9.3 and 15.3, the higher scores were observed for Italy, which is mainly attributed to their lower penalty score, i.e. NRDX.3, for the disqualifying nutrients of SFA and sodium. Because of the interrelation between food groups and nutrients intake, our results on variation in nutrient intakes can be partly reflected by our results on variation in food group intake. Low penalty score in Italy is likely to be in correspondence with its lower intakes for important sources of SFA intake such as butter and hard margarines, red and processed meat, and dairy products; however, with estimates of sodium intake, caution must be applied, as they are very likely to be under-estimated due to difficulties in quantifying sodium content in recipes and discretionary salt intake [44]. Moreover, when focussing on qualifying nutrients, higher sub-scores NRD9 and NRD15 were also observed for Italy, but intake for calcium, potassium and magnesium was lower when compared with Denmark; related to intake of dairy products and whole-grain products. It could, thus, be argued whether these summary estimates could be used solely to describe nutrient intakes, as they do not point out specific inadequate nutrient intakes.

In the context of the SUSFANS project, we prefer to describe dietary intakes in terms of foods rather than nutrients, since foods are the constituents of a dietary pattern and the common denominator for linking dietary intakes with health, environment, affordability, consumer's preferences, etc. Diet-associated environmental impact, in particular, has been attracting a lot of interest, as current food production and consumption patterns have been recognised as a major human-induced driver of climate change [45]. Some European countries have, therefore, developed guidelines for diets that are both healthy and environmentally-friendly [46-49]. Such recommendations mostly emphasise the reduction of greenhouse gas emissions through propagating a shift towards plant-based foods. However, given European dietary intakes, there is still much progress to be made in this respect, simply showed by a percentage of around 35% for the intake of plant protein as opposed to total protein for the countries we studied. Moreover, predominant food groups contributing to animal and plant protein intake have been associated with regional and cultural traditions around dietary habits. Meat intake is regarded as the most important contributor to animal protein in European diets, but with differences related to the amount and types of meat consumed, as also denoted by previous studies [50, 51]. With regard to plant protein, cereals and cereal products have been identified as the main contributor to plant protein in European diets [52], while joint contributions from vegetables, legumes and fruit varied between countries, as observed in the present study.

The present study provides further support for the application of individual-level dietary data to address the food-climate connection. Often diet-associated environmental impact was quantified using food availability data related to food production, but not to food consumption as such. Using individual-level reported dietary data might, therefore, be regarded as a useful tool in the connection between health and environment with foods as their common denominator. Cross-country comparison of individual-level dietary data is however challenged by the dietary surveys conducted with different survey characteristics and data collection methods that may influence the comparability of the results. First, sampling procedures used in the surveys reported in this study varied in terms of recruitment methods, household and individual representativeness, number of subjects per household and weighting factors used; however, they all aimed at including a nationally representative sample of at least all age-sex categories. It still remains a possibility that those who have agreed to participate form a group with a greater interest in health, hence more optimistic results.

Second, methods of dietary assessment used in the surveys reported were conducted differently, with regard to the methods used and in the manner in which the assessment was carried out. Replicates of 24-hour recall as applied in Czech Republic showed a higher mean energy intake compared to diet records as applied in Denmark, Italy and France. This might be explained by factors related to the methods themselves, such as reliance on memory and portion size estimations [53-55], and/or characteristics of the populations. Standardising intake data to a 2,000 kcal/d diet had, therefore, the largest impact on results of Czech Republic; lowering its mean dietary intakes under the assumption that energy intake is positively correlated with food group and nutrient intake. Standardisation for energy is one of the more practical ways of reducing part of the extraneous variation in dietary estimates [56], and enables to study the relative contribution of food groups and nutrients intake to the total diet, regardless of energy intake. In the European Food COnsumption VALidation project, it has been suggested to adjust for BMI instead when analysing and interpreting dietary data of nutritional monitoring surveys to reduce mean bias at population level [57]. Given that stratified analyses by overweight status showed no relevant differences in dietary intakes within a country, it is questionable whether BMI-adjusted values should be the main exposure of interest in the present study describing the heterogeneity of European diets.

Another important factor in estimating dietary intakes consistently is the number of days included in the dietary assessment to enable comparison between countries across Europe. In this study, dietary data were, therefore, standardised for the number of days, but have not been corrected for time-interval between the two selected record/recall days, hence not corrected for within-subject day-to-day variability. Correcting for within-subject day-to-day variability would have resulted in comparable means for dietary intakes compared to unadjusted data, though with a shrinkage of intake distributions which in turn would have decreased the percentage of the population above and below a cut-off point [58]. However, relying on consecutive days, including days spaced over a week time-interval, is likely to underestimate the within-subject day-to-day variation [59] because of the interdependence of days that captures some of the day-to-day variation in the between-subject variation [60, 61]. Thus, this day-interdependence would have resulted in a shrinkage of the observed intake distribution that is too much toward the group mean, hence an underestimation of true percentage of the population above and below a cut-off when statistically correcting intake distributions. Also, the use of country-specific food composition databases might affect the number of subjects whose intake was below the DRV. In particular, when using different food composition databases, potential systematic errors in estimating nutrient intake would be different between countries, and in all probability alternate with magnitude and direction. With increasing globalisation, however, the foods and mixed dishes available in different countries are not all grown/produced/prepared in the same manner, and therefore using a country-specific composition database is likely to reflect nutrient intake more accurately.

Exclusion of under-reporters would have increased the prevalence of adherence to the food-based dietary guidelines and decreased the prevalence of inadequate nutrient intakes, and inclusion of supplementation use would have decreased the prevalence of nutrient inadequacy even further. The present study did estimate the percentage of under- and over-reporters (Supplementary Table 1), but did not estimate intakes excluding them, because some of the mis-reporters may truly be consuming a low- or a high-energy diet. Over the past decades, dietary supplementation use has increased in Europe with a clear north-south gradient [62], showing a high number of users in Denmark (Supplementary Table 1). Hence, it is likely that in countries with higher level of supplementation use, dietary supplementation might have contributed to improved total nutrient intakes, with its impact dependent on the supplementation formulation, the frequency of use, and the level of micronutrient intakes of those taking supplements. However, our interest is on nutrient intakes from foods only in order to find nutritional gaps that are most in need to improve the healthiness of dietary intake.

CONCLUSION

In conclusion, there is considerable variation in food and nutrient intakes across European countries. The present study indicated that the intake of food groups showed larger deviations from food-based dietary guidelines for the overall population and population subgroups of the countries we studied. In addition, results suggested inadequate nutrient intakes from foods for dietary fibre and vitamin D in all countries, and for potassium, magnesium, vitamin E and folate in specific regions. Individual-level dietary data in different European population and population subgroups are therefore needed for balancing diets for European citizen.

Moreover, individual-level dietary data from national surveys serve as a practical tool for describing the healthiness of diet in terms of foods and nutrients, but dietary data harmonisation remains challenging. Using a common food classification system is a first step in the alignment of surveys and necessary to enable cross-country comparisons for food group intakes. However, further steps, such as standardisation for energy, number of days, etc., are needed for harmonisation of dietary data. Besides the healthiness of dietary intake, these dietary surveys might also be important in shaping optimised diets where other factors, such as environmental impact, affordability and consumer preferences are incorporated. We aim, therefore, to support further engagement of key stakeholders from the food supply chain and policy-makers in the next stages for the design of SHARP diets.

Financial support

Financial support for this original contribution was obtained from funding from the European Union’s H2020 Programme under Grant Agreement number 633692 (SUSFANS: Metrics, models and foresight for European sustainable food and nutrition security) and from the Top Consortia for Knowledge and Innovation of the Dutch Ministry of Economic Affairs.

Conflict of interest

The authors have no conflicts of interest.

REFERENCES

1. GBD 2016 Risk Factors Collaborators: **Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2016: a systematic analysis for the Global Burden of Disease Study 2016**. *The Lancet* 2017, **390**(10100):1345-1422.
2. Traill WB, Mazzocchi M, Shankar B, Hallam D: **Importance of government policies and other influences in transforming global diets**. *Nutr Rev* 2014, **72**(9):591-604.
3. Global Panel on Agriculture and Food Systems for Nutrition: **Food systems and diets: Facing the challenges of the 21st century**. In*.* London, UK; 2016.
4. Schmidhuber J, Traill WB: **The changing structure of diets in the European Union in relation to healthy eating guidelines**. *Public Health Nutr* 2006, **9**(05):584-595.
5. Balanza R, García-Lorda P, Pérez-Rodrigo C, Aranceta J, Bonet MB, Salas-Salvadó J: **Trends in food availability determined by the Food and Agriculture Organization's food balance sheets in Mediterranean Europe in comparison with other European areas**. *Public Health Nutr* 2007, **10**(02):168-176.
6. Gerbens-Leenes P, Nonhebel S, Krol M: **Food consumption patterns and economic growth. Increasing affluence and the use of natural resources**. *Appetite* 2010, **55**(3):597-608.
7. Mozaffarian D, Ludwig DS: **Dietary guidelines in the 21st century—a time for food**. *Jama* 2010, **304**(6):681-682.
8. Kromhout D, Spaaij C, de Goede J, Weggemans R: **The 2015 Dutch food-based dietary guidelines**. *Eur J C Nutr* 2016.
9. World Health Organisation (WHO): **Food based dietary guidelines in the WHO European Region**. In*.* Copenhagen, Denmark; 2003.
10. Rutten M, Achterbosch TJ, de Boer IJ, Cuaresma JC, Geleijnse JM, Havlík P, Heckelei T, Ingram J, Leip A, Marette S: **Metrics, models and foresight for European sustainable food and nutrition security: the vision of the SUSFANS project**. *Agricultural Systems* 2016.
11. Pedersen A, Fagt, S., Groth, MV., Christensen, T., Biltoft-Jensen, A., Matthiessen, J., Andersen, NL., Kørup, K., Hartkopp, H., Ygil, K., Hinsch, HJ., Saxholt, E., Trolle, E. : **Danskernes kostvaner 2003-2008**. In.: DTU Fødevareinstituttet; 2009.
12. **Individual food consumption - the national study SISP04** [http://www.chpr.szu.cz/spotrebapotravin.htm]
13. Leclercq C AD, Piccinelli R, Sette S, Le Donne C and Turrini A: **The Italian national food consumption survey INRAN-SCAI 2005-06: main results in terms of food consumption**. *Publ Health Nutr* 2009, **12(12)**:2504 - 2532.
14. Agence Française de Sécurité Sanitaire des Aliments (AFSSA): **Report of the 2006/2007 Individual and National Study on Food Consumption 2 (INCA 2). Synthèse de l'étude individuelle nationale des consommations alimentaires 2 (INCA 2), 2006-2007**. In.; 2009: 1-44.
15. Matthiessen J, Stockmarr A, Biltoft-Jensen A, Fagt S, Zhang H, Groth MV: **Trends in overweight and obesity in Danish children and adolescents: 2000-2008--exploring changes according to parental education**. *Scandinavian journal of public health* 2014, **42**(4):385-392.
16. European Food Safety Authority: **The food classification and description system FoodEx2 (revision 2)**. *EFSA supporting publication 2015* 2015, **En-804**:90.
17. EFSA (Eurepean Food Safety Authority): **Use of the EFSA Comprehensive European Food Consumption Database in Exposure Assessment**. *EFSA Journal 2011* 2011, **9**(9):2097.
18. Møller A SE, Christensen AT, Hartkopp H. : **Fødevaredatabanken version 6.0**. In., 2005 edn. Afdeling for Ernæring, Danmarks: Fødevareinformatik; 2005.
19. Saxholt E, Christensen, A.T., Møller, A., Hartkopp, H.B., Hess Ygil, K., Hels, O.H.: **Fødevaredatabanken, version 7**. In., 2008 edn. Afdeling for Ernæring, Fødevareinstituttet, Danmarks Tekniske Universitet: Fødevareinformatik; 2008.

20. Czech Centre for Food Composition Database: **Czech Food Composition Database Version 6.16**. In. Prague, Czech Republic: Institute of Agricultural Economics and Information,; 2016.
21. Food Research Institute: **Slovak Food Composition Data Bank**. In. Bratislava, Slovak Republic: Department of Risk Assessment Food Composition Data Bank and Consumer's Survey VUP Food Research Institute,; 2016.
22. Istituto Nazionale di Ricerca per gli Alimenti e la Nutrizione (INRAN): **Banca Dati di Composizione degli Alimenti** In. Roma, Italy: Istituto Nazionale di Ricerca per gli Alimenti e la Nutrizione,; 2016.
23. Feinberg M FJ-CLC: **Répertoire général des aliments (General Inventory of Foods)**. In. Paris: Institut national de la recherche agronomique: Technique & Documentation - Lavoisier.; 1995.
24. Ireland J dCL, Oseredczuk M, et al **French Food Composition Table, version 2008**. In.: French Food Safety Agency (AFSSA); 2008.
25. Goldberg G, Black A, Jebb S, Cole T, Murgatroyd P, Coward W, Prentice A: **Critical evaluation of energy intake data using fundamental principles of energy physiology: 1. Derivation of cut-off limits to identify under-recording**. *Eur J Clin Nutr* 1991, **45**(12):569-581.
26. Black AE: **Critical evaluation of energy intake using the Goldberg cut-off for energy intake: basal metabolic rate. A practical guide to its calculation, use and limitations**. *Int J Obes Relat Metab Disord* 2000, **24**(9).
27. **The official dietary guidelines (Danish: De officielle kostråd)** [http://www.fao.org/3/a-as675o.pdf]
28. Czech Society for Nutrition: **Nutrition recommendations for Czech Republic (Czech: Výživová doporučení pro obyvatelstvo České republiky)**. In. Prague, Czech Republic: Czech Society for Nutrition; 2012.
29. Italian National Research Institute on Food and Nutrition (INRAN; CRA-NUT): **Guidelines for healthy Italian food habits, 2003 (Italian: Linee guida per una sana alimentazione italiana. Revisione 2003).** . In. Roma, Italy: Italian National Research Institute on Food and Nutrition (INRAN; CRA-NUT); 2003.
30. **La Santé vient en mangeant Le guide alimentaire pour tous** [http://www.mangerbouger.fr/]
31. Van Kernebeek HRJ, Oosting SJ, Feskens EJM, Gerber PJ, De Boer IJM: **The effect of nutritional quality on comparing environmental impacts of human diets**. *Journal of Cleaner Production* 2014, **73**(0):88-99.
32. Roos E, Karlsson H, Witthoft C, Sundberg C: **Evaluating the sustainability of diets-combining environmental and nutritional aspects**. *Environmental Science & Policy* 2015, **47**:157-166.
33. Drewnowski A: **Defining nutrient density: development and validation of the nutrient rich foods index**. *J Am Coll Nutr* 2009, **28**(4):421s-426s.
34. Fulgoni VL, 3rd, Keast DR, Drewnowski A: **Development and validation of the nutrient-rich foods index: a tool to measure nutritional quality of foods**. *J Nutr* 2009, **139**(8):1549-1554.
35. EFSA (European Food Safety Authority): **Panel (EFSA Panel on Dietetic Products, Nutrition and Allergies), 2010. Scientific Opinion on principles for deriving and applying Dietary Reference Values**. *EFSA Journal 2010* 2010, **8**(3):1458
36. World Health Organisation (WHO): **Guideline: Sodium intake for adults and children.** In: *World Health Organisation (WHO).* Geneva; 2012.
37. World Health Organisation (WHO): **Guideline: Sugars intake for adults and children**. In: *World Health Organisation (WHO).* Geneva; 2015.
38. Food and Agriculture Organisation (FAO): **Fats and fatty acids in human nutrition. Report of an expert consultation**. *FAO Food and nutrition paper* 2010, **91**:1-166.
39. Institute of Medicine (IOM): **Dietary Reference Intakes: Applications in Dietary Assesement**. In.: National Academy Press Washington DC; 2000.

40. De Irala-Estevez J, Groth M, Johansson L, Oltersdorf U: **A systematic review of socio-economic differences in food habits in Europe: consumption of fruit and vegetables**. *Eur J Clin Nutr* 2000, **54**(9):706.
41. Prättälä R, Hakala S, Roskam A-JR, Roos E, Helmert U, Klumbiene J, Van Oyen H, Regidor E, Kunst AE: **Association between educational level and vegetable use in nine European countries**. *Public Health Nutr* 2009, **12**(11):2174-2182.
42. Roos E, Talala K, Laaksonen M, Helakorpi S, Rahkonen O, Uutela A, Prättälä R: **Trends of socioeconomic differences in daily vegetable consumption, 1979–2002**. *Eur J Clin Nutr* 2008, **62**(7):823-833.
43. de Boer J, Schosler H, Aiking H: **"Meatless days" or "less but better"? Exploring strategies to adapt Western meat consumption to health and sustainability challenges**. *Appetite* 2014, **76**:120-128.
44. McLean RM: **Measuring population sodium intake: a review of methods**. *Nutrients* 2014, **6**(11):4651-4662.
45. Tukker A. HG, Guinée J., Heijungs R., de Koning A., van Oers L., et al.: **Environmental Impact of Products (EIPRO) Analysis of the life cycle environmental impacts related to the final consumption of the EU25**. In: *European Commission Technical Report EUR 22284 EN.* Brussels: IPTS/ESTO, European Commission Joint Research Centre 2006.
46. German Nutrition Society: **Ten guidelines for wholesome eating and drinking from the German Nutrition Society (German: Vollwertig essen und trinken nach den 10 Regeln der DGE).** . In. Bonn: Deutsche Gesellschaft für Ernährungs e.V.; 2013.
47. The Swedish National Food Agency (Livsmedelsverket): **Find your way to eat greener, not too much and to be active! (Hitta ditt sätt att äta grönare, lagom mycket och röra på dig!)**. In. Uppsala: Livesmedelsverket; 2017.
48. Health Council of the Netherlands: **Guidelines for a Healthy Diet: The Ecological Perspective**. In. The Hague: Health Council of the Netherlands; 2011.
49. Macdiarmid J, Kyle J, Horgan G, Loe J, Fyfe C, Johnstone A, McNeill G: **Livewell: a balance of healthy and sustainable food choices. WWF-UK**. In.; 2011.
50. Linseisen J, Kesse E, Slimani N, Bueno-De-Mesquita H, Ocké M, Skeie G, Kumle M, Iraeta MD, Gómez PM, Janzon L: **Meat consumption in the European Prospective Investigation into Cancer and Nutrition (EPIC) cohorts: results from 24-hour dietary recalls**. *Public Health Nutr* 2002, **5**(6b):1243-1258.
51. Kushi LH, Lenart EB, Willett WC: **Health implications of Mediterranean diets in light of contemporary knowledge. 2. Meat, wine, fats, and oils**. *Am J Clin Nutr* 1995, **61**(6):1416S-1427S.
52. Halkjaer J, Olsen A, Bjerregaard L, Deharveng G, Tjønneland A, Welch A, Crowe F, Wirfält E, Hellstrom V, Niravong M: **Intake of total, animal and plant proteins, and their food sources in 10 countries in the European Prospective Investigation into Cancer and Nutrition**. *Eur J Clin Nutr* 2009, **63**:S16-S36.
53. Bingham S, Gill C, Welch A, Day K, Cassidy A, Khaw K, Sneyd M, Key T, Roe L, Day N: **Comparison of dietary assessment methods in nutritional epidemiology: weighed records v. 24 h recalls, food-frequency questionnaires and estimated-diet records**. *Br J Nutr* 1994, **72**(04):619-643.
54. Holmes B, Dick K, Nelson M: **A comparison of four dietary assessment methods in materially deprived households in England**. *Public Health Nutr* 2008, **11**(05):444-456.
55. De Keyzer W, Huybrechts I, De Vriendt V, Vandevijvere S, Slimani N, Van Oyen H, De Henauw S: **Repeated 24-hour recalls versus dietary records for estimating nutrient intakes in a national food consumption survey**. *Food & nutrition research* 2011, **55**.
56. Willett WC, Howe GR, Kushi LH: **Adjustment for total energy intake in epidemiologic studies**. *The American journal of clinical nutrition* 1997, **65**(4):1220S-1228S.

57. Crispim SP, Geelen A, De Vries JH, Freisling H, Souverein OW, Hulshof PJ, Ocke MC, Boshuizen H, Andersen LF, Ruprich J: **Bias in protein and potassium intake collected with 24-h recalls (EPIC-Soft) is rather comparable across European populations**. *Eur J Nutr* 2012, **51**(8):997-1010.
58. Dodd KW, Guenther PM, Freedman LS, Subar AF, Kipnis V, Midthune D, Tooze JA, Krebs-Smith SM: **Statistical methods for estimating usual intake of nutrients and foods: a review of the theory**. *J Am Diet Assoc* 2006, **106**(10):1640-1650.
59. Larkin FA, Metzner HL, Guire KE: **Comparison of 3 Consecutive-Day and 3 Random-Day Records of Dietary-Intake**. *J Am Diet Assoc* 1991, **91**(12):1538-1542.
60. Tarasuk V, Beaton GH: **The Nature and Individuality of within-Subject Variation in Energy-Intake**. *Am J Clin Nutr* 1991, **54**(3):464-470.
61. Ellozy M: **Dietary Variability and Its Impact on Nutritional Epidemiology**. *J Chron Dis* 1983, **36**(3):237-249.
62. Skeie G, Braaten T, Hjartåker A, Lentjes M, Amiano P, Jakszyn P, Pala V, Palanca A, Niekerk E, Verhagen H: **Use of dietary supplements in the European Prospective Investigation into Cancer and Nutrition calibration study**. *Eur J Clin Nutr* 2009, **63**:S226-S238.

SUPPLEMENTARY MATERIALS

Supplementary Methods

Reference values for the food group intake used for cross-country comparison.

Food-based dietary guidelines are defined at the national level, resulting in different set of food-based dietary guidelines across Europe. A summary of the food-based dietary guidelines of the European countries that are part of SUSFANS (Denmark, Czech Republic, Italy and France) is given in **Supplementary Methods Table 1.** Based on this information, a single set of reference values for the intake of food groups was used to facilitate cross-country comparison, as also shown in Table 2 and Table 3. Minimum intake levels were set for foods that are beneficial for health, such as fruits and vegetables, and maximum intake levels for foods that are unfavourable for health, such as red and processed meat. Cut-off points were defined in grams per day with the aim to increase the comparability of food intake between the countries, as serving sizes are country-specific. For most food groups, it was expected that actual dietary intake levels largely deviate from recommended intakes levels in European populations, and therefore cut-off level were loosened to be able to examine differences and shifts in nutritional adequacy across countries and across relevant population subgroups as a way of population dissimilation. Qualitative guidelines were formulated for food groups for which evidence only concerns the replacement of one food by another, such as replace white grains by whole grains, butter and hard margarine by vegetable oils and soft margarine.

Supplementary Methods Table 1 A summary of the food-based dietary guidelines of the European countries that are part of SUSFANS (Denmark, Czech Republic, Italy and France), including exposure definitions and their derived reference values used for cross-country comparison.

Denmark	Czech Republic	Italy	France	Reference values for cross-country comparison
Whole grains and grain-based products				
Whole grains (bran, germ, and endosperm in their natural proportion) from breakfast cereals, bread, rice, pasta, tortillas, pancakes and other sources				
A minimum of 75 grams a day; including whole grains in bread, grain flour, cereals, rice and pasta	Replace refined grains by whole grains	Replace refined grains by whole grains	Replace refined grains by whole grains	Replace refined grains by whole grains
Vegetables and vegetable products				
All kind of vegetables (including fresh, dried, tinned/canned, but excluding vegetable juices and vegetables from soup, sauces and ready-to-eat products)				
A minimum of 600 grams fruit and vegetables a day, with a minimum of 300 grams of vegetables a day, preferably the coarse vegetables	3 – 5 servings a day (300 – 500 grams a day)	2 servings a day (one serving is 200 gram raw or cooked vegetables and 80 gram leafy vegetables)	A minimum of 5 servings fruit and vegetables a day (one serving is 80 – 100 gram)	Minimum 200 grams a day
Legumes				
Kidney beans, pinto beans, white beans, black beans, garbanzo beans (chickpeas), lima beans, split peas, lentils, and edamame (green soybeans)				
Included in vegetable guideline.	Included in meat guideline.	Not specified	Included in fruit and vegetable guideline.	Minimum 135 grams a week ≈ 19 grams a day
Nuts and seeds				
Walnuts, almonds, hazel, cashew, pistachio, macadamia, Brazil, pecan, pine nuts, flax seeds, sesame seeds, sunflower seeds, pumpkin seeds, poppy seeds, and peanuts				
Around 30 grams a day	Not included	Included in fruit guideline.	Included in fruit and vegetable guideline.	Minimum 15 grams a day

Denmark	Czech Republic	Italy	France	Reference values for cross-country comparison
Fruit and fruit products				
All kind of fruits (including fresh, dried, tinned or canned fruit products, but excluding fruit juice)				
A minimum of 600 grams fruit and vegetables a day	2 – 4 servings a day (200 – 400 grams a day) preferably raw fruit and undiluted fruit juice	3 – 4 servings a day (one serving is 150 gram fresh fruit, 30 gram nuts, or 30 gram dried fruit)	A minimum of 5 servings fruit and vegetables a day (one serving is 80 – 100 gram)	Minimum 200 grams a day
Meat and meat products				
Red meat: all mammalian muscle meat, including beef, veal, pork, lamb, mutton, horse and goat, excluding rabbit meat; Processed meat: meat transformed through salting, curing, fermentations, smoking or other processed to enhance flavour or improve preservation (e.g. meat products as sandwich filling, ready-to-eat minced meat, sausages, etc.); White meat: poultry and rabbit meat				
Choose for lean meat, lean cold meat and/or poultry. A maximum of 500 grams a week from beef, veal, lamb or pork (prepared weight)	Choose for lean meat, lean cold meat and/or poultry. 1 – 2 servings a day (one serving is 125 gram meat, poultry or fish, 2 boiled egg whites, a bowl of soya beans, lentils or beans); eggs are limited to a maximum of 4 eggs a week	Choose for lean meat, lean cold meat and/or poultry. 1 – 2 servings a day (one serving is 100 gram meat or poultry, 50 gram processed meat, 150 gram fish and shellfish, 50 gram processed fish and shellfish, and one egg)	Choose for lean meat, lean cold meat and/or poultry. A maximum of 500 grams a week for red and processed meat, with a maximum of 25 grams of processed meat a day	Maximum 500 grams red and processed meat a day ≈ 71 grams a day Replace red and processed meat by white meat
Fish and fish products				
All kind of fish and fish products				
Around 350 grams a week; preferably 200 grams oily fish a week	1 – 2 servings a week (170 – 340 grams a week)	2 – 3 times a week (300 – 450 grams a week)	2 servings a week (200 grams a week), including one oily fish	Minimum 150 grams a week ≈ 21 grams a day

Denmark	Czech Republic	Italy	France	Reference values for cross-country comparison
Milk and milk products				
Food products produced from the milk of mammals, including milk, yoghurt, fresh cheese, quark, custard, milk puddings, and cheese excluding butter				
250 – 500 grams of dairy a day, excluding hard cheese; hard cheese 1 – 2 slices a day when eating healthy, with one slice corresponding to 25 grams	2 – 3 servings a day (one serving is 250 millilitres low-fat milk, 200 millilitres low-fat yoghurt, 55 gram cheese, and 40 gram cottage cheese)	3 servings a day (one serving is 125 millilitres milk, 125 gram yoghurt, 100 gram fresh cheese, and 50 gram hard cheese); hard cheese is limited to a maximum of 2 – 3 servings a week	3 servings a day (one serving is 200 millilitres milk, 125 gram yoghourt, 100 gram fromage blanc, 60 gram petit Suisse, and 30 gram hard cheese)	Minimum 300 grams dairy a day excluding butter and cheese Maximum 150 grams hard cheese a week ≈ 21 grams a day
Fats & Oils				
Replace butter, hard margarines and cooking fats by soft margarines, liquid cooking fats, and vegetable oils.	Replace butter, hard margarines and cooking fats by soft margarines, liquid cooking fats, and vegetable oils.	3 servings extra virgin olive oil or seed oil a day (one serving is 10 millilitres). Replace butter, hard margarines and cooking fats by soft margarines, liquid cooking fats, and vegetable oils.	Replace butter, hard margarines and cooking fats by soft margarines, liquid cooking fats, and vegetable oils. Plus, promote fats rich in ALA and limit fats rich in myristic, lauric and palmitic fatty acids	Replace butter, hard margarines and/or hard cooking fats by soft margarines, liquid cooking fats and/or vegetable oils
Sugar-sweetened beverages				
Cold beverages with added sugars (sucrose, fructose or glucose), including fruit/vegetable juices/ nectars, soft drinks, ice teas, other drinks with added sugars				
A maximum of 500 millilitres a week, including soft drinks, juice and energy drinks	Limit consumption	Limit consumption	Limit consumption. A maximum of one portion of fruit juice a day, corresponding to 150 millilitres a day	Maximum 500 millilitres a week ≈ 71 grams a day

Denmark	Czech Republic	Italy	France	Reference values for cross-country comparison
Alcoholic beverages				
Not in food-based dietary guidelines, but a separate guideline: a maximum of 14 glasses a week, corresponding to 20 grams a day, for men, and a maximum of 7 glasses a week, corresponding to 10 grams a day, for women, with a maximum of 5 glasses per occasion.	A maximum of 20 grams of alcohol a day, but avoid daily consumption	In controlled quantities	Not included, because considered as not good for health	Maximum one serving a day ≈ 10 grams ethanol a day
Salt				
Maximum 6 grams a day	Maximum 5 grams a day	Not specified	Not specified	Maximum 6 grams a day

Ministry of Food Agriculture and Fisheries (2013). "The official dietary guidelines (Danish: De officielle kostråd)."
Czech Society for Nutrition (2012). "Nutrition recommendations for Czech Republic (Czech: Výživová doporučení pro obyvatelstvo České republiky)."
Italian National Research Institute on Food and Nutrition (INRAN; CRA-NUT) (2003). "Guidelines for healthy Italian food habits, 2003 (Italian: Linee guida per una sana alimentazione italiana. Revisione 2003)."
Programme National Nutrition Santé (PNNS) (2016). "La Santé vient en mangeant Le guide alimentaire pour tous."

Supplementary Table 1 Percentage of under- and over-reporters as identified by Goldberg/Black equation, and percentage of dietary supplementation use in four European populations, aged ≥ 18 years.

	%under-reporters			%over-reporters			%supplement users		
	Total	Men	Women	Total	Men	Women	Total	Men	Women
Denmark	17.7%	18.2%	17.3%	1.4%	1.3%	1.5%	60.5%	55.0%	65.9%
Czech Republic	12.9%	7.0%	18.1%	3.6%	5.6%	1.9%	29.7%	23.3%	35.4%
Italy	11.0%	12.3%	9.9%	1.1%	0.9%	1.3%	4.5%	3.0%	5.8%
France	23.7%	22.9%	24.3%	1.6%	2.0%	1.2%	12.4%	6.1%	16.8%

CHAPTER 5

Dietary choices and environmental impact in four European countries

Elly Mertens
Anneleen Kuijsten
Hannah HE van Zanten
Gerdine Kaptijn
Marcela Dofková
Lorenza Mistura
Laura D'Addezio
Aida Turrini
Carine Dubuisson
Sabrina Havard
Ellen Trolle
Johanna M Geleijnse
Pieter van 't Veer

Published in: Journal of Cleaner Production 2019; 237:117827

ABSTRACT

Effective food policies in Europe require insight into the environmental impact of consumers' diet to contribute to global nutrition security in an environmentally sustainable way. The present study therefore aimed to assess the environmental impact associated with dietary intake across four European countries, and to explain sources of variations in environmental impact by energy intake, demographics and diet composition. Individual-level dietary intake data were obtained from nationally-representative dietary surveys, by using two non-consecutive days of a 24-hour recall or a diet record, from Denmark (DK, n=1,710), Czech Republic (CZ, n=1,666), Italy (IT, n=2,184), and France (FR, n=2,246). Dietary intake data were linked to a newly developed pan-European environmental sustainability indicator database that contains greenhouse gas emissions (GHGE) and land use (LU) values for ~900 foods. To explain the variation in environmental impact of diets, multilevel regression models with random intercept and random slopes were fitted according to two levels: adults (level 1, n=7,806) and country (level 2, n=4). In the models, diet-related GHGE or LU was the dependent variable, and the parameter of interest, i.e. either total energy intake or demographics or food groups, the exploratory variables. A 200-kcal higher total energy intake was associated with a 9% and a 10% higher daily GHGE and LU. Expressed per 2,000 kcal, mean GHGE ranged from 4.4 (CZ) to 6.3 kgCO$_2$eq/2,000 kcal (FR), and LU ranged from 5.7 (CZ) to 8.0 m^2*year/2000kcal (FR). Dietary choices explained most of the variation between countries. A 5 energy percent (50g/2,000 kcal) higher meat intake was associated with a 10% and a 14% higher GHGE and LU density, with ruminant meat being the main contributor to environmental footprints. In conclusion, intake of energy, total meat and the proportion of ruminant meat explained most of the variation in GHGE and LU of European diets. Contributions of food groups to environmental footprints however varied between countries, suggesting that cultural preferences play an important role in environmental footprints of consumers. In particular, Findings from the present study will be relevant for national-specific food policy measures towards a more environmentally-friendly diet.

INTRODUCTION

Current food production and consumption patterns in Europe are held responsible for more than 25% of anthropogenic greenhouse gas emissions (GHGE) and more than 80% of arable land globally [1, 2] with animal-sourced foods being the major contributors [3]. In line with the framework of the Lancet EAT Commission [4], studies on food patterns compared theoretically-constructed diets with national average diets [5-7] and showed that current diets high in animal-sourced foods, in particular red meat and dairy, have a higher environmental impact. Effective policies for food system transformation in Europe require insight into the environmental impact of consumers' usual diet and detailed information on food consumption over a wide range of dietary patterns.

Initially, environmental impact of diets was assessed using national averages derived from per capita food availability statistics collected at the national level [5]; and more recently actual food intake data at the refined level of individual daily consumption have been used [8, 9]. The method of dietary assessment is however likely to affect the estimated environmental impact. Food availability statistics typically disaggregate and quantify food consumption in about 25 primary agricultural commodities, whereas individual-based food frequency questionnaires typically include 50-150 food items, and it may range up to ~1,000 food items for individual-based survey data using 24-hour recalls or diet records [10]. These individual-level dietary data reflect a wide variety of realistic food choices in the consumer domain, and therefore allow for studying the variability in diet-related footprints of individual' diets across population (sub)groups.

A number of studies have assessed the environmental impact of food intake using individual-level data [11-16]. As these studies were conducted within single European countries, a European comparison of diet-related environmental impact is hampered, as these national averages may be biased by the ecological fallacy, lack of comparability of dietary assessment methods [17] and systematic differences in life cycle assessment (LCA) databases [18, 19]. Comparable individual-level intake data and LCA databases allow to evaluate environmental impact at the level of consumers' food choices and allow to explain variation between- and within countries, between population (sub)groups and between subjects.

The aim of this study was to analyse diet-related GHGE and LU using reported food intake data obtained from national dietary surveys from four European countries that reflect heterogeneity of diets in different European regions, i.e. Denmark (DK; Scandinavia), Czech Republic (CZ; Central East Europe), Italy (IT; Mediterranean) and France (FR; Western Europe). Moreover, the present study aimed to study the variability in diet-related environmental footprints between and within countries, and to explain this by energy intake, and by demographics and diet composition.

MATERIALS AND METHODS

Study population and food intake data

Individual-level dietary intake data were obtained from nationally-representative dietary surveys for each of the countries studied, and for each country adults aged 18-64 years were included. The National Survey on Diet and Physical Activity (2005-2008) in DK was based on a seven-day diet record on consecutive days and included 1,739 adult men and women [20]. The national SISP04 (2003-2004) in CZ was based on two replicates of 24-hour recall spaced over three-to-five months and included 1,666 adult men and women [21]. The national INRAN-SCAI (2005-2006) in IT was based on a three-day diet record on consecutive days and included 2,313 adult men and women [22]. The national INCA-2 Study (2006-2007) in FR was based on a seven-day diet record on consecutive days and included 2,276 adult men and women [23]. Surveys were organised throughout the entire year, covering all four seasons, and proportionally included week- and weekend-days.

For comparison across countries, dietary intake data of two non-consecutive days were used, hereby sampling two non-consecutive days in DK, IT and FR, and using both available days in CZ. Intakes of food groups and individual food items were classified according to the FoodEx2 classification that was developed by the European Food Safety Authority (EFSA) [24, 25]. Intake data coded by FoodEx2 were disaggregated in 287 FoodEx2-codes in DK, 338 in CZ, 423 in IT, and 662 in FR.

Pan-European environmental sustainability indicator database

To estimate the environmental impact of the diets, we developed the SHARP Indicators Database (SHARP-ID). This database contains GHGE and LU as indicators of the environmental impact and can be extended to other indicators. These two indicators relate to at least four of the planetary boundaries identified by Rockström [26], i.e. biodiversity loss, nitrogen cycle disruption, carbon cycle disruption, and land use change, as discussed by Aiking [27].

Environmental impact was assessed using attributional LCA, an internationally accepted standardised methodology in accordance with ISO14040 and 14044:2006, with the aim to gain insight into the environmental impact of foods within the current food production practices [28]. To construct the database, we identified a total of 182 primary products relevant to the selected four European countries, using various publicly accessible data sources, e.g.: Agri-footprint (Europe) [29, 30], Ecoinvent (Global, Swiss Confederation) [31], and primary production reports [32-39], combined with European production, trade and transport data (FAOstat, BACI World Trade Database, and GTAP). Starting from these 182 primary products, estimates were obtained for GHGE and LU for 944 FoodEx2 codes in the diet surveys covering 95% of the energy intake; for 134 FoodEx2 codes no estimate was obtained; these codes were herbs and spices, other ingredients, such as food additives, vitamin supplements, condiments, etc. For each food item, the LCA contained the whole product's life cycle [40, 41], from cultivations of (feed) crop to consumption at home, i.e. including primary production, use of primary packaging, transport, food losses and waste, and food preparations (such as boiling, frying, oven backing, roasting and microwaving). Due to limited availability of data, we excluded the contributions of industrial food processing (such as grinding, cutting, centrifuging and washing), storage, and transport from retail to home; these phases have been estimated to contribute up to 32% to the environmental impact measures for highly processed foods such as pizza [42]. To divide environmental impacts between a product and its co-products, economic allocation was used for all foods, except for animal-sourced foods where nitrogen allocation was used because the nitrogen content serves as an indicator of the physical and causal relationship between products and emissions [43]. GHGE and LU of products derived from milk, such as cream, cheese and butter, were estimated by their mass fractions using the technical conversion factors of the FAO [44], and those of processed foods by their ingredient composition using recipes from the Dutch food composition table [45]. GHGE and LU data were adjusted to reflect the foods as eaten to be comparable with the national dietary survey data by using appropriate conversion factors for edible portion, cooking losses and gains, and food losses and waste [46, 47].

For each FoodEx2-code, total GHGE per kg of food as eaten was calculated by multiplying the life cycle inventory data by appropriate conversions factors to reflect amount as consumed, i.e. conversion factors for production, edible portion, cooking losses and gains during preparation, and food losses and waste at production and consumption phase, and then adding impacts from packaging, transport and home preparation, and total LU per kg of food as eaten by multiplying the life cycle inventory data by appropriate conversions factors. Calculated GHGE (in kgCO_2equivalents per kg food as eaten) covers carbon dioxide (CO_2) emissions through the use of fossil fuels, methane (CH_4) released during rearing of the cattle and cultivations of certain crops, and nitrous oxide (N_2O) released from fertilizers, manure and ploughing of grassland where 1 kg CH_4 equals 25 kg CO_2 and 1 kg N_2O equals 298 kg CO_2 [48]. Calculated LU covers the surface needed for the production of food accounting for conventional agricultural practices (m^2*year per kg food as eaten). Under the assumption of a homogeneous European market, we assigned one value for GHGE and LU to each food item, and this value was applied to the food intake data of the four countries under study.

Environmental impact of the diet

For the selected two days of each subject, the intake of foods and drinks (in g/day) and total energy intake (in kcal/day) were obtained from the national dietary survey data. Using the above-mentioned SHARP-ID, GHGE and LU were calculated, both per day (GHGE in kgCO_2-eq/day and LU in m^2*year/day) and as densities, i.e. relative to reported daily energy intake [49]. Densities of food group intake, and of GHGE and LU were expressed per 2,000 kcal and for energy as the percentage of total energy contributed by that food group. The density method preserves the relative consumption quantities of the foods and food groups in the diet; this is considered to compensate both for proportional systematic errors that are specific for the dietary assessment methods in the four countries as well as for individual-level non-differential over- or underestimation of food intake. In this way, it accounts for observed differences in food intake between big and small eaters with similar dietary patterns, and it allows to disentangle diet composition from reported energy intake in further analyses.

Demographics

Data were collected on age (years), gender, educational level (low: primary or lower secondary degree; intermediate: higher secondary degree; and high: university or post-university degree), body weight (kg) and height (m) by means of questionnaires. Age was categorised in three categories (18-34 years, 35-49 years and 50-64 years), and overweight was defined as Body Mass Index (BMI)

≥ 25 kg/m^2, calculated as body weight (kg) divided by height squared (m^2). In statistical analyses, subjects with missing data for educational level (n=134) and/or overweight status (n=56) were excluded, leaving 7,806 adults for analysis.

Statistical analyses

To remove within-subject variation and obtain usual energy intake and usual diet-related GHGE or LU, either per day or for densities, we used the NCI-method [50, 51] (Table 1, 2 and 3, Figure 2 and 3). The distribution of intake at food level however did not allow to use the NCI-method, therefore we used the average of the two selected days to describe diets in terms of foods by country using food groups (Figure 3) and to explain densities by diet composition (Table 4 and 5, Figure 4).

Stratified analysis was used to obtain country- and gender-specific associations of diet-related usual GHGE and LU with usual energy intake; results are plotted for country- and gender-specific quintiles (Figure 2). Usual GHGE and LU densities were also used to describe environmental impact of the diet by energy intake (quintiles derived from continuous analysis) and by individual-level demographics in a univariate way (Figure 3).

Multilevel regression models with random intercept and random slopes were used to explain variations in GHGE and LU by country, and by energy intake (continuously, Table 2), individual-level demographics (using categories, Table 3), and diet composition (using the percentage of energy contributed by food groups continuously, Table 5). These models used either environmental impact for a daily diet or for a 2,000 kcal diet (densities) (see Figure 1), and were fitted according to two levels of variance: individuals (level 1, n=7,806), and country (level 2, n=4).

In the multilevel analyses on diet composition, the percentage of energy contributed by a food group was included as an explanatory variable if that food group explained ≥ 2.5% of the variation in GHGE and LU density in the four countries in a univariate model, or if that food group had specific reasons of interest. To enhance the interpretation of the results, however, the percentage of energy was translated into an approximation of grams per 2,000 kcal; calculated by dividing the average amount of grams/2,000 kcal by the average percentage of energy multiplied by the unit as used in the regression coefficient of that food group, and this averaged for the four countries. For coffee and tea, gram per 2,000 kcal was used instead, as they barely contribute to total energy intake. Furthermore, if interested in the role of food choices within the main food group, we entered both the main food group and one of its subgroups in the model, the latter as a proportion of that subgroup to the main food group; this implies that the regression coefficient for the subgroup reflects the impact of the subgroup as part of the main food group.

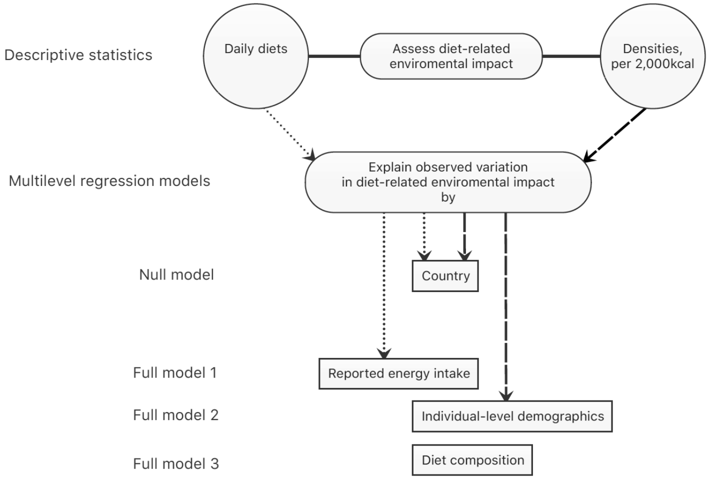


Figure 1 Flowchart of the multilevel regression models to explain variations in diet-related environmental impact.

Dotted lines refer to multilevel regression models using environmental impact of daily diets as the dependent variable, and the dashed lines refer to multilevel regression models using densities of environmental impact, i.e. environmental impact expressed per 2,000 kcal, as the dependent variable. In the null model, diet-related environmental impact was the dependent variable and a random intercept for country was included. In the full models, diet-related environmental impact was the dependent variable, and the parameter of interest, i.e. either reported energy intake (Full model 1), individual-level demographics (Full model 2), or diet composition (Full model 3), the explanatory variables.

To quantify the variation between countries, we fitted a null model that included a random intercept for country; the variation in GHGE and LU explained by country (either daily or as densities) was calculated as the intercept variance divided by total variance. For the full model, explanatory variables and interactions were successively added, first as fixed effects and next with random slopes. The variation in GHGE and LU explained by all explanatory variables in the full multilevel model was calculated as the squared correlation coefficient between observed and predicted values obtained from the full model. The variation explained by one of the explanatory variables was calculated by subtracting the squared correlation coefficient between observed and predicted values obtained from the full model without the explanatory variable of interest from that obtained from the full model, while the variation explained by country in the full model was calculated by subtracting the squared correlation coefficient between observed and predicted values obtained from a full fixed effect model from that obtained from the full multilevel model.

To assess the strength of associations, fixed and, if applicable, random effects for the explanatory variables were represented by the regression coefficients with 95% confidence intervals (CI); all parameters were tested using Wald tests and a two-sided P-value below 0.05 was considered as statistically significant. Model fit was examined by Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). All statistical analyses were performed using SAS version 9.3 (SAS Institute Inc.).

RESULTS

Variation in diet-related GHGE and LU between four European countries

Table 1 shows the usual reported energy intake and usual GHGE and LU in four European populations, aged 18-64 years. Reported average energy intake varied from 1960 (FR) to 2572 kcal/d (CZ), whereas estimated average energy requirements varied from 2358 (FR) to 2497 kcal/d (DK), with a variance explained by country of 11% for reported energy intake and of 3% for estimated energy requirement.

Average GHGE of a daily diet ranged from 5.2 (IT) to 6.0 kgCO$_2$eq/d (DK), and average LU of a daily diet ranged from 6.8 (IT) to 7.6 m^2*year/d (FR). According to the null model of multilevel analyses, the variation explained by country was less than 5% for GHGE and LU. Country-specific daily GHGE and LU varied around the overall mean with a standard deviation (SD) of 0.08 and 0.10, and a coefficient of variation (CV) of 1.4% and 1.4%, respectively.

When diet composition was addressed by accounting for differences in reported energy intake by using densities of GHGE and LU, the average density of GHGE ranged from 4.4 (CZ) to 6.4 kgCO$_2$eq/2,000 kcal (FR), and of LU the density ranged from 5.7 (CZ) to 8.0 m^2*year/2,000 kcal (FR), whereby the variation explained by country was 49% and 45%, respectively. Country-specific densities of GHGE and LU varied around the overall mean with an SD of 0.7 and 1.0, and a CV of 9.5% and 13.8%, respectively.

Table 1 Diet-related greenhouse gas emissions (GHGE) and land use (LU), and general characteristics of the study sample, aged 18-64 years (Mean, median and interquartile range, number and percentage).

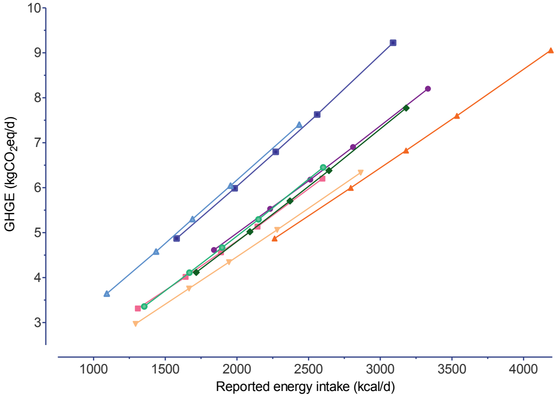
	Denmark		Czech Republic		Italy		France	
	(n = 1,739)		(n = 1,666)		(n = 2,313)		(n = 2,276)	
	Mean	P50 (P25;P75)	Mean	P50 (P25;P75)	Mean	P50 (P25;P75)	Mean	P50 (P25;P75)
BMI, kg/m^2	25.1[f]	24.4 (22.2; 27.0)	25.6	25.2 (22.8; 28.0)	24.2[g]	23.7 (21.7; 26.1)	24.6[h]	23.8 (21.5; 26.9)
Energy, kcal[a]								
Usual daily intake, /day	2201	2153 (1760;2577)	2572	2491 (1874;3191)	2149	2106 (1753;2479)	1960	1917 (1544;2343)
Requirements, /day[b]	2497	2404 (2161;2781)	2487	2389 (2163;2800)	2368	2286 (2059;2657)	2358	2273 (2060;2610)
Usual GHGE, kgCO_2eq[a]								
Daily, /day	5.4	5.2 (4.3; 6.3)	5.6	5.4 (4.2; 6.9)	5.2	5.1 (4.3; 6.0)	6.0	5.9 (4.8; 7.1)
Density, /2,000kcal[c]	5.0	4.9 (4.5; 5.4)	4.4	4.4 (4.1; 4.8)	4.9	4.9 (4.4; 5.3)	6.4	6.2 (5.5; 7.0)
Usual LU, m^2*year[a]								
Daily, /day	6.9	6.7 (5.3; 8.2)	7.4	7.1 (5.0; 9.4)	6.8	6.6 (5.4; 7.9)	7.6	7.3 (5.9; 9.0)
Density, /2,000kcal[c]	6.3	6.3 (5.7; 6.9)	5.7	5.7 (5.2; 6.2)	6.3	6.2 (5.7; 6.8)	8.0	7.8 (6.9; 8.9)
		N (%)		N (%)		N (%)		N (%)
Age								
- 18 – 34 y		484 (27.8%)		517 (31.0%)		699 (30.2%)		689 (30.3%)
- 35 – 49 y		639 (36.8%)		479 (28.8%)		815 (35.2%)		837 (36.8%)
- 50 – 64 y		616 (35.4%)		670 (40.2%)		799 (34.6%)		750 (32.9%)
Gender, men		777 (44.7%)		793 (47.6%)		1,068 (46.2%)		936 (41.1%)
Educational level						[d]		[e]
- Low		248 (14.2%)		345 (20.7%)		692 (31.7%)		1,039 (45.8%)
- Intermediate		943 (54.1%)		1,194 (71.7%)		985 (45.1%)		495 (21.8%)
- High		548 (31.5%)		127 (7.6%)		507 (23.2%)		737 (32.4%)
Overweight,BMI≥25kg/m^2		739 (43.2%)[f]		864 (51.9%)		828 (35.8%)[g]		871 (38.7%)[h]

[a] Country explained 10.6% of the variation in usual reported energy intake of a daily diet and 2.6% of the variation in energy needs; 3.4% of the variation in GHGE of a daily diet and 49.1% of the GHGE density; and 1.9% of the variation in LU of a daily diet and 44.7% of the LU density (null model of the multilevel analyses with random intercept for country only). [b] Energy needs calculated using the formula of Harris and Benedict based on gender, age, weight, height assuming a PAL of 1.55. [c] Densities calculated as daily values/daily energy x 2000 kcal. [d] Data were available for 2,184 subjects (129 missing). [e] Data were available for 2,271 subjects (5 missing). [f] Data were available for 1,710 subjects (29 missing). [g] Data were available for 2,312 subjects (1 missing). [h] Data were available for 2,250 subjects (26 missing)

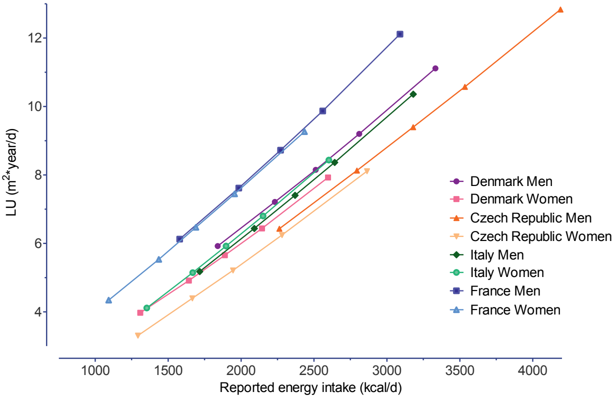
Regarding the demographic factors, age and gender distributions were comparable between countries, while distributions of educational level varied markedly with a low proportion of low educated subjects in DK (14%) and a high proportion in FR (46%); the proportion of high educated subjects being the lowest in CZ (8%). Overweight was the most prevalent in CZ (52%) and the least in Italy (36%).

Daily reported energy intake in relation to daily GHGE and LU

Figure 2 shows the GHGE and LU of a daily diet according to usual daily reported energy intake, stratified by country and gender. There was a positive association between reported usual energy intake and usual daily GHGE and LU in all four countries, with gender differences mainly attributable to energy intake. Furthermore, at the same level of energy intake, daily GHGE and LU differed between countries, suggesting variation in diet composition between countries, this was already visible in GHGE and LU densities (Table 1): multilevel analyses of daily GHGE and LU with energy intake showed that country explained 8% and 3% of the total variation in GHGE and LU respectively. Energy intake explained 41% of the variation in daily GHGE, and 33% of the variation in daily LU, given country and gender (Table 2). Per 200 kcal difference in energy intake, daily environmental impact significantly differed by 9% for GHGE (0.50 kgCO_2eq/d; 95%CI: 0.42; 0.58) and by 10% for LU (0.72 m^2*year/d; 95%CI: 0.64; 0.80). Magnitude of the association with energy intake however varied slightly between countries, as shown by the country-specific regression coefficients (random effects in the multivariate multilevel models (in line with Figure 2)). In addition, energy intake showed interaction with gender, indicating that for women daily environmental impact increased a little less steeply per 200 kcal, i.e. 8.8% for GHGE and 9.4% for LU. As shown in Figure 3 and Supplementary Table 1, the strong correlation between reported usual energy intake, GHGE and LU disappeared when they were expressed as densities: GHGE and LU densities within countries were similar across quintiles of energy intake, and did not differ per 200 kcal difference in energy intake.



2A: Greenhouse gas emissions



2B: Land use

Figure 2 Mean usual daily greenhouse gas emissions (GHGE, in $kgCO_2eq/d$) (2A) and land use (LU, in m^2*year/d) (2B) of men and women in four European countries according to usual reported energy intake of their diets. Dots are the mean observed values of the usual GHGE and LU of a daily diet, for the mean of quintiles for mean usual reported energy intake

Table 2 Usual reported GHGE and LU of a daily diet as related to usual reported energy intake [a].

	Explained variation	Fixed regression coefficients [b]	Country-specific regression coefficients [c]			
			Denmark	Czech Republic	Italy	France
		Beta (95%CI)	Beta (95%CI)	Beta (95%CI)	Beta (95%CI)	Beta (95%CI)
Daily GHGE						
Country (null model) [d]	3.4%	5.58 (5.55; 5.62)	5.40 (5.08; 5.73)	5.63 (5.32; 5.96)	5.26 (4.94; 5.59)	6.02 (5.70; 6.35)
Country (full model)	7.9%	5.58 (5.55; 5.62)	5.68 (5.45; 5.92)	5.49 (5.26; 5.73)	5.32 (5.09; 5.56)	5.84 (5.61; 6.08)
Gender, women vs men	0.0%	0.22 (0.13; 0.31)	0.16 (0.07; 0.25)	0.25 (0.16; 0.34)	0.19 (0.10; 0.28)	0.28 (0.19; 0.37)
Reported energy intake, 200 kcal	41.1%	0.50 (0.42; 0.58)	0.47 (0.34; 0.60)	0.44 (0.31; 0.57)	0.51 (0.37; 0.64)	0.58 (0.44; 0.71)
Women*reported energy intake	0.1%	-0.01 (-0.04; 0.00)	-0.03 (-0.05;-0.01)	-0.01 (-0.02; 0.01)	0.00 (-0.02; 0.01)	-0.02 (-0.03; 0.00)
Daily LU						
Country (null model) [d]	1.9%	7.16 (7.11; 7.21)	6.95 (6.57; 7.32)	7.37 (6.99; 7.74)	6.77 (6.40; 7.15)	7.55 (7.18; 7.92)
Country (full model)	3.3%	7.16 (7.11; 7.21)	7.34 (6.92; 7.76)	6.75 (6.33; 7.17)	6.87 (6.45; 7.29)	7.68 (6.45; 7.29)
Gender, women vs men	0.0%	0.43 (0.32; 0.53)	0.40 (0.30; 0.51)	0.44 (0.34; 0.55)	0.37 (0.26; 0.47)	0.50 (0.40; 0.61)
Reported energy intake, 200 kcal	33.0%	0.72 (0.64; 0.80)	0.68 (0.55; 0.81)	0.67 (0.54; 0.80)	0.73 (0.60; 0.83)	0.79 (0.66; 0.92)
Women*reported energy intake	0.1%	-0.05 (-0.09; -0.02)	-0.08 (-0.11;-0.04)	-0.05 (-0.09;-0.02)	-0.02 (-0.05; 0.02)	-0.06 (-0.09;-0.02)

[a] Best fitted multilevel model for daily GHGE and LU with reported energy intake and gender as explanatory variables using a random intercept for country and random slopes for explanatory variables gender and energy intake, if necessary, to allow for variation in associations between countries; the multilevel model explained 53.2% of the variation in daily GHGE and 48.4% of the variation in daily LU. Grand mean for all four countries was 5.58 (SD 1.58) kgCO_2eq for daily GHGE and 7.16 (SD 2.29) m^2*year for daily LU.

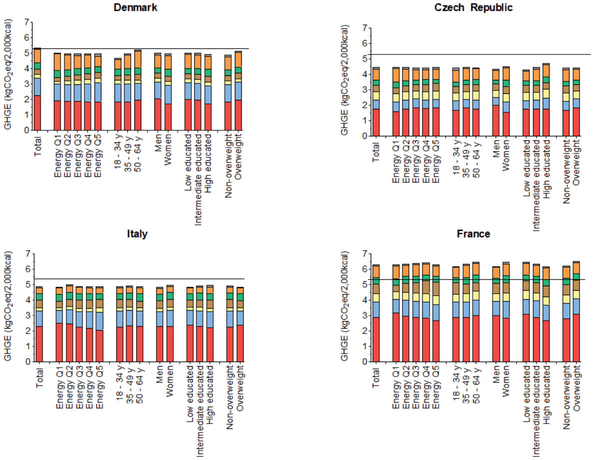
[b] Fixed regression coefficients represents the difference in diet-related daily GHGE or LU density for women and per 200kcal increase in energy intake.

Individual-level demographics in relation to GHGE and LU densities

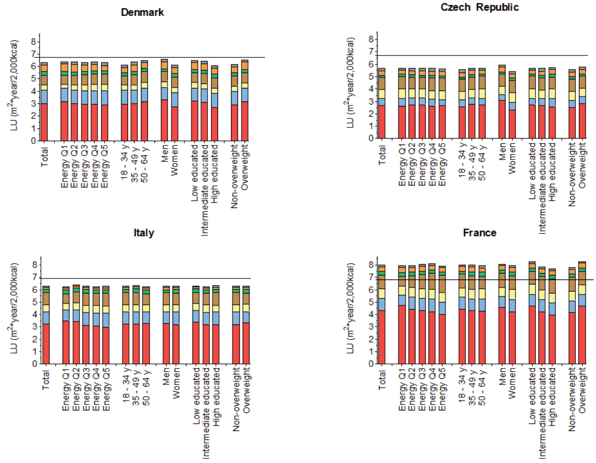
Apart from quintiles for energy, Figure 3 shows univariate associations of GHGE and LU densities with demographics, stratified by country. GHGE density increased with age in DK and FR. Diets of women had a higher GHGE density in CZ and FR. GHGE density increased with educational level in CZ, however decreased with educational level in FR. Subjects with overweight had a higher GHGE density in DK and FR. For LU, there were no clear differences between the age groups, except for DK where LU density increased with age. LU density was also higher among men in DK and CZ, among the lower educated subjects in DK and FR, and among the subjects with overweight in DK and FR.

When the demographic variables were combined in a multilevel model, this explained a total of 47% and 42% of the variation in usual diet-related GHGE and LU densities, respectively, with country explaining most of the variation (41% and 36%, Table 3). Direction and/or magnitude of the association with demographics varied between countries, as shown by the country-specific regression coefficients (random effects in the multivariate multilevel models). Fixed effects did not exceed 5% of the mean GHGE density (coefficient 0.23 for age 50-64y) and 4% of the LU density (coefficient -0.22 for high educated).

Taken together, fixed and random effects of demographic variables were trivial, explained variation of the individual demographics was less than 1.5% for the individual variables, and expressed relative to the mean densities, regression coefficients were less than 5% for fixed effects, as mentioned before, and varied randomly though not significantly up to more than 10% for country-specific effects (random coefficient 0.48 for age 50-64y and GHGE density in DK, and -0.55 for women and LU density in CZ).



3A: Greenhouse gas emissions



3B: Land use

Figure 3 Density of usual greenhouse gas emissions (GHGE, in kgCO$_2$eq/2,000kcal) (3A) and of usual land use (LU, in m^2*year/2,000kcal) (3B). Depicted is total density for each of the four countries, and stratified by energy intake (in gender-specific quintiles), and by demographic variables (age, gender, educational level, and overweight status). Colours refer to the contributions of major food groups to total GHGE and LU density (see legenda). Horizontal line refers to the average impact of the four countries.

🟥 Meat, Fish, Eggs
🟦 Milk & Cheese
🟨 Fats & Oils
🟫 Grains
🟩 Fruit & Vegetables
🟧 Beverages
⬜ Miscellaneous

Table 3 Association of usual diet-related GHGE and LU densities (per 2,000 kcal) with individual-level demographics in four European countries[a].

	Explained variation	Fixed regression coefficients [b]		Country-specific regression coefficients [c]							
				Denmark		Czech Republic		Italy		France	
		Beta	(95%CI)	Beta	(95%CI)	Beta	(95%CI)	Beta	(95%CI)	Beta	(95%CI)
GHGE density											
Country (null model) [d]	49.1%	5.24	(5.21; 5.26)	5.05	(4.22; 5.88)	4.51	(3.67; 5.33)	4.98	(4.14; 5.81)	6.42	(5.58; 7.25)
Country (full model)	40.7%	5.24	(5.21; 5.26)	5.04	(4.32; 5.77)	4.55	(3.82; 5.28)	4.98	(4.24; 5.71)	6.38	(5.64; 7.11)
Age	1.2%										
35-49y vs 18-34y		0.11	(-0.08; 0.30)	0.25	(0.06; 0.44)	0.05	(-0.14; 0.24)	0.07	(-0.12; 0.27)	0.07	(-0.12; 0.26)
50-64y vs 18-34y		0.23	(0.04; 0.42)	0.48	(0.29; 0.68)	0.03	(-0.16; 0.22)	0.06	(-0.13; 0.25)	0.34	(0.14; 0.53)
Gender, women vs men	0.9%	0.18	(-0.01; 0.37)	0.06	(-0.13; 0.25)	0.16	(-0.03; 0.35)	0.14	(-0.05; 0.33)	0.35	(0.16; 0.54)
Educational level	0.3%										
Intermediate vs low		0.05	(-0.12; 0.23)	0.05	(-0.12; 0.22)	0.13	(-0.04; 0.30)	0.06	(-0.11; 0.23)	-0.03	(-0.20; 0.15)
High vs low		0.06	(-0.12; 0.24)	-0.01	(-0.19; 0.16)	0.32	(0.13; 0.50)	0.08	(-0.10; 0.26)	-0.15	(-0.33; 0.03)
Overweight status, BMI≥25 vs <25	0.4%	0.10	(-0.09; 0.29)	0.21	(0.02; 0.40)	0.01	(-0.18; 0.20)	-0.02	(-0.21; 0.17)	0.21	(0.02; 0.40)
LU density											
Country (null model) [d]	44.7%	6.67	(6.62; 6.69)	6.44	(5.41; 7.43)	5.77	(4.74; 6.76)	6.39	(5.36; 7.38)	8.09	(7.06; 9.08)
Country (full model)	36.4%	6.67	(6.62; 6.69)	6.46	(5.54; 7.35)	5.81	(4.89; 6.69)	6.40	(5.48; 7.29)	8.02	(7.10; 8.91)
Age	0.3%										
35-49y vs 18-34y		0.02	(-0.15; 0.18)	0.13	(-0.03; 0.29)	0.08	(-0.09; 0.24)	0.02	(-0.14;0.18)	-0.16	(-0.32; 0.00)
50-64y vs 18-34y		0.05	(-0.11; 0.21)	0.23	(0.07; 0.40)	0.10	(-0.06; 0.27)	-0.06	(-0.23;0.10)	-0.07	(-0.24;-0.09)
Gender, women vs men	1.2%	-0.21	(-0.62; 0.20)	-0.35	(-0.77; 0.06)	-0.55	(-0.96;-0.13)	0.01	(-0.40; 0.42)	0.05	(-0.36; 0.47)
Educational level	1.0%										
Intermediate vs low		-0.13	(-0.35; 0.01)	-0.01	(-0.23; 0.21)	-0.04	(-0.26; 0.18)	-0.11	(-0.34; 0.11)	-0.35	(-0.57;-0.12)
High vs low		-0.22	(-0.45; 0.01)	-0.32	(-0.54;-0.09)	-0.06	(-0.30; 0.18)	-0.01	(-0.25; 0.22)	-0.48	(-0.71;-0.24)
Overweight status, BMI≥25 vs <25	0.6%	0.16	(-0.09; 0.41)	0.25	(-0.01; 0.50)	0.07	(-0.18; 0.33)	-0.02	(-0.27; 0.23)	0.34	(0.09; 0.60)

[a] Best fitted multilevel model for GHGE and LU densities with individual-level demographics as explanatory variables using a random intercept for country and random slopes for demographics, if necessary, to allow for variation in associations between countries; the multilevel model explained 46.5% of the variation in GHGE density and 42.4% of the variation in LU density. Grand mean for all four countries was 5.24 (SD 1.11) kgCO$_2$eq/2,000kcal for GHGE density and 6.66 (SD 1.41) m^2*year/2,000kcal for LU density.

[b] Fixed regression coefficients represents the difference in diet-related GHGE or LU density for the demographic factor of interest.

[c] Country-specific regression coefficients were calculated from the fixed regression coefficients corrected for the random effect, i.e. the additional change in GHGE or LU density due to country.

[d] Obtained from multilevel model with random intercept for country only

Contribution of food groups in GHGE and LU density

Table 4 shows intakes of food groups (as densities, i.e. g/2,000 kcal), and their contribution to total energy (per 100 kcal, i.e. en%), and diet-related GHGE and LU (% of daily level, equal to % of density) for each of the four European countries.

Contributions of animal-sourced foods to GHGE ranged between 63-69% (CZ, IT), of plant-sourced foods between 19-23% (DK, IT), and of beverages between 8-17% (IT, DK). In all countries, the main contributor to total GHGE was meat products with a relative contribution for total meat between 36 and 38%. Other major food groups' contribution to GHGE differed between countries: milk products (14%) and coffee/tea (10%) were relatively high in DK, animal fat, such as butter and lard (11%) and grains (10%) in CZ, cheese (14%) and grains (10%) in IT, and grains (10%) and cheese (9%) in FR.

The last two columns of Table 4 describe the between-country variation based on densities for GHGE and LU. As mentioned before, total between country variation of GHGE was 49%. For the separate food groups, between-country variation amounted 12% for animal-sourced foods, 6% for plant-sourced foods, and 15% for beverages. Meat products explained 5% of the variation in GHGE density between countries, however the type of meat products varied between countries with country explaining 10% of the variation for ruminants and 7% of the variation for non-ruminants. Animal-sourced food groups with an observed between-country variation in the GHGE density of at least 10% were animal fat (21%) and milk products (16%), for plant-sourced foods plant fat (15%) and sugar and sweets (14%) were the most important, and for beverages it was coffee and tea (14%). GHGE density was explained by country for less than 5% for poultry, fish, eggs, vegetables, fruit, potatoes, legumes, nuts and seeds, composite dishes and alcoholic beverages.

For LU, contributions of animal-sourced foods to density ranged between 66-72% (CZ, FR), of plant-sourced foods between 23-28% (FR, CZ), and of beverages between 2-8% (IT, DK). Main contributors to total LU were meat (45-52%) and grain products (13-18%). Other major food groups' contribution to LU differed between countries: milk products (11%) and cheese (7%) were relatively high in DK, animal fat (9%) and cheese (5%) in CZ, cheese (11%) and plant fat (8%) in IT, and cheese (7%), animal fat (5%) and milk products (5%) in FR.

Table 4 Contribution of the different food groups in daily diet weight per 2,000 kcal and in percent contribution to energy intake and environmental impact for four European countries, and the variability in diet composition explained by country.

	Denmark				Czech Republic				Italy				France			
	Weight	%en	%GHGE	%LU	Weight	%en	%GHGE	%LU	Weight	%en	%GHGE	%LU	Weight	%en	%GHGE	%LU
Animal-sourced foods	*493*	*29.1%*	*63.7%*	*66.9%*	*302*	*29.2%*	*63.1%*	*65.7%*	*339*	*26.7%*	*69.2%*	*68.5%*	*438*	*36.6%*	*68.5%*	*71.9%*
Meat products	103	10.4%	34.9%	45.6%	116	13.5%	35.8%	45.4%	91	9.4%	37.0%	48.9%	130	13.7%	38.4%	51.9%
Ruminants [b]	27	2.6%	18.1%	25.3%	11	0.8%	9.0%	10.6%	46	2.3%	32.2%	42.5%	45	4.5%	23.8%	33.1%
Non-ruminants	77	7.8%	16.1%	20.6%	105	12.7%	27.0%	33.5%	63	6.2%	14.1%	17.3%	85	9.2%	14.3%	19.1%
Pork, etc.	58	6.3%	12.8%	16.3%	81	10.5%	22.2%	27.2%	44	4.2%	10.7%	12.9%	52	6.0%	9.8%	13.1%
Poultry	19	1.5%	3.3%	4.3%	24	2.2%	4.8%	6.3%	19	2.0%	3.4%	4.4%	33	3.2%	4.5%	6.0%
Fish	17	1.4%	2.3%	0.3%	14	1.1%	3.1%	0.5%	40	2.1%	9.2%	0.9%	34	2.5%	6.9%	1.1%
Eggs	16	1.2%	0.6%	1.5%	14	1.0%	0.6%	1.4%	19	1.3%	0.8%	1.8%	17	1.1%	0.6%	1.3%
Dairy products [c]	353	14.5%	22.9%	17.2%	143	7.5%	13.1%	9.8%	186	12.8%	20.4%	15.6%	244	14.7%	15.9%	12.2%
Milk products	321	9.1%	14.3%	10.5%	120	4.4%	6.2%	4.5%	132	4.7%	6.1%	4.5%	208	8.4%	7.3%	5.3%
Cheese	32	5.3%	8.6%	6.7%	23	3.1%	6.9%	5.3%	54	8.1%	14.3%	11.2%	36	6.3%	8.5%	6.9%
Animal fat [d]	5	1.7%	3.0%	2.4%	16	6.2%	10.5%	8.6%	3	1.0%	1.8%	1.4%	13	4.6%	6.7%	5.4%
Plant-sourced foods	*752*	*60.0%*	*18.9%*	*24.7%*	*605*	*61.7%*	*20.8%*	*28.3%*	*914*	*69.3%*	*23.1%*	*29.1%*	*732*	*55.7%*	*19.9%*	*23.4%*
Plant fat [e]	22	8.0%	1.8%	4.5%	16	6.5%	1.4%	4.0%	35	15.7%	2.6%	7.7%	22	9.3%	1.7%	4.2%
Grain products	218	27.8%	6.8%	12.7%	243	38.5%	9.7%	17.5%	349	38.2%	10.0%	15.1%	254	31.1%	10.5%	13.6%
Vegetables	161	2.8%	4.2%	1.2%	95	1.3%	3.9%	0.6%	231	2.5%	5.5%	1.5%	183	2.6%	3.7%	1.6%
Fruit	196	7.1%	2.7%	1.6%	117	3.8%	2.0%	1.0%	190	4.7%	2.4%	1.5%	148	5.2%	1.9%	1.0%
Potatoes	88	4.7%	0.9%	0.6%	78	3.8%	1.1%	0.8%	45	2.1%	0.5%	0.3%	66	2.7%	0.6%	0.4%
Legumes	21	0.3%	0.2%	0.4%	8	1.1%	0.1%	0.3%	30	0.7%	0.5%	0.9%	16	0.7%	0.2%	0.4%
Nuts and seeds	3	0.8%	0.1%	0.4%	3	0.8%	0.1%	0.5%	1	0.3%	0.0%	0.1%	2	0.5%	0.1%	0.2%
Sugar and sweets	30	6.8%	1.5%	1.7%	17	3.4%	0.6%	0.7%	19	3.7%	0.4%	0.5%	14	2.8%	0.2%	0.2%
Composite dishes	1	0.0%	0.2%	0.2%	12	1.2%	1.5%	2.1%	8	1.0%	1.0%	1.1%	9	0.1%	1.0%	1.4%
Miscellaneous	12	1.8%	0.5%	1.4%	15	1.3%	0.3%	0.8%	6	0.4%	0.1%	0.3%	17	0.8%	0.1%	0.3%
Beverages, excl. milk	*2373*	*11.0%*	*17.4%*	*8.4%*	*1443*	*9.1%*	*16.1%*	*6.1%*	*963*	*4.0%*	*7.8%*	*2.4%*	*1673*	*7.7%*	*11.5%*	*4.7%*
Coffee and tea	796	0.3%	9.7%	4.4%	566	0.8%	8.3%	2.2%	140	0.3%	2.1%	1.1%	457	1.0%	5.8%	2.9%
Alcoholic beverages	230	6.4%	3.7%	2.0%	273	5.9%	3.3%	2.8%	94	3.0%	2.0%	0.8%	105	3.8%	2.0%	0.8%
Sweet beverages	236	4.2%	3.3%	2.0%	111	2.4%	1.9%	1.1%	52	0.7%	0.9%	0.5%	133	2.9%	1.7%	1.0%
Drinking water	1111	0.0%	0.8%	0.0%	493	0.0%	2.7%	0.0%	678	0.0%	2.7%	0.0%	978	0.0%	2.1%	0.0%

	Between country variation[a]			
	Weight	%en	GHGE/ 2,000kcal	LU/ 2,000kcal
Animal-sourced foods	*14.2%*	*13.3%*	*11.8%*	*7.9%*
Meat products	4.8%	6.2%	4.5%	4.9%
Ruminants [b]	9.6%	9.2%	9.6%	9.6%
Non-ruminants	5.8%	9.7%	6.9%	6.7%
Pork, etc.	8.5%	8.5%	9.4%	9.4%
Poultry	2.0%	2.2%	2.0%	2.0%
Fish	5.5%	2.9%	4.8%	2.2%
Eggs	0.5%	0.3%	0.7%	0.6%
Dairy products [c]	15.4%	12.8%	11.3%	11.2%
Milk products	15.9%	11.3%	16.2%	16.2%
Cheese	9.7%	10.1%	9.0%	9.2%
Animal fat [d]	23.8%	23.7%	20.9%	21.0%
Plant-sourced foods	*15.9%*	*16.8%*	*6.3%*	*4.2%*
Plant fat [e]	21.6%	29.0%	14.5%	21.0%
Grain products	20.3%	14.9%	5.6%	2.9%
Vegetables	11.1%	6.0%	2.4%	5.6%
Fruit	3.5%	5.4%	2.0%	3.9%
Potatoes	4.3%	6.9%	4.4%	2.8%
Legumes	2.6%	1.5%	2.8%	1.6%
Nuts and seeds	0.8%	1.2%	0.6%	0.9%
Sugar and sweets	9.3%	11.9%	14.4%	15.5%
Composite dishes	2.2%	4.4%	1.9%	2.3%
Miscellaneous	2.1%.	6.0%	7.8%	7.9%
Beverages, excl. milk	*19.9%*	*9.8%*	*14.9%*	*20.0%*
Coffee and tea	18.2%	3.5%	14.0%	12.6%
Alcoholic beverages	7.9%	4.3%	2.4%	8.0%
Sweet beverages	8.3%	7.9%	6.7%	7.1%
Drinking water	7.4%	0.3%	5.7%	n.a.

[a] Between-country variation in diet composition was obtained from the null model of the multilevel analyses with random intercept for country only and using densities of the different food groups, i.e. for each food group weight (gram per 2,000 kcal), energy (per 100 kcal, i.e. percentage of energy contributed by the food group) and diet-related GHGE and LU both per 2,000 kcal, as outcome variable. [b] Ruminant meat includes meat from beef, goat, sheep, deer, etc. [c] Dairy excludes butter [d] Animal fat includes butter and lard [e] Plant fat includes vegetables oils and margarines

The between-country variation of total LU density was 45%. For the food groups separately, the between country variation was 8% for animal-sourced foods, 4% for plant-sourced foods, and 20% for beverages. Food groups with an observed between-country variation in LU density of at least 10% were similar as for GHGE, i.e. animal and plant fat (each 21%), milk products, sugar and sweets (each 16%), and coffee and tea (13%). Food groups with a between-country variation in their contribution to total LU of less than 5% were also similar as for GHGE, and additionally included grain products (4%), but did not include alcoholic beverages (8%).

Diet composition in relation to GHGE and LU density

Per 2,000 kcal, the percentage of energy from ruminant meat explained most of the variation in GHGE and LU density, 33% and 54% respectively (results of the univariate multilevel models not shown). For GHGE, the next food groups were total meat (12%), grain products (7%), coffee and tea (4.5%), with other food groups explaining < 2.5%. Apart from ruminant meat, variation in LU density was explained by total meat (26%), fish and grain products (each 4%), with other food groups explaining < 2.5% (results of the univariate multilevel models not shown). In this univariate multilevel model, dairy products explained less than 2% of the GHGE and LU density. We however extended the multivariate multilevel model with dairy products and with the percentage of milk consumed as dairy, as the role of dairy products is often debated. Total fat and the percentage of fat consumed as animal fat were also added to the multivariate model, as animal and plant fat showed the most between-country variation (Table 4).

Inclusion of diet composition variables in the multilevel model resulted in a decrease in the variation in diet-related GHGE and LU densities explained by country (from 20.5 to 5.9%, and from 13.3 to 4.4%, respectively, Table 5). These multivariate multilevel analyses of GHGE and LU density with diet composition showed that meat products and the proportion ruminant to total meat explained most of the variation in GHGE and LU density, i.e. 11% and 17%, and 19% and 24%, respectively given country, gender, observed energy intake and the other dietary factors included. Observed energy intake was included to cancel out any residual confounding by energy intake, and – as expected – had a minor residual contribution to the observed variation.

For meat, the environmental impact significantly differed by 39% for GHGE density (2.08 kgCO_2eq/2,000 kcal; 95%CI: 1.36; 2.80) and by 57% for LU density (3.92 m^2*year/2,000 kcal; 95%CI: 2.63; 5.20) for a 20 energy percent difference in meat intake (about 200g/2,000 kcal). Noteworthy, the average contribution of meat intake and its range differed between the countries: in FR and CZ, meat contributed on average 13.7% and 13.5% to total country-specific energy intake (Table 4) with a much wider range between the quintiles (Figure 4) as compared to IT and DK where meat contributed 9.4% and 10.4% to total country-specific energy intake. Moreover, the country-specific regression coefficient estimates showed random effects, and were the lowest in CZ and the highest in IT and DK, and differed (slightly more than) twofold, contributing 25% (CZ) to 50% (IT, DK) to country-specific mean GHGE density, and 36% (CZ) to 83% (DK) to country-specific mean LU density, respectively.

Figure 4 shows that in an unadjusted model slopes of the regression lines of meat differed largely by country, in line with the meat-mix of that country, i.e. proportion of energy from ruminant to energy from total meat was the lowest in CZ (6%), followed by DK (25%) and IT (28%) and the highest in FR (33%). The increase in environmental impact of meat became more homogeneous when holding the proportion ruminant to total meat constant.

For a 70% difference in the proportion ruminant to total meat, the daily environmental impact significantly differed by 34% for GHGE density (1.84 kgCO_2eq/2,000 kcal; 95%CI: 1.73; 1.96) and by 48% for LU density (3.25 m^2*year/2,000 kcal; 95%CI: 2.84; 3.65), with less between-country random effects, as also seen in Figure 4. This heterogeneity of the country-specific estimates for ruminant meat was however related to the translation of energy percentage into grams per 2,000 kcal that differed between the countries, i.e. grams of ruminant meat per energy percent was the lowest in FR (45g/2,000 kcal for 4.5 energy percent) and the highest in IT (46g/2,000 kcal for 2.3 energy percent) (Table 4). An increase in energy percentage of ruminant meat would therefore result in a higher increase in grams of ruminant meat for IT than for FR, hence a higher increase in environmental impact, as this is based on absolute consumption amounts.

For fish products, the daily environmental impact significantly differed by 7% for GHGE density (0.36 kgCO_2eq/2,000 kcal; 95%CI: 0.14; 0.58), but non-significantly by 2% for LU density (-0.14 m^2*year/2,000 kcal; 95%CI: -0.28; 0.00) for each 4 energy percent difference (about 60g/2,000 kcal; 0.5 portion per week). Between-country variation was more prominent for GHGE density than for LU density, but still random country effects were trivial.

Table 5 Association of diet-related GHGE and LU density (per 2,000 kcal) with diet composition in four European countries [a].

	Unit [e]	Explained variation	Fixed regression coefficients [b]	Country-specific regression coefficients [c]			
				Denmark	Czech Republic	Italy	France
			Beta (95%CI)	Beta (95%CI)	Beta (95%CI)	Beta (95%CI)	Beta (95%CI)
GHGE density							
Country (null model) [d]		20.5%	5.40 (5.36; 5.44)	5.19 (4.32; 6.06)	4.56 (3.69; 5.43)	5.05 (4.19; 5.92)	6.80 (5.93; 7.66)
Country (full model)		5.9%	5.40 (5.36; 5.44)	4.85 (4.09; 5.61)	5.30 (4.09; 5.61)	4.94 (4.17; 5.72)	6.50 (5.74; 7.27)
Gender, women vs men		0.0%	0.04 (-0.06; 0.14)				
Observed energy intake	200kcal	0.5%	-0.03 (-0.06; 0.00)	-0.02 (-0.08; 0.03)	-0.02 (-0.07; 0.03)	-0.03 (-0.08; 0.03)	-0.06 (-0.12; -0.01)
Meat products	5vs25en%	11.1%	2.08 (1.36; 2.80)	2.41 (1.22; 3.59)	1.36 (0.18; 2.53)	2.44 (1.25; 3.62)	2.12 (0.94; 3.29)
Fish products	0vs4en%	2.3%	0.36 (0.14; 0.58)	0.22 (-0.15; 0.59)	0.29 (-0.08; 0.65)	0.56 (0.19; 0.92)	0.37 (0.01; 0.72)
Dairy products	5vs25en%	2.1%	0.84 (0.59; 1.09)	0.92 (0.50; 1.35)	0.84 (0.41; 1.27)	0.95 (0.53; 1.37)	0.66 (0.24; 1.08)
Fats and oils	5vs20en%	0.1%	0.14 (-0.11; 0.38)	-0.03 (-0.44; 0.39)	0.29 (-0.12; 0.70)	0.18 (-0.23; 0.59)	0.10 (-0.30; 0.50)
Grain products	20vs50en%	0.2%	-0.26 (-0.47;-0.05)	-0.18 (-0.54; 0.18)	-0.34 (-0.69; 0.01)	-0.31 (-0.67; 0.04)	-0.20 (-0.55; 0.15)
Coffee and tea	100vs1100ml	2.6%	0.65 (0.56; 0.74)				
Ruminant/total meat	0vs70%	16.5%	1.84 (1.73; 1.96)	1.82 (1.66; 1.99)	1.85 (1.68; 2.02)	1.85 (1.68; 2.02)	1.85 (1.68; 2.02)
Milk/total dairy	10vs95%	0.1%	-0.16 (-0.34; 0.03)	-0.15 (-0.47; 0.17)	-0.13 (-0.44; 0.18)	-0.08 (-0.39; 0.23)	-0.26 (-0.57; 0.05)
Animal fat/total fat	0vs55%	0.8%	0.40 (0.24; 0.57)	0.41 (0.12; 0.70)	0.32 (0.04; 0.60)	0.43 (0.13; 0.72)	0.46 (0.19; 0.74)
LU density							
Country (null model) [d]		13.3%	6.84 (6.84; 6.90)	6.59 (5.55; 7.64)	5.81 (4.77; 6.86)	6.46 (5.42; 7.50)	8.49 (7.45; 9.54)
Country (full model)		4.4%	6.84 (6.84; 6.90)	6.27 (5.55; 6.98)	7.03 (6.33; 7.74)	6.43 (5.73; 7.14)	7.63 (6.94; 8.32)
Gender, women vs men		0.0%	0.01 (-0.12; 0.14)				
Observed energy intake	200kcal	0.2%	-0.02 (-0.08; 0.03)	-0.01 (-0.10; 0.08)	0.01 (-0.08; 0.09)	-0.02 (-0.10; 0.07)	-0.07 (-0.16; 0.01)
Meat products	5vs25en%	18.5%	3.92 (2.63; 5.20)	5.21 (2.28; 6.48)	2.55 (0.47; 4.64)	4.50 (2.41; 6.60)	4.22 (2.14; 6.31)
Fish products	0vs4en%	0.2%	-0.14 (-0.28; 0.00)	-0.07 (-0.32; 0.18)	-0.12 (-0.36; 0.13)	-0.22 (-0.46; 0.02)	-0.14 (-0.37; 0.10)
Dairy products	5vs25en%	0.6%	0.69 (0.52; 0.87)				
Fats and oils	5vs20en%	0.3%	0.44 (0.28; 0.60)				
Grain products	20vs50en%	0.1%	0.09 (-0.30; 0.48)	0.21 (-0.38; 0.95)	-0.08 (-0.73; 0.57)	-0.11 (-0.77; 0.55)	0.28 (-0.37; 0.92)
Coffee and tea	100vs1100ml	0.3%	0.30 (0.06; 0.54)	0.43 (0.02; 0.80)	0.17 (-0.23; 0.56)	0.30 (-0.15; 0.74)	0.34 (-0.05; 0.73)
Ruminant/total meat	0vs70%	24.3%	3.25 (2.84; 3.65)	3.59 (2.21; 3.58)	3.33 (2.61; 4.04)	3.29 (2.62; 3.95)	3.47 (2.80; 4.13)
Milk/total dairy	10vs95%	0.1%	-0.17 (-0.44; 0.11)	-0.24 (-0.69; 0.28)	-0.10 (-0.58; 0.37)	-0.02 (-0.49; 0.46)	-0.33 (-0.81; 0.14)
Animal fat/ total fat	0vs55%	0.2%	0.30 (0.10; 0.49)	0.24 (-0.05; 0.60)	0.23 (-0.09; 0.54)	0.33 (0.00; 0.66)	0.35 (0.04; 0.67)

[a] Best fitted multilevel model for GHGE and LU densities with the percentage of energy from the food groups as explanatory variables using a random intercept for country and random slope for the food groups, if necessary, to allow for variation between countries; the multilevel model explained 60.0% of the variation in GHGE density and 67.2% of the variation in LU density. Grand mean for all four countries was 5.40 (SD 1.87) $kgCO_2eq$/2,000kcal for GHGE density and 6.84 (SD 2.75) m^2*year/2,000kcal for LU density.

[b] Fixed regression coefficients represent the change in diet-related GHGE or LU density for one unit increase in food group.

[c] Country-specific regression coefficients were calculated from the fixed regression coefficients corrected for the random effect, i.e. the additional change in GHGE or LU density due to country.

[d] Obtained from multilevel model with random intercept for country only.

[e] Unit was based on the mean of quintile 5 minus quintile 1, and for fish based on consumers versus non-consumers.

For dairy products, a 20 energy percent difference (about 375g/2,000 kcal) was associated with a significant 16% difference in GHGE density (0.84 $kgCO_2eq$/2,000 kcal; 95%CI: 0.59; 1.09), and a significant 10% difference in LU density (0.69 m^2*year/2,000 kcal; 95%CI: 0.52; 0.87), whereas a 85% difference in the proportion milk to total dairy was associated with a non-significant 3% difference in GHGE density (-0.16 $kgCO_2eq$/2,000 kcal; 95%CI: -0.34; 0.03) and a non-significant 2% difference in LU density (-0.17 m^2*year/2,000 kcal; 95%CI: -0.44; 0.11, respectively). Country-specific estimates showed random effects, however they were negligible compared to those of meat and not present for total dairy in association with LU density.

For fats and oils, a 15 energy percent difference (about 35g/2,000 kcal) was associated with a non-significant 3% difference in GHGE density (0.14 $kgCO_2eq$/2,000 kcal; 95%CI: -0.11; 0.38) and a significant 6% difference in LU density (0.44 m^2*year/2,000 kcal; 95%CI: 0.28; 0.60), with a 55% difference in proportion animal fat to total fat being associated with a significant 7% difference in GHGE density (0.40 $kgCO_2eq$/2,000 kcal; 95%CI: 0.24; 0.57) and a smaller but significant 4% difference in LU density (0.30 m^2*year/2,000 kcal; 95%CI: 0.10; 0.49). Random country effects were trivial, and not present for fats and oils in association with LU density.

For grain products, a 30 energy percent (about 210g/2,000 kcal) difference was associated with a significant 5% difference in GHGE density (-0.26 $kgCO_2eq$/2,000 kcal; 95%CI: -0.47; -0.05) and a non-significant 1% difference in LU density (0.09 m^2*year/2,000 kcal; 95%CI: -0.30; 0.48), and country-specific estimates showed only small differences, and were non-significant.

For coffee and tea, the environmental impact for each 1000ml difference significantly differed by 12% for GHGE density (0.65; $kgCO_2eq$/2,000 kcal; 95%CI: 0.56; 0.74) and by 4% for LU density (0.30 m^2*year/2,000 kcal; 95%CI: 0.06; 0.54). Random country effects were not present for GHGE density, and trivial for LU density.

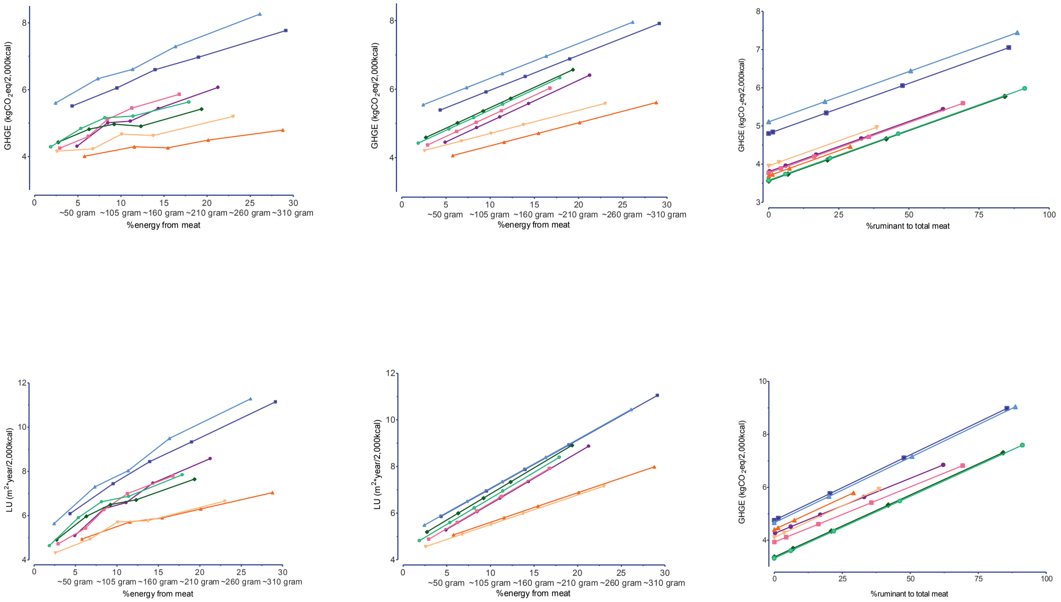


Figure 4 Greenhouse gas emissions (GHGE density, in kgCO$_2$eq/2,000kcal) and land use per 2,000 kcal (LU density, in m^2*year/2,000kcal) associated with the diets of men and women in four European countries according to percentage of energy from meat and percentage ruminant to total meat.

Left figure shows the observed values, second and third figure the modelled results from the full model.

Dots represent the mean GHGE and LU density for the mean of quintiles on the X-axis, i.e. the percentage of energy from meat, and mean percentage ruminant of total meat.

DISCUSSION

This paper shows the added value of individual level food intake data to study environmental impact of diets at the detailed level of foods and across subjects, population (sub)groups and countries. Our analysis of survey data from four European countries shows that GHGE and LU footprints are proportionally related to energy intake, i.e. the amount of food consumed, and to diet composition, i.e. relative consumption quantities and the type of foods chosen within a food group. Of animal-sourced foods, variation in total meat, and in particular the proportion of ruminant meat, was the most important, while variation in fish products, dairy products, and the proportion of animal to total fats explained hardly any variation in environmental footprints. For plant-sourced foods, higher consumption of grains was associated with a reduction in environmental footprints, but that of coffee and tea with an increase. As compared to energy intake and dietary choices, the demographic factors age, gender, educational level and overweight status were of minor importance to explain environmental impact for a 2,000 kcal diet.

Cross-country comparison of dietary intake data is a challenge as dietary surveys in the four countries had different survey characteristics and dietary assessment methods which may have influenced the comparability of the results. Therefore, we used a common food classification system, harmonisation of recipe disaggregation, the same number of days, and standardisation to a 2,000 kcal diet using densities as attempts for dietary data harmonisation in this study [52]. The number of food items reported reflects a difference in coding-details and/or range of foods available in that country. However, this does not influence the results as the product-specific footprint values were based on similarities in primary product, type of food, production system and ingredient composition. Intra-class correlation coefficients for the two assessment days of dietary survey ranged from 0.26 (IT) to 0.51 (FR) for reported energy intake, from 0.16 (DK) to 0.31 (CZ/FR) for daily GHGE, and from 0.14 (DK) to 0.35 (CZ) for daily LU, hereby indicating no clear influence of the different dietary assessment methods regarding the time span between the two days included. Removing the within-subject variation using the NCI-method resulted – as expected – in a higher variation explained by country (Table 1, 2, and 3) than when using the average of observed values of GHGE and LU density (Table 5).

Reported energy intake varied much more than estimated energy requirement, which is in line with poor reliability of estimating energy intake [53, 54] and known differences between dietary assessment methods [55]. Relative estimates of calculated nutrient intakes are however known to perform better [49]. Therefore, we expressed the diet-related GHGE and LU as densities (standardised to a 2,000 kcal diet), and we also expressed the food groups relative to energy by expressing them as energy percentages. This allows to study potential reduction in GHGE and LU by changing diet composition, independently of total energy intake.

Our mean estimate of diet-related GHGE ranged from 5.2 to 6.0 $kgCO_2eq/d$ for the four European countries, which is 17% higher than those previously reported for DK (4.6 $kgCO_2eq/d$) [56], 53% higher for IT (3.4 $kgCO_2eq/d$) [14], and 46% higher for FR (4.1 $kgCO_2eq/d$) [12]. Such a direct comparison of daily footprints to other studies is, however, hampered because of differences in the underlying LCA-methodology. First, we used the same standardised method to derive GHGE and LU values in all countries, but they may differ between countries because of intensive versus extensive animal production systems, greenhouse versus open-field (animal feed, crop growth methods), supply chain (use of side products, domestic versus foreign production, modes and distances of transportation, packaging and preparation methods), food losses and waste, etc. [18]. The choices related to the inventory data used, including system boundaries and management practices, and to transport distances and modes, food packaging and food preparation, are key to explain the inherent relevant variability in food-item LCA data [19]. Yet, the greatest environmental burden in food production originates for most food items from the primary production phase, i.e. the agricultural phase that involves all activities related to crop production and animal breeding, and this burden is highly related to management practices, spatial and temporal circumstances [57]. Conventional management practices were only captured in the present study, however they do not necessarily underperform organic practices [58-60]. Accounting for eating seasonal, for example, is expected to lower footprints of plant production, but reduction potentials are only minor on an absolute scale [61]. Second, our higher estimates could result from using the same primary product but different methods to derive product-specific footprint values at a detailed level, e.g. by the use of other standards for production and conversion factors to adjust for foods as eaten. Yet, the contribution of food groups for daily footprints ranked similarly as in previous studies [11, 12, 14, 56], which is in line with the assumption that diet composition can be assessed more robustly than daily footprints. Thus, our analysis precludes comparison of national food supply systems, however it allows for direct comparison of dietary patterns, as differences in national environmental footprints of the diets exclusively originate from energy intake and diet composition. Further work is required to understand the variation originating from the nationally different agricultural systems. In particular, standardised refinement of LCA values to national food systems [19] and addition of e.g. fresh water use, nitrogen and phosphorus flows, biodiversity loss and land-system change to our SHARP-ID, would give a more balanced picture of environmental footprints in different countries.

Reducing energy intake and modifying dietary choices are the corner stones of public health policies. A reduction in energy intake, in particular tackling overconsumption, is needed to improve health [62]. A prolonged pattern of overconsumption leads to a positive energy balance, hence a higher body weight that in turn results in a higher energy requirement. When overweight subjects would re-match their energy intake with an energy requirement for a 10-15% lower body weight, they could lower their energy intake by on average 6-9% (150 - 230 kcal), and thereby decrease their daily GHGE and LU up to 6-9%. A similar reduction would be obtained when the total population would reduce their average energy intake by 200 kcal, as shown in Table 2. Because of the positive relationship between reported energy intake and environmental impact (Figure 2), and no clear relationship with the densities (per 2,000 kcal, Figure 3), our results suggest that lowering energy intake without changing diet composition, i.e. proportionally lowering intake from each food group, would be one strategy for reducing GHGE and LU of the daily diet. This is conceptually in line with strategies that target to reduce portion sizes [63].

In addition to lowering body weight and energy requirements, environmental impact of the diet can be reduced by modifying diet composition, i.e. by iso-caloric substitution that underlies diet modelling studies that keep energy intake constant [64]. In line with literature [65], our results show that dairy products contribute substantially less to the variation in environmental footprints than meat products. This suggests that dairy products can be part of an environmentally-friendly diet, and that reducing meat products has by far the largest potential for reducing the environmental impact of the diet, as often applied in theoretical replacement scenarios [7, 10]. A reduction of 5 energy percent in meat intake, i.e. corresponding to match food-based dietary guidelines for meat (71 g/day), with an iso-caloric increase in grain products decreased GHGE density and LU density by 10% and 15%, respectively. This reduction in meat consumption is however highly related to the origin of meat products chosen, as the regression coefficient for the proportion of ruminant meat to total meat is nearly as large as that for total meat.

Moreover, our results on current dietary practices in the four European countries suggests that other small, but feasible, efforts to reduce daily footprints are related to changes within a food group. For example, in a theoretical replacement scenario, replacing all animal fat by plant fat would on a population level have the largest reduction potential in CZ (9% and 5% for GHGE and LU density, respectively) and FR (6% and 4%); however, it would not result in a decrease in DK and IT where their current mean intake of animal fat was low (Table 4). Replacing two cups of coffee or tea by tap water will decrease GHGE and LU density by on average 6 and 2%. A caveat to such replacements is however that they are based on attributional LCAs, describing the potential impact of diet composition on GHGE and LU under the current architecture of the food system, probably applicable for 10-25 years depending on changes in food markets [40]. Thus, to assess long term impact of dietary changes, theoretical replacement scenarios should be evaluated using consequential LCA or food systems models, that account for potential changes in environmental flows resulting from adaptation of the food system, i.e. production, processing, waste streams, and consumers' demand [66]. Recent studies demonstrate, for example, that diets containing a small amount of animal products from livestock raised under a circular economy concept, would use less arable land compared to a vegan diet [67]. In this food systems study, livestock is not fed with human-edible biomass, such as grains, but convert leftovers from arable land and grass resources into food, something which is not accounted for in LCA that are based on current food production systems.

Lowering footprints via dietary changes is likely to influence nutritional quality of the diet. Our analyses quantified food intakes as contributions to energy. Among the plant-sourced foods, fruit, vegetables, potatoes, legumes, and nuts and seeds did not appear as relevant predictors of environmental footprints, because of their low observed energy contribution and low GHGE and LU values. This implies that increasing these food groups, as recommended by food-based dietary guidelines [68], would improve nutritional quality of the diet without substantially compromising environmental sustainability. Including these food groups in our multivariate multilevel analyses on diet composition enabled us to simulate influences of dietary shifts, like an x% replacement of energy from meat either by grains or by fruit, vegetables, legumes and nuts. In our analyses, a replacement of 50% (i.e. 6 energy percent of meat) was predicted to decrease environmental footprints by 12% for GHGE and 16% for LU, with minor improvements in nutritional quality, i.e. an increase of 1% in the nutrient density of the diet as quantified by the Nutrient Rich Diet 15.3 score (NRD15.3) when using grain products as replacement; it improved by 4% when using fruit, vegetables, legumes and nuts as replacement instead of grain products (Supplementary Table 2). Moreover, simulating more rigorous changes in diet composition, e.g. by using the healthy reference diet proposed by the EAT-Lancet Commission [4], predicted a substantial 26% decrease in environmental footprints and 12% increase in NRD15.3. A more detailed analyses of nutritional quality is however warranted, as summary indicators fail to point out specific nutrient improvements and/or deficiencies. In our data, simple replacements of meat by fruit, vegetables, legumes and nuts and in particular the reference diet alleviated the nutritional inadequacy of fibre, potassium, magnesium and vitamin E, whereas for nutrients vitamin B2 and vitamin B12 substantial decreases were observed, of which the latter might become a nutrient of concern, in particular in the EAT-lancet reference diet. Thus, strategies that target environmental impact by shifts in diet composition need to focus on an increase in nutrient-dense foods, like fruit, vegetables, legumes and nuts and seeds, while decreasing animal-sourced foods but not eliminating them.

In our analyses of environmental footprints of the diet, demographic subgroups did not explain appreciable variation once energy and country were taken into account. In line with our earlier paper on dietary quality [52], we observed that the contributions of food groups to GHGE and LU did vary across population subgroups (Figure 3, Table 4). Higher intakes of fruit and vegetables, along with lower intakes of red and processed meat, were observed among women and subjects with a higher educational level. Diet composition is however influenced by much more determinants than only demographics factors, as outlined in the Determinants Of Nutrition and Eating (DONE) framework that mapped a total 441 determinants of food choice, eating behaviours and dietary intake in the individual and interpersonal domain, and in the food environmental and policy domain [69]. Moreover, a recent report from the SUSFANS project showed that willingness to change meat consumption as a way of improving environmentally-friendliness of the diet highly depends on consumers' psychographics (e.g.: knowledge, attitude, social and personal norms, perceived effectiveness), next to consumers' demographics [70]. Although long-term trends in food consumption show that major dietary changes have occurred in Europe, food policy measures towards a more environmentally-friendly diet should also account for consumers' attitude and provide options that are incremental to national diets, affordable and widely accessible.

CONCLUSION

In conclusion, observed variation in daily footprints of consumers' diets was mainly explained by the amount of energy consumed, which suggests that fighting obesity and reducing environmental footprints could go hand in hand. Once energy intake was accounted for, of our set of demographics, only country explained variation in footprints, which could not be unravelled into characteristics of the national food supply chains due to limitations of our standardised database of GHGE and LU values. Contributions of food groups to footprints however varied between countries, suggesting that the national food system is a likely determinant of dietary choices of consumers. Once country and reported energy intake were accounted for, total meat – especially ruminant meat –, explained most of the variation in environmental footprints, while variation by other animal-sourced foods, such as fish, dairy products and animal fats, were less prominent.

Acknowledgements

This work was supported by the European Union's H2020 Programme under Grant Agreement number 633692 (SUSFANS: Metrics, models and foresight for European sustainable food and nutrition security); and TiFN under Project Agreement number 15SD01 (SHARP-BASIC). A. Kuijsten, G. Kaptijn and J.M. Geleijnse received research funding from TiFN (grant 15SD01_SHARP) and A. Kuijsten received funding from Top sector Agri&Food & Alpro (grant AF-16507) for research on healthy and sustainable diets.

REFERENCES

1. Mottet A, de Haan C, Falcucci A, Tempio G, Opio C, Gerber P: **Livestock: On our plates or eating at our table? A new analysis of the feed/food debate**. *Global Food Security* 2017, **14**:1-8.
2. Poore J, Nemecek T: **Reducing food's environmental impacts through producers and consumers**. *Science* 2018, **360**(6392):987-992.
3. Steinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M, de Haan C: **Livestock's long shadow**. *Environmental issues and options FAO, Rome* 2007.
4. Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A *et al*: **Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems**. *The Lancet* 2019.
5. Springmann M, Wiebe K, Mason-D'Croz D, Sulser TB, Rayner M, Scarborough P: **Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail**. *The Lancet Planetary health* 2018, **2**(10):e451-e461.
6. Gonzalez-Garcia S, Esteve-Llorens X, Moreira MT, Feijoo G: **Carbon footprint and nutritional quality of different human dietary choices**. *The Science of the total environment* 2018, **644**:77-94.
7. Hallström E, Carlsson-Kanyama A, Börjesson P: **Environmental impact of dietary change: a systematic review**. *Journal of Cleaner Production* 2015, **91**:1-11.
8. Heller MC, Keoleian GA, Willett WC: **Toward a life cycle-based, diet-level framework for food environmental impact and nutritional quality assessment: A critical review**. *Environmental science & technology* 2013, **47**(22):12632-12647.
9. Auestad N, Fulgoni VL: **What current literature tells us about sustainable diets: emerging research linking dietary patterns, environmental sustainability, and economics**. *Advances in Nutrition: An International Review Journal* 2015, **6**(1):19-36.
10. Mertens E, van't Veer P, Hiddink GJ, Steijns JM, Kuijsten A: **Operationalising the health aspects of sustainable diets: a review**. *Unpublished report Wageningen University, Human Nutrition* 2016.
11. Temme EH, Toxopeus IB, Kramer GF, Brosens MC, Drijvers JM, Tyszler M, Ocke MC: **Greenhouse gas emission of diets in the Netherlands and associations with food, energy and macronutrient intakes**. *Public health nutrition* 2015, **18**(13):2433-2445.
12. Vieux F, Darmon N, Touazi D, Soler LG: **Greenhouse gas emissions of self-selected individual diets in France: Changing the diet structure or consuming less?** *Ecological Economics* 2012, **75**:91-101.
13. Saxe H, Larsen TM, Mogensen L: **The global warming potential of two healthy Nordic diets compared with the average Danish diet**. *Climatic Change* 2013, **116**(2):249-262.
14. Germani A, Vitiello V, Giusti AM, Pinto A, Donini LM, del Balzo V: **Environmental and economic sustainability of the Mediterranean Diet**. *International journal of food sciences and nutrition* 2014, **65**(8):1008-1012.
15. Capone R, Iannetta M, Bilali HE, Colonna N, Debs P, Dernini S, Maiani G, Intorre F, Polito A, Turrini A *et al*: **A Preliminary Assessment of the Environmental Sustainability of the Current Italian Dietary Pattern: Water Footprint Related to Food Consumption**. *Journal of Food and Nutrition Research* 2013, **1**(4):59-67.
16. Meier T, Christen O: **Environmental impacts of dietary recommendations and dietary styles: Germany as an example**. *Environ Sci Technol* 2013, **47**(2):877-888.
17. Bingham SA, Gill C, Welch A, Day K, Cassidy A, Khaw K, Sneyd M, Key T, Roe L, Day N: **Comparison of dietary assessment methods in nutritional epidemiology: weighed records v. 24 h recalls, food-frequency questionnaires and estimated-diet records**. *British Journal of Nutrition* 1994, **72**(4):619-643.

18. Garnett T: **Cooking Up a Storm. Food, Greenhouse Gas Emissions and Our Chaning Climate**. In. Edited by Food Climate Research Network Centre for Environmental Strategy University of Surrey. Guildford; 2008.
19. Notarnicola B, Sala S, Anton A, McLaren SJ, Saouter E, Sonesson U: **The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges**. *Journal of Cleaner Production* 2017, **140**:399-409.
20. Pedersen A, Fagt, S., Groth, MV., Christensen, T., Biltoft-Jensen, A., Matthiessen, J., Andersen, NL., Kørup, K., Hartkopp, H., Ygil, K., Hinsch, HJ., Saxholt, E., Trolle, E. : **Danskernes kostvaner 2003-2008**. In.: DTU Fødevareinstituttet; 2009.
21. Leclercq C AD, Piccinelli R, Sette S, Le Donne C and Turrini A: **The Italian national food consumption survey INRAN-SCAI 2005-06: main results in terms of food consumption**. *Publ Health Nutr* 2009, **12(12)**:2504 - 2532.
22. **Individual food consumption - the national study SISP04** [http://www.chpr.szu.cz/spotrebapotravin.htm]
23. Agence Française de Sécurité Sanitaire des Aliments (AFSSA): **Report of the 2006/2007 Individual and National Study on Food Consumption 2 (INCA 2). Synthèse de l'étude individuelle nationale des consommations alimentaires 2 (INCA 2), 2006-2007**. In.; 2009: 1-44.
24. European Food Safety Authority: **The food classification and description system FoodEx2 (revision 2)**. *EFSA supporting publication 2015* 2015, **En-804**:90.
25. EFSA (Eurepean Food Safety Authority): **Use of the EFSA Comprehensive European Food Consumption Database in Exposure Assessment**. *EFSA Journal 2011* 2011, **9**(9):2097.
26. Rockström J, Steffen W, Noone K, Persson Å, Chapin Iii FS, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ *et al*: **A safe operating space for humanity**. *Nature* 2009, **461**:472.
27. Aiking H: **Protein production: planet, profit, plus people?** *The American journal of clinical nutrition* 2014, **100 Suppl 1**:483s-489s.
28. Ekvall T, Azapagic A, Finnveden G, Rydberg T, Weidema BP, Zamagni A: **Attributional and consequential LCA in the ILCD handbook**. *The International Journal of Life Cycle Assessment* 2016, **21**(3):293-296.
29. BlonkConsultants: **Agri-footprint 2.0–Part 1: Methodology and Basic Principles**. In. Gouda, the Netherlands; 2015.
30. BlonkConsultants: **Agri-footprint 2.0–Part 2: Description of data.** . In. Gouda, the Netherlands.; 2015.
31. Weidema B P BC, Hischier R, Mutel C, Nemecek T, Reinhard J, Vadenbo C O, Wernet G.: **Overview and methodology. Data quality guideline for the ecoinvent database version 3.** In: *Ecoinvent Report 1(v3).* St. Gallen: The ecoinvent Centre; 2013.
32. Marinussen M, Kernebeek, H.v., Broekema, R., Groen, E., Kool, A., Van Zeist, W., Blonk, H., : **LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization: Cultivation cereal grains.** . In. Edited by Research BCaWL. Gouda, the Netherlands.; 2012a.
33. Marinussen M, Kernebeek, H.v., Broekema, R., Groen, E., Kool, A., Van Zeist, W., Dolman, M., Blonk, H., : **LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization: Cultivation of roots and tubers.** . In. Edited by Blonk Consultants and WUR Livestock Research. Gouda, the Netherlands.; 2012b.
34. Marinussen M, Kernebeek, H.v., Broekema, R., Groen, E., Kool, A., Van Zeist, W., Dolman, M., Blonk, H.,: **LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization: Cultivation oil seeds and oil fruits.** . In. Edited by Blonk Consultants and WUR Livestock Research. Gouda, the Netherlands; 2012c.
35. Marinussen M, Kernebeek, H.v., Broekema, R., Groen, E., Kool, A., Van Zeist, W., Dolman, M., Blonk, H., : **LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization: Cultivation of legumes.** In. Edited by Blonk Consultants and WUR Livestock Research. Gouda, the Netherlands.; 2012d.

36. Van Zeist W, Marinussen, M., Broekema, R., Groen, E., Kool, A., Dolman, M., Blonk, H.,: **LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization: Crushing Industry.** In. Edited by Blonk Consultants and Wageningen University and Research Centre. Gouda, the Netherlands; 2012a.
37. Van Zeist W, Marinussen, M., Broekema, R., Groen, E., Kool, A., Dolman, M., Blonk, H., : **LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization: Animal products.** In. Edited by Blonk Consultants and Wageningen University and Research Centre. Gouda, the Netherlands; 2012b.
38. Van Zeist W, Marinussen, M., Broekema, R., Groen, E., Kool, A., Dolman, M., Blonk, H.,: **LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization: Dry Milling Industry.** . In. Edited by Blonk Consultants and Wageningen University and Research Centre. Gouda, the Netherlands; 2012c.
39. Van Zeist W, Marinussen, M., Broekema, R., Groen, E., Kool, A., Dolman, M., Blonk, H.,: **LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization: Sugar industry.** . In. Edited by Blonk Consultants and Wageningen University and Research Centre. Gouda, the Netherlands; 2012d.
40. Guinée JB GM, Heijungs R, Huppes G, Kleijn R, De Koning A, Van Oers L, Wegener Sleeswijk A, Suh S, Udo De Haes HA, De Bruijn H, Van Duin R, Huijbregts MAJ, Lindeijer E, Roorda AAH, Van der Ven BL, Weidema BP ,: **Life cycle assessment: an operational guide to the ISO standards**. In. Edited by Centrum voor Milieukunde Leiden University. Leiden; 2002.
41. Bauman H TA: **The hitchhiker's guide to LCA**. In. Edited by Chalmers University of Technology. Götenborg; 2004.
42. Foster C, Green K, Bleda M: **Environmental impacts of food production and consumption: final report to the Department for Environment Food and Rural Affairs**. 2007.
43. Weiss F, Leip A: **Greenhouse gas emissions from the EU livestock sector: a life cycle assessment carried out with the CAPRI model**. *Agriculture, Ecosystems & Environment* 2012, **149**:124-134.
44. FAO: **Technical Conversion Factors For Agricultural Commodities**. In.; 1996.
45. Stichting NEVO: **Dutch food consumption table 2016 (in Dutch: NEVO-tabel 2016)**. In. The Hague (the Netherlands): Dutch Nutrition Centre; 2016.
46. Hoge Gezondheidsraad: **Maten en Gewichten. Handleiding voor gestandardiseerde kwantificering van voedingsmiddelen in België: revisie januari 2005 (HGR 6545-2)**. In. Edited by Minsterie van Sociale Zaken Volksgezondheid en Leefmilieu: Hoge Gezondheidsraad. Brussels, Belgium; 2005.
47. Bognar A: **Tables on Weight Yield of Food and Retention Factors of Food Constituents for the Calculation of Nutrient Composition of Cooked Foods (Dishes).** In. Edited by Berichte der Bundesforschungsanstalt für Ernährung. BFE-R--02-03. Karlsruhe, Germany; 2002.
48. IPCC: **IPCC Fourth Assessment Report: Climate Change 2007**. In. Edited by Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge; 2007.
49. Willett WC, Howe GR, Kushi LH: **Adjustment for total energy intake in epidemiologic studies**. *The American journal of clinical nutrition* 1997, **65**(4):1220S-1228S.
50. Tooze JA, Midthune D, Dodd KW, Freedman LS, Krebs-Smith SM, Subar AF, Guenther PM, Carroll RJ, Kipnis V: **A new statistical method for estimating the usual intake of episodically consumed foods with application to their distribution**. *Journal of the American Dietetic Association* 2006, **106**(10):1575-1587.
51. Freedman LS, Guenther PM, Dodd KW, Krebs-Smith SM, Midthune D: **The population distribution of ratios of usual intakes of dietary components that are consumed every day can be estimated from repeated 24-hour recalls**. *The Journal of nutrition* 2010, **140**(1):111-116.

52. Mertens E, Kuijsten A, Dofkova M, Mistura L, D'Addezio L, Turrini A, Dubuisson C, Favret S, Havard S, Trolle E *et al*: **Geographic and socioeconomic diversity of food and nutrient intakes: a comparison of four European countries**. *European journal of nutrition* 2018.
53. Kipnis V, Subar AF, Midthune D, Freedman LS, Ballard-Barbash R, Troiano RP, Bingham S, Schoeller DA, Schatzkin A, Carroll RJ: **Structure of Dietary Measurement Error: Results of the OPEN Biomarker Study**. *Am J Epidemiol* 2003, **158**(1):14-21.
54. Banna JC, McCrory MA, Fialkowski MK, Boushey C: **Examining Plausibility of Self-Reported Energy Intake Data: Considerations for Method Selection**. *Frontiers in nutrition* 2017, **4**:45-45.
55. De Keyzer W, Huybrechts I, De Vriendt V, Vandevijvere S, Slimani N, Van Oyen H, De Henauw S: **Repeated 24-hour recalls versus dietary records for estimating nutrient intakes in a national food consumption survey**. *Food & nutrition research* 2011, **55**.
56. Werner LB, Flysjo A, Tholstrup T: **Greenhouse gas emissions of realistic dietary choices in Denmark: the carbon footprint and nutritional value of dairy products**. *Food Nutr Res* 2014, **58**.
57. Notarnicola B, Tassielli G, Renzulli PA, Castellani V, Sala S: **Environmental impacts of food consumption in Europe**. *Journal of Cleaner Production* 2017, **140**:753-765.
58. Lacour C, Seconda L, Allès B, Hercberg S, Langevin B, Pointereau P, Lairon D, Baudry J, Kesse-Guyot E: **Environmental Impacts of Plant-Based Diets: How Does Organic Food Consumption Contribute to Environmental Sustainability?** *Frontiers in nutrition* 2018, **5**:8-8.
59. Forleo MB, De Boni A, Di Cesare C, Roma R, Salvatori G: **Conventional and organic food styles in a multidimensional perspective of sustainability**. *Italian Review of Agricultural Economics* 2016, **71**(1):347-357.
60. Castellini C, Boggia, A. , Paolotti, L. , Thoma, G. J. and Kim, D.: **Environmental Impacts and Life Cycle Analysis of Organic Meat Production and Processing**. In: *Organic Meat Production and Processing.* 2012.
61. Röös E, Karlsson H: **Effect of eating seasonal on the carbon footprint of Swedish vegetable consumption**. *Journal of Cleaner Production* 2013, **59**:63-72.
62. Perignon M, Vieux F, Soler L-G, Masset G, Darmon N: **Improving diet sustainability through evolution of food choices: review of epidemiological studies on the environmental impact of diets**. *Nutr Rev* 2017, **75**(1):2-17.
63. Marteau TM, Hollands GJ, Shemilt I, Jebb SA: **Downsizing: policy options to reduce portion sizes to help tackle obesity**. *BMJ* 2015, **351**:h5863.
64. Gazan R, Brouzes CMC, Vieux F, Maillot M, Lluch A, Darmon N: **Mathematical Optimization to Explore Tomorrow's Sustainable Diets: A Narrative Review**. *Advances in Nutrition* 2018, **9**(5):602-616.
65. Hallström E, Carlsson-Kanyama A, Börjesson P: **Environmental impact of dietary change: a systematic review**. *J Clean Prod* 2015, **91**(0):1-11.
66. Keating BA, Herrero M, Carberry PS, Gardner J, Cole MB: **Food wedges: Framing the global food demand and supply challenge towards 2050**. *Global Food Security* 2014, **3**(3):125-132.
67. Van Zanten HHE, Herrero M, Van Hal O, Röös E, Muller A, Garnett T, Gerber PJ, Schader C, De Boer IJM: **Defining a land boundary for sustainable livestock consumption**. *Global Change Biol* 2018, **24**(9):4185-4194.
68. World Health Organisation (WHO): **Food based dietary guidelines in the WHO European Region**. *Copenhagen, Denmark: WHO* 2003.
69. Stok FM, Hoffmann S, Volkert D, Boeing H, Ensenauer R, Stelmach-Mardas M, Kiesswetter E, Weber A, Rohm H, Lien N *et al*: **The DONE framework: Creation, evaluation, and updating of an interdisciplinary, dynamic framework 2.0 of determinants of nutrition and eating**. *PLoS One* 2017, **12**(2):e0171077.
70. Bouwman E, Verain M, Snoek H: **Deliverable No. 2.1: Consumers’ knowledge about the determinants fo a sustainable diet**. In.: SUSFANS; 2016.

SUPPLEMENTARY MATERIALS

Supplementary Table 1 Usual GHGE and LU densities (per 2,000kcal) as related to usual reported energy intake [a].

	Explained variation	Fixed regression coefficients [b]	Country-specific regression coefficients [c]			
			Denmark	Czech Republic	Italy	France
		Beta (95%CI)	Beta (95%CI)	Beta (95%CI)	Beta (95%CI)	Beta (95%CI)
GHGE density						
Country (null model) [d]	49.1%	5.24 (5.21; 5.26)	5.05 (4.22; 5.88)	4.51 (3.67; 5.33)	4.98 (4.14; 5.81)	6.42 (5.58; 7.25)
Country (full model)		5.24 (5.21; 5.26)	5.07 (4.35; 5.78)	4.52 (3.80; 5.23)	4.99 (4.27; 5.69)	6.39 (5.67; 7.10)
Gender, women vs men		0.15 (-0.12; 0.43)	0.12 (-0.16;0.39)	0.15 (-0.13;0.43)	0.14 (-0.13;0.42)	0.20 (-0.07;0.48)
Reported energy intake, 200kcal		0.00 (-0.02; 0.02)				
Women*reported energy intake		0.01 (-0.03; 0.03)				
LU density						
Country (null model) [d]	44.7%	6.67 (6.62; 6.69)	6.44 (5.41; 7.43)	5.77 (4.74; 6.76)	6.39 (5.36; 7.38)	8.09 (7.06; 9.08)
Country (full model)		6.67 (6.62; 6.69)	6.45 (5.55; 7.33)	5.80 (4.89; 6.67)	6.38 (5.48; 7.26)	8.05 (7.14; 8.92)
Gender, women vs men		-0.27 (-0.80; 0.27)	-0.45 (-0.99;0.09)	-0.58 (-1.12;0.04)	-0.01 (-0.55;0.53)	-0.02 (-0.56;0.52)
Reported energy intake, 200kcal		0.00 (-0.02; 0.02)				
Women*reported energy intake		0.02 (-0.03; 0.03)				

[a] Best fitted multilevel model for GHGE and LU densities with gender and reported energy intake as explanatory variables using a random intercept for country and random slopes for explanatory variables gender and energy intake, if necessary, to allow for variation in associations between countries; the multilevel model explained 44.2% of the variation in GHGE density and 40.3% of the variation in LU density. Grand mean for all four countries was 5.24 (SD 1.11) kgCO$_2$eq/2,000kcal for GHGE density and 6.66 (SD 1.41) m^2*year/2,000kcal for LU density. [b] Fixed regression coefficients represents the difference in diet-related GHGE or LU density for women and per 200kcal increase in energy intake. [c] Country-specific regression coefficients were calculated from the fixed regression coefficients corrected for the random country effect, i.e. the additional difference in daily GHGE or LU due to country. [d] Obtained from multilevel model with random intercept for country only.

Supplementary Table 2 Evaluation of the environmental and the nutritional health impact under the current scenario and under more environmentally sustainable scenarios for the four European countries under study [ab].

	GHGE	LU	NRD9.3 [e]	NRD15.3 [e]	Protein	Fibre	Calcium	Iron	Potassium	Magnesium	Vitamin A	Vitamin C	Vitamin E	Zinc	Vitamin B1	Vitamin B2	Vitamin B12	Folates	SFA	Sodium
Current situation	100	100	100	100	202	78	123	191	90	101	198	130	96	157	188	126	145	126	74	73
Replacement of meat by grains [c]																				
10% replacement	98	97	101	100	199	79	123	188	89	101	196	130	97	154	185	125	141	126	75	74
25% replacement	94	92	102	101	194	80	124	185	88	101	192	129	97	150	181	123	134	127	76	75
50% replacement	88	84	104	101	185	82	125	179	87	101	186	129	99	142	174	120	123	129	79	77
Replacement of meat by fruit, vegetables, legumes and nuts [c]																				
10% replacement	98	96	102	101	199	81	125	191	91	102	201	138	98	154	187	126	140	130	75	74
25% replacement	94	91	105	102	194	86	127	191	94	105	204	151	101	151	186	126	134	137	77	75
50% replacement	88	82	110	104	186	95	132	192	97	108	210	171	107	144	184	125	122	148	81	78
The EAT-LANCET healthy diet [d]																				
Reference diet	74	65	130	112	175	143	125	218	116	124	297	287	147	135	210	118	92	202	87	77

[a] Environmental impact was evaluated using the current impact as reference. Nutritional health impact was evaluated using percentage daily values for nutrients to encourage and percentage maximum recommended values for nutrients to limit. Daily nutrient intakes were averaged for the four European countries, reference values of EFSA were used, i.e. Average Requirement (AR) and Adequate Intake if AR cannot be set, and maximum references values of World Health Organisation.

[b] Calculations were based on predicted values using the regression model for the association with dietary quality as specified under Table 5 extended by food groups as mentioned by the EAT-LANCET commission [1], such as potatoes, vegetables, fruit, eggs, legumes, nuts, and sugars, i.e. the sum of sugar and sweets and sweet beverages, and using observed values in this regression model for the current scenario, i.e. 33.8%energy from total grains, 3.2%energy from potatoes, 2.3%energy from vegetables, 5.2%energy from fruits, 12.6%energy from dairy with a proportion milk to total dairy of 52.7%, 11.8%energy from meat with a proportion ruminant to total meat of 24.6%, 1.1%energy from eggs, 1.8%energy from fish, 0.7%energy from legumes, 0.6%energy from nuts, 13.5%energy from fats and oils with a proportion animal fat to total fat of 24.6%, and 6.5%energy from sugars that included sugar and sweets and sweet beverages. These food groups covered 93.1% of the total energy intake, as the consumption of the food groups alcoholic beverages (4.6%energy), miscellaneous (1.6%energy) and composite dishes (0.6%energy) were excluded.

[c] In the meat replacement scenarios, we modelled that energy from total meat were reduced by x% and replaced by grains or by fruit, vegetables, legumes and nuts and seeds.

[d] For the EAT-LANCET healthy diet, we modelled 32.4%energy from total grains, 1.6%energy from potatoes, 3.1%energy from vegetables, 5.0%energy from fruits, 6.1%energy from dairy, 3.7%energy from meat including beef, lamb, pork and poultry with a proportion ruminant to total meat of 16%, 0.8%energy from eggs, 1.6%energy from fish, 11.3%energy from legumes, 11.6%energy from nuts, 17.9%energy from fats and oils with a proportion animal fat to total fat of 21%, and 4.8%energy from sugars that included sugar and sweets and sweet beverages [1].

[e] NRD was based on the principles of the Nutrient Rich Food Index, NRF [2, 3], that is the unweighted sum of percentage daily references values (DRVs) for nutrients to encourage minus the sum of percentage maximum recommended values (MRV) for nutrients to limit, calculated per 100 kcal and capped at 100%DRV. We expressed nutrient intakes relative to a daily energy intake of 2,500 kcal for men and of 2,000 kcal for women to obtain a daily nutrient density score. NRD9.3 included nine nutrients for which intake should be promoted (protein, dietary fibre, calcium, iron, potassium, magnesium, vitamin A, C and E) and three nutrients for which intake should be limited (saturated fatty acids, added sugar and sodium), while NRD15.3 additionally included mono-unsaturated fatty acids, zinc, vitamin D and B-vitamin B1, B2, B12 and folate, but excluded magnesium. DRVs are defined using reference values from European Federation of Safety Authority (EFSA) [4], i.e. average requirement (AR) and adequate intake (AI) if AR cannot be set, and MRVs using references values of World Health Organisation [5, 6] and Food and Agriculture Organisation [7]. The final score resulted in an overall theoretical score range from 0 (minimal adequacy) to 900 or 1500, respectively (maximal adequacy).

References

1. Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A *et al*: **Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems**. *The Lancet* 2019.
2. Drewnowski A: **Defining nutrient density: development and validation of the nutrient rich foods index**. *J Am Coll Nutr* 2009, **28**(4):421s-426s.
3. Fulgoni VL, 3rd, Keast DR, Drewnowski A: **Development and validation of the nutrient-rich foods index: a tool to measure nutritional quality of foods**. *J Nutr* 2009, **139**(8):1549-1554.
4. EFSA (European Food Safety Authority): **Dietary Reference Values for nutrients Summary report**. *EFSA Supporting Publications* 2017, **14**(12):e15121.
5. World Health Organisation (WHO): **Guideline: Sodium intake for adults and children.** In: *World Health Organisation (WHO).* Geneva; 2012.
6. World Health Organisation (WHO): **Guideline: Sugars intake for adults and children**. In: *World Health Organisation (WHO).* Geneva; 2015.
7. Food and Agriculture Organisation (FAO): **Fats and fatty acids in human nutrition. Report of an expert consultation**. *FAO Food and nutrition paper* 2010, **91**:1-166.

APPENDIX

SHARP-Indicators Database towards a public database for environmental sustainability

Elly Mertens

Gerdine Kaptijn

Anneleen Kuijpers

Hannah van Zanten

Johanna M Geleijnse

Pieter van 't Veer

Published in: Data In Brief 2019;104617

ABSTRACT

To initiate the achievement of an European-wide applicable public database for indicators of environmental sustainability of the diet, we developed the SHARP Indicators Database (SHARP-ID). A comprehensive description of the development of the SHARP-ID is provided in this article. In the SHARP-ID, environmental impact assessment was based on attributional life cycle analyses using environmental indicators greenhouse gas emission (GHGE) and land use (LU). Life cycle inventory data of 182 primary products were combined with data on production, trade and transport, and adjusted for consumption amount using conversions factors for production, edible portion, cooking losses and gains, and for food losses and waste in order to derive estimates of GHGE and LU for the foods as eaten. Extrapolations based on similarities in type of food, production system and ingredient composition were made to obtain estimates of GHGE and LU per kg of food as eaten for 944 food items coded with a unique FoodEx2-code of EFSA and consumed in four European countries, i.e. Denmark, Czech Republic, Italy and France. This LCA-food-item database can be linked to food intake data collected at the individual level in order to calculate the environmental impact of individual's diets. The application of this database to European survey data is described in an original research article entitled "Dietary choices and environmental impact in four European countries" [1].

SPECIFICATIONS TABLE

Subject area	Nutrition sciences
More specific subject area	Diet-related environmental sustainability
Type of data	Figures and tables
How data was acquired	Raw data on the environmental impact of all the food's life cycle stages were extracted from existing public databases and from recent publications. Life cycle inventory data of Agri-footprint and Ecoinvent were accessed using the software program SimaPro (Multi-user version 8.4.0.0). Raw data on the environmental impact of all the food's life cycle stages were compiled to calculate environmental impact of the food as consumed using Microsoft Excel.
Data format	Raw processed and analysed data, descriptive statistics The raw data are available on a data repository.
Experimental factors	Data taken from published sources were processed to provide estimates of GHGE and LU for assessing the environmental impact of an individual diet.
Experimental features	No experimental work was carried out; calculations were based on published data.
Data source location	Foods included in the SHARP-ID were based on the reported food intake of the four European countries included in the SUSFANS project, i.e. Denmark, Czech Republic, Italy and France, resulting in a list of 944 food items coded with a unique FoodEx2-code.
Data accessibility	Estimates of environmental impact for a food, as coded by the FoodEx2, are available on a data repository with the following doi https://doi.org/10.17026/dans-xvh-x9wz. The associated file that includes all the calculations is available upon request for scientific applications. Contact point for further use is prof Pieter van 't Veer at the Division of Human Nutrition and Health, Wageningen University (pieter.vantveer@wur.nl). Reproduction and translation for non-commercial purposes are authorised, provided the source is acknowledged and the publisher is given prior notice and sent a copy.
Related research article	Mertens, E., A. Kuijsten, H.H.E. van Zanten, G. Kaptijn, M. Dofková, L. Mistura, L. D'Addezio, A. Turrini, C. Dubuisson, S. Havard, E. Trolle, J.M. Geleijnse, and P.v.t. Veer, Dietary choices and environmental impact in four European countries. Journal of Cleaner Production, 2019. 237: p. 117827.

VALUE OF THE DATA

- The data serve to quantify the environmental impact of the diet in the consumer domain using highly-disaggregated food consumption data collected at the individual level. Using this consumption-oriented approach allows studying environmental impact of the diet with other diet-related aspects, like dietary quality, food preferences, food affordability, etc.
- The data permit comparisons of environmental impact of individual’s diets within and between populations, if using comparable dietary assessment methods.
- The data provide a basis for new research undertakings that are directed to broadening the understanding of the interrelationships between environment, food, and health.

DATA

The SHARP-Indicators Database (SHARP-ID) presented here constitute the basis for quantifying the environmental impact of an individual’s diet. This database provides for each single food item an estimate on greenhouse gas emissions (GHGE) and land use (LU) per kg of food as eaten. Food items included in the SHARP-ID were based on the reported food intake of the four European countries included in the SUSFANS project [2], i.e. Denmark, Czech Republic, Italy and France. Intake data of these four countries were coded using FoodEx2 Exposure Hierarchy of the European Food Safety Authority (EFSA) [3, 4], resulting in a list of 944 food items coded with a unique FoodEx2-code for which environmental footprint of the food product’s life cycle was assessed using attributional life cycle analyses (LCA). Table 1 shows the summary descriptive statistics of GHGE (in kgCO_2eq/kg food as eaten) and LU (in m^2*year/kg food as eaten) for different food groups. Starting from life cycle inventory data on primary products, estimates were obtained for GHGE and LU per kg of food as eaten by using appropriate conversions factors to reflect amount as consumed and including impacts from packaging, transport and home preparation. Life cycle inventory data were retrieved from Agri-Footprint 2.0 [5, 6] , Ecoinvent 3.3 [7], CAPRI [8], and supplemented by recent literature and technical reports (Figure 1 and Table 2). Impacts of composite foods were estimated using the ingredients/primary products that make up the foods using recipes from the Dutch food composition table [9] or the first hit on internet. Conversion factors for production were taken from Bowman [10, 11] and FAO [12], for edible part and for weight gain or losses during preparation from Bognar [13] and the Health Council of Belgium [14], and for food losses and waste from Broekema and Kuling, as documented in [15]. Impacts from packaging were retrieved from Ecoinvent 3.3 [7], using the most common packaging format, as reported by [16] (Table 3). Impacts from transport were retrieved from RVO [17], using information on trade and transport from FAOstat, BACI World Trade Database, GTAP and Geodis. Impacts from home preparation in energy use (MJ) were based on Foster [18] and Carlsson-Kanyama [19] (Table 4), and recalculated into GHGE (CO_2eq) using the methods of H Mombarg and A Kool [20].

Table 1 Average GHGE (in kgCO_2/kg food as eaten) and average LU (in m^2*year/kg food as eaten) for 17 food groups according to level 1 of the FoodEx2 Exposure Hierarchy. Values are means with their standard deviations.

Food groups according to level 1 of the FoodEx2 Exposure Hierarchy	Number of food items	GHGE		LU	
		Mean	(SD)	Mean	(SD)
Grains and grain-based products	139	3.9	(5.9)	5.8	(6.0)
Vegetable and vegetable products	109	1.8	(3.7)	0.8	(1.9)
Starchy root or tubers and products	14	0.8	(0.4)	0.8	(0.6)
Legumes, nuts and oilseeds	43	2.1	(1.9)	7.9	(13.6)
Fruit and fruit products	90	0.9	(0.6)	0.8	(0.7)
Meat and meat products	113	17.1	(9.5)	28.5	(17.4)
Fish and fish products	96	15.2	(16.7)	2.1	(4.3)
Milk and dairy products	111	11.5	(6.6)	11.5	(7.0)
Eggs and egg products	13	5.3	(5.3)	16.1	(17.0)
Sugar and confectionary	30	2.6	(2.7)	3.7	(3.6)
Animal and vegetable fats and oils	29	7.1	(9.1)	16.9	(13.8
Fruit and vegetable juices	27	1.2	(0.5)	1.0	(0.9)
Water and water-based beverages	27	0.4	(0.1)	0.3	(0.2)
Alcoholic beverages	33	1.1	(0.3)	0.7	(0.2)
Coffee, cocoa, tea	30	1.5	(3.4)	1.6	(4.7)
Composite dishes	20	4.8	(2.5)	7.5	(4.2)
Miscellaneous	20	2.2	(1.2)	6.3	(6.9)

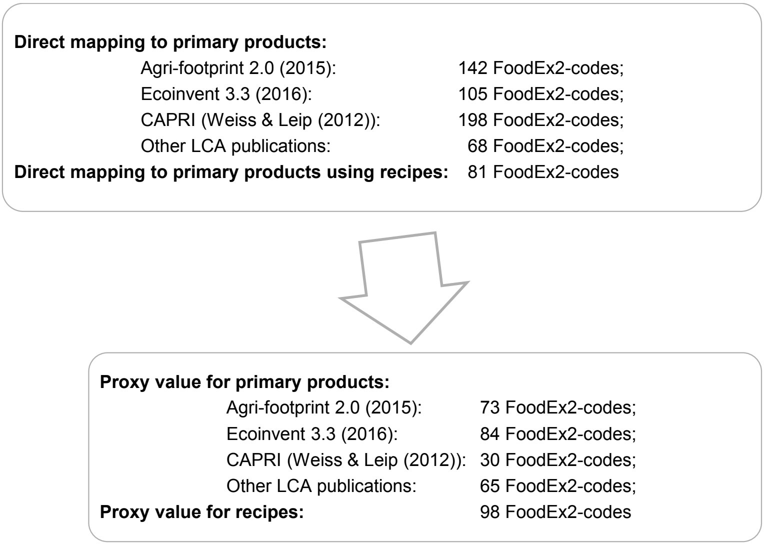
EXPERIMENTAL DESIGN, MATERIALS, AND METHODS

Environmental impact of primary productions

Life cycle inventory data of Agri-Footprint 2.0 [5, 6], Ecoinvent 3.3 [7] and CAPRI [8] were used as an input for the SHARP-ID and provided information on greenhouse gas emissions (GHGE) and land use (LU) of primary food products, i.e. environmental impacts until the farm gate. GHGE was expressed in kilogram CO_2equivalents (kgCO_2eq) per kg primary product, with 1 kgCH_4 equal to 25 kgCO_2, and 1 kgN_2O equal to 298 kgCO_2 (IPCC 2007). LU was expressed in m^2*year per kg primary product, and was calculated as 10000/yield. With SimaPro (Multi-user version 8.4.0.0), life cycle inventory data of Agri-footprint and Ecoinvent were accessed. Agri-footprint was used as a first data source, and was where needed supplemented by Ecoinvent and other data sources. For livestock products, i.e. all meat, milk and egg products, we used data from CAPRI, as these data cover an European average for these animal-sourced foods. Relevant recent literature and technical reports were used to fill data gaps, for example for fish products. For the FoodEx2-codes where no primary product data were available, extrapolations were made based similarities in cultivation and production method, and the producing country. Impacts between products and co-products were based on economic allocation for all foods, except for animal-sourced foods where nitrogen allocation was used because the nitrogen content serves as an indicator of the physical and causal relationship between products and emissions [8].

For composite foods, a break-down into their ingredients is needed before linking these to their corresponding primary products. Food items consisting of two or more primary products, for example grain-based products like bread, cookies and cakes, composite dishes like pizza, hamburger, goulash, soups and salads, and milk desserts like pudding and milkshake, etc. are regarded as a composite food; regardless whether they are prepared at home or manufactured. To calculate the environmental impact of a composite food, recipes taken from the Dutch food composition table [9] or the first hit on internet were used to break-down composite foods into its ingredients. Using the mass balance and the environmental impact of the ingredients, a weighted impact of the composite dish was calculated. In total, we used 42 different recipes, and a recipe was also used as a proxy for composite foods with comparable ingredient composition. All recipes for composite foods were assumed to be homogenous across Europe.

Figure 1 shows the process of mapping food to primary products from different life cycle inventory data sources, and table 2 shows for each food group of the FoodEx2-classification (at Level 1) their corresponding life cycle inventory data source used for quantifying environmental impact.



Direct mapping to primary products:
Agri-footprint 2.0 (2015): 142 FoodEx2-codes;
Ecoinvent 3.3 (2016): 105 FoodEx2-codes;
CAPRI (Weiss & Leip (2012)): 198 FoodEx2-codes;
Other LCA publications: 68 FoodEx2-codes;
Direct mapping to primary products using recipes: 81 FoodEx2-codes

Proxy value for primary products:
Agri-footprint 2.0 (2015): 73 FoodEx2-codes;
Ecoinvent 3.3 (2016): 84 FoodEx2-codes;
CAPRI (Weiss & Leip (2012)): 30 FoodEx2-codes;
Other LCA publications: 65 FoodEx2-codes;
Proxy value for recipes: 98 FoodEx2-codes

Figure 1 Mapping foods to primary products from different life cycle inventory data sources.

Table 2 Food groups of the foodEx2-classification (at Level 1) and their corresponding life cycle inventory data source used for quantifying environmental impact.

Level 1 food groups of the FoodEx2-classification system	Number of foods					Main data sources
	Total	via direct mapping	via proxy	via recipes	via proxy recipes	
Grains and grain-based products	137	48	9	25	55	Agri-footprint
Vegetable and vegetable products	109	44	65	-	-	Agri-footprint, Ecoinvent
Starch roots or tubers and products thereof	9	9	-	-	-	Agri-footprint
Legumes, nuts and oilseeds	42	25	17	-	-	Agri-footprint, Other publications
Fruit and fruit products	90	35	45	8	2	Ecoinvent
Meat and meat products	107	81	26	-	-	CAPRI, Other publications
Fish and fish products	93	41	52	-	-	Other publications
Milk and dairy products	110	102	3	3	2	CAPRI, Other publications
Eggs and egg products	12	12	-	-	-	CAPRI, Other publications
Sugar and confectionary	30	7	10	6	7	Agri-footprint
Animal and vegetables fats	29	17	6	2	4	Agri-footprint, Ecoinvent, CAPRI
Fruit and vegetable juices	27	13	14		-	Ecoinvent, Agri-footprint
Water and water-based beverages	27	9	1	17	-	Agri-footprint
Alcoholic beverages	34	21	-	1	12	Agri-footprint, Ecoinvent
Coffee, cocoa, tea	30	27	-	3	-	Ecoinvent, Agri-footprint, Other publications
Composite dishes	38	10	2	13	13	Agri-footprint, CAPRI, Other publications
Miscellaneous, including food products for young population, non-standard diets, seasoning and sauces	20	13	1	3	3	Ecoinvent, Agri-footprint

Environmental impact from production until consumption

Conversion factors to reflect amount as consumed

To calculate the environmental impact for foods as consumed, we applied conversion factors for production, for edible part, for weight gain or losses during preparation, and for food losses and waste at production and at consumption phase.

A production factor was applied for primary products that undergo further production processing to extend shelf life, to render palatability, edibility, safety, etc. Examples of this kind of products are wheat that is milled into flour, grapes that are dried to render raisins, fruits that are squeezed to render fruit juice. This kind of processing results in a mass change of the primary product (the production amount is not the same as the amount of retail), hence the need for a production factor. This production factor is usually higher than 1.0; with its magnitude depending on the primary product and its undergoing production process. Production factors, as documented by Bowman [10], were applied to convert a processed food item to its raw primary product as found at retail level; herby only accounting for mass differences [11]. Technical production factors for products derived from milk, such as cream, cheese and butter, were taken from FAO [12]; because production yields of products derived from milk tend to vary between countries, as these are highly dependent on the composition of the raw milk, for example cheese yield is related to casein and fat content of the milk. None of the production factors accounted for water and energy consumed, however the latter was taken into account in a later stage by adding preparation at home to the GHGE of that food item.

Conversion factors for consumption refuse (e.g.: skin, peel, core, pits, trimming), weight losses and gains during preparation were applied for products where the amount bought at retail differs from the amount of consumed. Examples of this kind of conversion factors are the adjustment of bananas for its peel (using a factor for edible portion), cooked vegetables for their raw amount (using a factor for weight loss during cooking), cooked rice for uncooked rice (using a factor for weight gain during cooking). Conversion factors were taken from Bognar [13] and from the Health Council of Belgium [14]. For processed foods, these kind of conversion factors were already included in the production factor.

Percentage of food losses and waste, estimated by Broekema et al. (2015) and Kuling et al. (2015), as documented in [15], were applied to further adjust consumption amount to production amount. Food losses included losses during storage, processing, packaging and transport, and losses at the supermarket and at home (i.e. losses of the edible parts of the food, i.e. waste). Percentage of food losses were estimated at the level of food groups, and food groups not included were assumed to have an average food loss percentage.

Environmental impact of packaging

For the packaging of food products, we included primary packaging (Table 3), but excluded secondary and tertiary packaging, such as carton boxes and pallets. The main reason for only including primary packaging was that this has the highest impact on the environment. Data on packaging were retrieved from Ecoinvent 3.0; using the most common packaging format for that food item, as reported by [16].

Table 3. Packaging and their associated foods.

Packaging material	Foods
Average of glass bottle and can (for 0.3L drinks)	Beer
Average of glass bottle and can (for 0.3L drinks), and PET bottle (for 1L drinks)	Soft drinks, fruit juices and water
Glass bottle (for 150g jam)	Jam, peanut butter, chestnut puree, honey
Average of glass bottle (for 500g dressing) and HDPE container (for 1L ketchup)	All kind of sauces, dressing and syrups
Average of HDPE container and glass bottle (for 500mL oil)	Oils
Glass bottle (for 500mL oil)	All kind of alcoholic beverages other than beer
PE bag (for 500g of pasta)	Pasta, rice, bread, coffee, tea, milk powder
PP bag (for 400g of cereals)	Cornflakes, candies
Drink carton (for 1L milk)	Milk, plant-based alternative for milk
HDPE container (for 1L ice cream)	Ice cream, sorbet, composite dishes like soups, goulash
HDPE container(for 400g margarine)	Margarine, spreadable cheese, composite salad dishes
PS container (for 2dL yoghurt)	Yoghurt, quark, dairy desserts, soft cheeses
PS container (for 500g meat)	Meat, fish, tofu, hard cheese, nuts
Pulp tray (for 10 eggs)	Eggs, composite pizza-like dishes like
PS bag (for fruit, vegetables, potatoes)	Fruit, vegetables, potatoes
Average of aluminium and tin can (for 500g food)	Canned fruit and vegetables
Average of aluminium and tin can (for 150g food)	Canned meat and fish, condensed milk

Abbreviations: PET, PolyEthylene Terephthalate, HDPE, High-Density PolyEthylene; PE, PolyEthylene; PP, PolyPropylene; PS, PolyStyrene.

Environmental Impact of transport

Trade and transport data were obtained from FAOstat, BACI World Trade Database and GTAP using reference year 2011; these data provided information about the countries of trade and its corresponding amount, ratio imported domestically produced, and the ratio for mode of travel (air, water, land). Distances between trading countries were obtained from Geodist. Transport distances for imported food items were taken from the producing country of the raw primary product to the country that will manufacture/consume that raw primary product, and thus excluding transport within that country from retailers to home. For locally produced and locally consumed food items, distance for travelling by truck within an average European country was used. Emissions of transport by airplane, ship, and truck were taken from RVO [17]. Refrigeration of a vehicle adds 20% to the emissions; a chilled vehicle was assumed for all dairy, meat, vegetables (except for tubers) and fruit products. Chilled transport was not considered for composite dishes, processed foods, cacao, drinks, including sweet and alcoholic drinks, coffee and tea, and water, as they were assumed to be prepared at home and/or packaged in a tin/glass/can/bottle, and thus no need to be chilled.

Environmental impact of food preparation

Values for home preparation were based on Foster [18] who based his values on Carlsson-Kanyama [19]; information was available for boiling, frying, oven baking, roasting and microwaving (Table 4). Energy use (MJ) was recalculated into GHGE (CO_2eq) using the methods of H Mombarg and A Kool [20], and under the assumption that half the energy use was from gas and half from electricity. No values were assigned to alcoholic beverages, animal and vegetable fats and oils, salads of composite dishes, unprepared eggs, fruits except for jams, fruit and vegetables juices and nectars, flours, unprocessed breakfast cereals, nuts, milk and dairy products except for puddings, plant alternatives for milk, seasoning, sauces and condiments, except for white and tomato sauce, confectionary and water-based sweet desserts, vegetables and vegetables products regularly consumed as raw , water and water-based beverages; because not home-prepared and/or counted by food products with whom it is consumed together, and/or consumed as raw.

Table 4. Environmental impact of home preparation.

Way of home preparation	Foods
Boiling water	Coffee, tea, cocoa beverages
Boiling potatoes	Potatoes, soups, grains, vegetables, jams and juices, legumes, puddings
Frying	Fried dishes
Microwaving	Oat porridge
Oven baking	Bread products and cookies, dried eggs and dried vegetables
Roasting	Meat and fish products

Calculations of the final values of GHGE and LU, as included in the SHARP-ID

For each FoodEx2-code, total GHGE and LU per kg of food as eaten were calculated using the following formula, respectively:

GHGE = GHGE at farm gate x production factor x (1/edible factor) x (1/shrinkage, swelling factor) x (1/losses, waste factor) + packaging + transport + preparation at home

LU = LU at farm gate x production factor x (1/edible factor) x (1/shrinkage, swelling factor) x (1/losses, waste factor)

Acknowledgments

The work has received funding from TiFN under Project agreement number 15SD01 (SHARP-BASIC) for the development of the SHARP Indicators Database (SHARP-ID).

REFERENCES

1. Mertens E, Kuijsten A, van Zanten HHE, Kaptijn G, Dofková M, Mistura L, D'Addezio L, Turrini A, Dubuisson C, Havard S *et al*: **Dietary choices and environmental impact in four European countries**. *Journal of Cleaner Production* 2019, **237**:117827.
2. Rutten M, Achterbosch TJ, de Boer IJM, Cuaresma JC, Geleijnse JM, Havlík P, Heckelei T, Ingram J, Leip A, Marette S *et al*: **Metrics, models and foresight for European sustainable food and nutrition security: The vision of the SUSFANS project**. *Agricultural Systems* 2016.
3. European Food Safety Authority: **The food classification and description system FoodEx2 (revision 2)**. *EFSA supporting publication 2015* 2015, **En-804**:90.
4. EFSA (Eurepean Food Safety Authority): **Use of the EFSA Comprehensive European Food Consumption Database in Exposure Assessment**. *EFSA Journal 2011* 2011, **9**(9):2097.
5. BlonkConsultants: **Agri-footprint 2.0–Part 1: Methodology and Basic Principles**. *Gouda, the Netherlands* 2015.
6. BlonkConsultants: **Agri-footprint 2.0–Part 2: Description of data**. *Gouda, the Netherlands* 2015.
7. Weidema BP, Bauer C, Hischier R, Mutel C, Nemecek T, Reinhard J, Vadenbo C, Wernet G: **Overview and methodology: Data quality guideline for the ecoinvent database version 3**. In.: Swiss Centre for Life Cycle Inventories; 2013.
8. Weiss F, Leip A: **Greenhouse gas emissions from the EU livestock sector: a life cycle assessment carried out with the CAPRI model**. *Agriculture, Ecosystems & Environment* 2012, **149**:124-134.
9. NEVO: **Recepten NEVO-online 2016**. 2016.
10. Bowman S, Martin C, Carlson J, Clemens J, Lin B-H, Moshfegh A: **Food Intakes Converted to Retail Commodities Databases: 2003-08: Methodology and User Guide**. In.: U.S. Department of Agriculture, Agricultural Research Service, Beltsville, MD and U.S. Department of Agriculture, Economic Research Service, Washington, D.C.; 2013.
11. Bowman S, Martin C, Friday J, Moshfegh A, Lin B-H: **Converting food intakes to retail commodities: A novel approach to identify trends in food commodity usage by Americans**. *The FASEB Journal* 2010, **24**(1 Supplement):943.942.
12. FAO: **Technical Conversion Factors For Agricultural Commodities**. In.; 1996.
13. Bognar A: **Tables on Weight Yield of Food and Retention Factors of Food Constituents for the Calculation of Nutrient Composition of Cooked Foods (Dishes).** In. Edited by Berichte der Bundesforschungsanstalt für Ernährung. BFE-R--02-03. Karlsruhe, Germany; 2002.
14. Hoge Gezondheidsraad: **Maten en Gewichten. Handleiding voor gestandardiseerde kwantificering van voedingsmiddelen in België: revisie januari 2005 (HGR 6545-2)**. In. Edited by Minsterie van Sociale Zaken Volksgezondheid en Leefmilieu: Hoge Gezondheidsraad. Brussels, Belgium; 2005.
15. De Valk E, Hollander A, Zijp M: **Milieubelasting van de voedselconsumptie in Nederland**. *RIVM rapport 2016-0074* 2016.
16. Pongráz E: **Chapter 9 the environmental impact of packaging**. In: *Environmentally Conscious Materials and Chemicals Processing.* Edited by Kutz M. Hoboken, New Jersey: John Wiley & Sons Inc.; 2007.
17. **GER-waarden en CO2-lijst - januari 2017** [https://www.rvo.nl/file/ger-waarden-en-co2-lijst-januari-2017]
18. Foster C, Green K, Bleda M: **Environmental impacts of food production and consumption: final report to the Department for Environment Food and Rural Affairs**. 2007.

19. Carlsson-Kanyama A, and K. Bostrom-Carlsson.: **Energy Use fo Cooking and Other stages in the Life Cycle of Food: a study of wath, spaghettie, pasta, barley, rice, potatoes, couscous and mashed potatoes**. In. Stockholm Sweden: Stockhoms Universitet; 2001.
20. Mombarg H, Kool A: **Telen met toekomst energie-en klimaatmeetlat: eindrapport**. In.: Plant Research International; 2004.

PART III

Identification of dietary improvement options for European consumers that integrate health, environmental sustainability and dietary preferences

CHAPTER 6

A brief introduction to the benchmark diet model

Elly Mertens

Argyris Kanellopoulos

Anneleen Kuijsten

Marianne Geleijnse

Pieter van 't Veer

RATIONALE

Composing healthy diets is quite complex, as each food has a different mixture of nutrients, non-nutrients and bio-actives, but also differently affects non-communicable disease risk. Current dietary practices fail to meet guidelines for a healthy diet, hereby contributing to the triple burden of malnutrition, including undernutrition, obesity and non-communicable diseases. Apart from that, they also have a major impact on the environment, affecting greenhouse gas emissions, biodiversity, land and freshwater use, and nitrogen and phosphorous cycles. The key challenge is therefore to design future diets that not only meet guidelines for a healthy diet, but also reduce environmental impact of the diet.

Previous research has addressed this problem of designing improved diets by using food-based mathematical diet optimisation models [1]. Such diet models construct linear combinations of foods, in which the total nutrient intake and environmental impact meets *a priori* defined criteria for a healthy diet at minimum environmental impact. The weights of the various foods then reflect an optimised dietary pattern. As these improved diets are just linear combinations of foods, they ignore intrinsic interdependencies in the diet pattern, unless additional *a priori* criteria on food habits are added to the model. Defining these food-habit criteria, however, involves expert judgements on basic food interrelationships, realistic food quantities and dietary preferences of consumers. There is thus a need for a diet model that implicitly accounts for these aspects without specifying these as additional subjective constraints on foods or dietary preferences.

A benchmarking diet model does not calculate optimal diets as linear combination of foods, but as linear combinations of whole diets, and consequently preserves many of the intrinsic interdependencies between foods [2]. It therefore contributes to the literature by composing diets that are not only healthy and environmentally sustainable, but also implicitly account for dietary preferences. In a benchmarking diet model, starting from a set of observed diets, those diets that perform better than others are identified and are used to improve the diet of others. In this way, improved diets are assumed to be realistic and feasible for each consumer in the population as they are within the range of observed diets and preserve intrinsic interdependencies between foods.

THE METHOD OF BENCHMARKING DIETS

The benchmarking diet model builds on a Data Envelopment Analysis (DEA) model. Briefly, starting from all observed diets within a population sample, the DEA-model identifies efficient diets, and subsequently uses this set of existing efficient diets to generate linear combinations in order to arrive at a healthier diet for others. Unlike the food-based diet optimisation models, the benchmarking approach does not necessarily imply that the modelled diets do fully comply with the *a priori* defined criteria, but modelled diets are closer to this set of criteria than observed diets, and thus they move in the proper direction.

Identification of existing efficient diets

The identification of efficient diets starts with a set of existing diets (or day menus) as observed in the population, for example obtained from dietary survey data collected at the individual level. In our model, observed diets are standardised for energy using the density method in order to allow for a fair comparison of the diet quality between the diets [3].

While benchmarking diets for health, the identification of existing efficient diets is based on a comparison of each observed diet with all other diets regarding *a priori* defined criteria for a healthy diet. A diet is identified as efficient when this diet has the most “dietary components to increase” for the least “dietary components to decrease”, as compared to the other diets, or vice versa. Criteria for a healthy diet should thus enclose both “dietary components to increase” and “to decrease”. Staring from the observed diet, the “dietary components to increase” represent the additions to the diet for arriving at a heathier diet, and the “to decrease” the sacrifices.

Using the criteria for a healthy diet, the set of existing efficient diets creates a ‘solution space’ (an ‘envelop’) to arrive at healthier diets for the others, hence the term Data Envelopment Analysis. This implies that the included criteria for a healthy diet and the set of existing efficient diets are the starting point to set the direction for dietary improvement. The rationale for selecting criteria for a healthy diet is therefore of crucial importance, while the set of efficient diets determines the range of dietary improvement options to arrive at realistic and feasible healthier diets.

Modelled healthier diets,
i.e. diets generated from the set of existing efficient diets
In the benchmarking diet model, for each observed inefficient diet, options for a healthier diet are sought within the range of observed diets in the population under study. These healthier diet options are defined by the so-called efficient frontier (see Figure). The efficient frontier includes all efficient diets, as identified by the DEA-model, and is used to generate healthier diets as linear combinations (weighted averages) of those efficient diets. For each inefficient diet, options for healthier diets are calculated by minimising the distance to the efficient frontier, i.e. either by increasing “the components to increase” for the same level of “to decrease” or analogously decreasing “the components to decrease” for the same level of “to increase”. Similar to food-based diet optimisation models, to increase the likelihood of adopting the modelled diets, the benchmarking diet model also aims to minimise some measure of distance between the modelled and observed diets. Such measures of distance still require expert evaluation. Nevertheless, the benchmarking diet model builds on empirical diets as a way to implicitly account for dietary preferences. The assumption underlying this is that peer resemblance is one of the most important determinants to affect consumer diets.

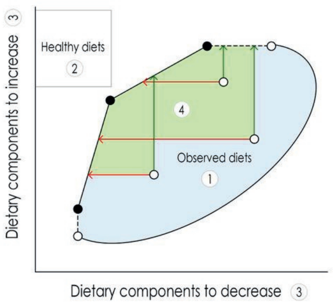


Figure A benchmarking diet model derives options for dietary improvement within the range of observed diets.

The benchmarking diet model derives options for dietary improvements within the range of observed diets (ellipse, #1), but not necessarily in the normative domain for a healthy diet (upper-left rectangle, #2). In the diet benchmark, a diet that performs better than others with regard to the ratio of “dietary components to increase” to “to decrease” (Y and X-axis respectively, #3) is identified as an efficient diet. All those efficient diets lie on the efficient frontier, and they determine the “envelop” for dietary improvements (#4).

The model enables to study trade-offs between different objectives for dietary change, related to e.g. dietary preferences, healthiness or environmental sustainability. Within the envelop for dietary improvement, these options for healthier diets can be explored by taking different linear combinations of the existing efficient diets on the efficient frontier. In our model, trade-offs between pairs of objectives were studied as a weighted sum objective function to calculate a set of so-called pareto optima solutions [3]. In our case, objective functions were a measure of absolute deviations from the observed diet for dietary preferences, a nutrient-based diet score for healthiness in terms of nutrient quality, and diet-related greenhouse gas emissions for environmental sustainability. After normalising these objective functions, a set of pareto optima solutions were calculated by giving full weight to one objective (e.g. dietary preferences), followed by stepwise increasing the weight for another objective (e.g. healthiness), and calculating the alternative diet after each step until full weight was given to that second objective. In particular, in our model, trade-offs of dietary preferences against nutrient quality and against environmental sustainability were studied, and this resulted in three dietary improvement options, i.e. modelled diets that (a) remain close to the observed diet, (b) have a high nutrient quality or (c) have a low environmental impact [3].

CONCLUSION

A benchmarking diet model allows for the identification of existing better diets and provides a framework for improvement of diets and making trade-offs between different objectives. As compared to the food-based diet optimisation model, the advantage of benchmarking diets is that the improved diets are a combination of existing diets, and thus they implicitly account for intrinsic relationships between foods in the diet. Benchmarked diets that are frequently used for dietary improvements can provide guidance for defining policy goals to improve human health and to protect the environment. In addition, using the efficient frontier of existing healthier diets enables to model diets that offer policymakers and consumers options to improve the diet by giving weights to their public or personal priorities. Thus, by using peer resemblance, the benchmarking diet model provides different solutions for an improved diet within the range of observed diets.

SUPPLEMENTARY MATERIALS

Description of the Data Envelopment Analyses (DEA) model

As described by Kanellopoulos et al. [2], the DEA-model can be used as an alternative for designing options for dietary improvement by benchmarking diets. The DEA-model identifies efficient diets in two stages [4]. The first stage maximises the value of the decision variable θ $(0 \leq \theta \leq 1)$ which is the relative efficiency score of the evaluated diet. The higher the value of θ, the higher the efficiency of the evaluated diet, and an efficient diet receives the value of 1. The efficiency score θ is obtained as follows:

$$\min \left\{ \theta - \epsilon \left(\sum s_i^- + \sum s_j^+ \right) \right\}$$

Subject to:

$$\sum x_{ik}\,\lambda_k + s_i^- = \theta x_{i0} \qquad i = 1,2\ldots,p$$

$$\sum y_{jk}\lambda_k - s_j^+ = y_{j0} \qquad j = 1,2\ldots,q$$

$$\sum^{n} \lambda_k = 1$$

$$\lambda_k \geq 0 \qquad k = 1,2\ldots,n$$

$$s_i^- \geq 0 \qquad i = 1,2\ldots,p$$

$$s_j^+ \geq 0 \qquad j = 1,2\ldots,q$$

Where λ_k is the decision variables and the weight of diet *k* in the efficient alternative of the evaluated diet, s_i^- is the slack decision variable for the decreasing dietary component and captures the deviation between the amount of decreasing dietary component i of the improved diet and that of the observed diet, s_j^+ is the slack decision variable for the increasing dietary components and captures the deviation between the amount of the increasing dietary component j of the improved diet and that of the observed diet, ε is a marginal positive number, x_{ik} and y_{jk} are the amounts of the dietary components to decrease i and to increase j respectively of the observed diet k, , and x_{i0} and y_{j0} are the amounts of the decreasing dietary components i and increasing dietary components j in the evaluated diet. In the first stage, ε is set to a very small number, which effectively negates the contributions from the slack terms s_i^- and s_j^+; and the second stage maximises the total slack.

REFERENCES

1. Gazan R, Barré T, Perignon M, Maillot M, Darmon N, Vieux F: **A methodology to compile food metrics related to diet sustainability into a single food database: Application to the French case**. *Food Chemistry* 2016.
2. Kanellopoulos A, Gerdessen J, Ivancic A, van 't Veer P, Geleijnse JM, Bloemhof JM: **Designing Healthier and Acceptable Diets Using Data Envelopment Analysis**. *Public Health Nutr* 2019.
3. Mertens E, Kuijsten A, Kanellopoulos A, Dofkova M, Mistura L, D'Addezio L, Turrini A, Dubuisson C, Havard S, Trolle E *et al*: **Improving health and environmental sustainability of European diets using a benchmarking approach**. *(submitted)* 2019.
4. Cooper WW, Seiford LM, Kaoru T: **Data Envelopment Analysis**: Springer; 2007.

CHAPTER 7

Improving health and environmental sustainability of European diets using a benchmarking approach

Elly Mertens
Anneleen Kuijsten
Argyris Kanellopoulos
Marcela Dofková
Lorenza Mistura
Laura D'Addezio
Aida Turrini
Carine Dubuisson
Sabrina Havard
Ellen Trolle
Sander Biesbroek
Jacqueline Bloemhof
Johanna M Geleijnse
Pieter van 't Veer

Submitted

ABSTRACT

Background: Dietary practices have a major impact on non-communicable disease risk and the environment. To facilitate the transition to healthy and environmentally sustainable diets, future food and nutrition policies need to respect the environment and dietary preferences. The present study aimed to identify diets with improved nutrient quality and environmental sustainability, within the boundaries of dietary practices in four European countries.

Methods: Based on national dietary surveys, we used Data Envelopment Analysis (DEA) to benchmark diets from Denmark, Czech Republic, Italy, and France (~6,500 adults) for improved adherence to food-based dietary guidelines (FBDGs). We then optimised these diets for dietary preferences, nutrient quality, and environmental sustainability. Diets were evaluated using the Nutrient Rich Diet score (NRD15.3), diet-related greenhouse gas emission (GHGE), and a diet similarity index that quantified the proportion of food intake that remained similar as compared to the observed diet.

Results: When dietary preferences were prioritised, NRD15.3 was ~6% higher*,* GHGE was ~4% lower and ~85% of food intake remained similar to the observed diets; this diet had higher amounts of fruits, vegetables and whole grains than observed. When nutrient quality was prioritised, NRD15.3 was ~16% higher, GHGE was ~3% lower, and ~72% of food intake remained similar; this diet had even higher amounts of fruit, vegetables, legumes and fish, and lower amounts of sweet and alcoholic beverages. When environmental sustainability was prioritised, NRD15.3 was ~9% higher, GHGE was ~21% lower, and ~73% of food intake remained similar; this diet had a higher amount of animal-sourced foods but protein sources shifted from red and processed meat to either eggs, fish or dairy. Modelled diets had a similar proportion of animal- and plant-sourced foods as the observed diet, but energy density was lower.

Conclusion: Benchmark modelling can generate alternative diets with improved nutrient quality and environmental sustainability within the range of common dietary practices. While improving adherence to FBDGs, consumers may improve their nutrient quality up to 16% and reduce GHGE up to 20%, but these objectives cannot be achieved simultaneously. For larger improvements in nutrient quality or environmental sustainability, complementary policy measures or larger dietary changes are required.

BACKGROUND

Unhealthy diets, including overconsumption, contribute to a substantial rise in the incidence of obesity and non-communicable diseases, including coronary heart disease, type 2 diabetes and cancer, in Europe [1]. Diets not only impact human health, but also the environment [2-4], hence an urgent need to shift towards more healthy and environmentally sustainable diets. Such diets would fulfil nutritional requirements, reduce overall disease risk, and can be produced within planetary boundaries. To find the best balance between the health and environmental dimension of a diet, mathematical modelling and optimisation techniques are used [5, 6].

In recent years, various models have been developed to optimise diets using individual-level data from specified countries and with objectives for health and the environment [7, 8]. Usually, these diet models have taken the form of linear programming (LP) and started from a set of food items from dietary surveys, with the goal to compose a total diet that satisfies a predefined set of norms for nutritional requirements and environmental footprints. As these models are based on single and unrelated food items, additional constraints are needed to account for cultural acceptance and dietary preferences of the optimised diet [6, 9]. Examples are minimum and maximum amount of foods consumed; and/or associations between foods in meals, such as cereals and milk, bread and jam, and/or popularity of foods by minimising deviations from the observed average diet [10].

Recently, Kanellopoulos et al. (2019) [11] presented Data Envelopment Analysis (DEA) as a benchmark approach that models new diets as a linear combination of observed diets, which implicitly keeps basic interrelationships between food items in the diet of the study population intact. This allows to model diets from different countries in a comparable way, and to account for cultural acceptance and dietary preferences without specifying additional constraints for each country. The present study applies this benchmarking approach to individual-level food consumption data from four European countries, i.e. Denmark, Czech Republic, Italy and France. For men and women in each country, trade-offs are addressed between nutrient quality, environmental impact and dietary preferences. By providing solutions within the range of existing diets, such benchmark models could be useful to guide policies towards healthy and environmentally sustainable diets that are culturally acceptable for each country and that contribute to health and environmental sustainability goals at the national and European level.

METHODS

Study population and food intake data

Food consumption data for the adult population, aged 18-64 years, were obtained from nationally-representative dietary surveys in four countries, i.e. DANSDA (2005-2008) in Denmark, based on seven-day diet records on consecutive days [12]; SISP04 (2003-2004) in Czech Republic, based on two 24-hour recalls spaced over three to five months [13]; INRAN-SCAI (2005-2006) in Italy, based on three-day diet records on consecutive days [14]; and INCA-2 Study (2006-2007) in France, based on seven-day diet record on consecutive days [15]. For each country, we sampled two non-consecutive days [16].

Food intakes were classified for each country according the FoodEx2 classification developed by the European Food Safety Authority (EFSA) [17, 18]. Nutrient composition of the consumed foods was estimated using country-specific food composition databases [19-25]. Estimates of greenhouse gas emission (GHGE, in kgCO_2equivalents (kgCO_2eq)/kg food as eaten) were assigned to each of the 944 FoodEx2-codes that were consumed in the four countries, obtained from a standardised life-cycle-assessment (LCA) database of GHGE values (SHARP-Indicator Database; [26]).

Quantities of foods were calculated for each individual from the mean of two days, and were expressed per 2500 kcal for men and per 2000 kcal for women [27]. In this way, we accounted for the observed variation in amount of foods consumed for different levels of reported energy intake, while composition of the diet is maintained. Under- and over-reporters were excluded from the analysis using the Goldberg equation [28] as adopted by Black [29], i.e. cut-off value of 0.96 and 2.49 for ratio of reported to energy requirement. Present analyses were conducted on a final sample of 1385 adults in Denmark, 1386 adults in Czech Republic, 1978 adults in Italy, and of 1713 adults in France.

The benchmark diet model

As described by Kanellopoulos et al [11]., the DEA-model can be used as an alternative for modelling healthier diets based on a nutritional benchmarking that starts from the observed diets in a population sample. We used the DEA-model to identify efficient diets, i.e. diets that perform better with respect to an *a priori* defined set of FBDGs specified as dietary components to in- or decrease in order to arrive at a healthier diet (see Table 1); basically, a diet performs better if the ratio of “dietary components to increase” to “dietary components to decrease” is higher. This identification of efficient diets was solved in two stages following [11, 30], using Xpress-IVE release 1.24. Subsequently, for each of the observed inefficient diets, this set of observed efficient diets was used to calculate healthier diets as a linear combination of existing efficient diets. In this study, the DEA-model was used to generate linear combinations that remain as close as possible to the observed diet, are the most healthy or the most environmentally sustainable. Diets were modelled for each country, and for men and women separately.

Table 1 Dietary components to identify existing healthier diets while benchmarking diets, including capping values if necessary [a].

Dietary component to increase	Dietary component to decrease
Consolidated knowledge on diet and health, based on food-based dietary guidelines [31, 32]	
Fruit (200g/2000kcal)	Red and processed meat
Vegetables (200g/2000kcal)	Sweet beverages
Legumes	Alcoholic beverages (ethanol)
Nuts and seeds	Refined grains
Fish (21g/2000kcal)[b]	Saturated fatty acids
Whole grains	
Unsaturated fatty acids (20E%)	
Nutrients to increase, to safeguard nutrient quality in the eight population subgroups[c]	
Calcium (750mg/d)	
Zinc (7.5mg/d for men; 6.2mg/g for women)	
Vitamin B2 (1.3 mg/d)	
Vitamin B12 (4.0 µg/d)	

[a] Capping values for food groups were based on an inventory of current food-based dietary guidelines of European countries [16], for nutrients were obtained from EFSA using average requirement (AR), and adequate intake, if AR cannot be set [33].

[b] Amount of fish consumed on an intake day cannot be representative for a usual day due to toxicological risks [34], therefore high intake amounts of above 64g/d were replaced by the lowest observed non-zero intake divided by two to put high intakes at a disadvantage while benchmarking diets.

[c] Nutrients to be safeguarded, i.e. nutrients were to be safeguarded when modelled nutrient intake, as calculated using the DEA-model based on food-based dietary guidelines variables, was lower than the observed intake and less than 125% of the reference value for that nutrient. This criterion was added because of the data on Czech women; and did not affect the modelling results for other population groups.

Model variables and identification of efficient diets

The energy-standardised survey data were used as the set of observed diets from which efficient diets were identified. For the variable selection, foods were classified into food groups that correspond to health-based food-based dietary guidelines (FBDGs) based on the scientific evidence for diets to reduce non-communicable disease risk (factors) in the four countries [16]; instead of oils we included unsaturated fats (to increase) and saturated fats (to decrease), for alcoholic drinks we used calculated ethanol intake. After including these FBDG-based variables in the model, we subsequently identified and added nutrients that needed to be safeguarded. These were defined as nutrients for which the modelled mean intake was lower than the observed intake and was less than 125% of the reference value for that nutrient (Table 1).

For each observed diet and all dietary components included, the DEA model compares and weighs the multidimensional ratio of “dietary components to increase” to “dietary components to decrease”. As this decision variable is essentially based on ratios, zero intakes are not permitted. Therefore, zero intakes of food groups were replaced by the observed lowest non-zero intake of that food group divided by two [35]. Similar to the calculation of the Nutrient Rich Diet score (NRD) [36, 37], the amount consumed for certain food groups and nutrient intakes was capped if higher intakes were not considered to provide additional health benefits (Table 1). For example, consuming more than 200g fruits per 2000 kcal was considered equally healthy as consuming 200g per 2000 kcal. Furthermore, for food group fish where amounts higher than a certain level of intake are harmful (see Table 1), observed intakes higher than this level were also replaced by the lowest observed non-zero intake divided by two; this gives these diets a low likelihood for inclusion as a benchmark.

Modelled diets and trade-offs

For each inefficient diet in the observed data, an alternative healthier diet was modelled as a linear combination of the existing efficient diets (the benchmarks). However, by taking different linear combinations, more options for dietary improvement were explored, i.e. trade-offs of dietary preferences against nutrient quality and environmental sustainability. All modelled diets had improved adherence to FBDGs and had either the least deviation from the observed diet (MaxP, for the most preferred diet), the highest nutrient quality (MaxH, for the healthiest diet), or the lowest environmental impact (MaxS, for the most environmentally sustainable diet). Modelled diets were compared with observed diets for dietary preferences, nutrient quality, environmental impact, and food and nutrient composition.

To characterise dietary preferences, we used the minimum deviation (MINDV) approach [11], which minimises the sum of positive and negative deviations (absolute values) of food group intake from the observed diet. For interpretation purposes, we used a so-called diet similarity index, as simple description of the overall similarity between observed and alternative healthier diet. For each individual, this diet similarity index was calculated as the summed amount of each food group that remains the same in the modelled diet as compared to the observed diet divided by total diet weight of the observed diet. To characterise nutrient quality and environmental sustainability of the diet, we used NRD15.3 [36, 37] and GHGE respectively. NRD15.3 is the unweighted sum of percentage daily values for fifteen nutrients to encourage (protein, mono-unsaturated fatty acids, dietary fibre, calcium, iron, potassium, zinc, vitamin A, D, E, C, B1, B2, B12, and folate) minus the sum of percentage maximum recommended values for three nutrients to limit (saturated fat, added sugar and sodium), calculated per 2500 kcal for men and 2000 kcal for women and capped at 100% of the dietary value. Because of slight between-country differences in the definition of sodium and added sugar, the NRD15.3 was not entirely comparable between the countries. Therefore, we expressed the results relative to the observed diet, in strata of country and gender, and calculated averages by country. The trade-offs were done by first giving full weight to dietary preferences in the MaxP model (i.e. minimum deviation form observed diet), followed by stepwise increasing the weight for either nutrient quality or environmental sustainability by 10%, and calculating the alternative diet after each step until full weight was given to either nutrient quality (MaxH) or environmental sustainability (MaxS).

RESULTS

Identification of efficient diets

Table 2 shows the general characteristics of subjects in the study sample and those with efficient diets. The proportion of subjects with an efficient diet varied from 23% (Italian women) to 45% (Czech women). General characteristics were similar to the overall sample for age, educational level and overweight.

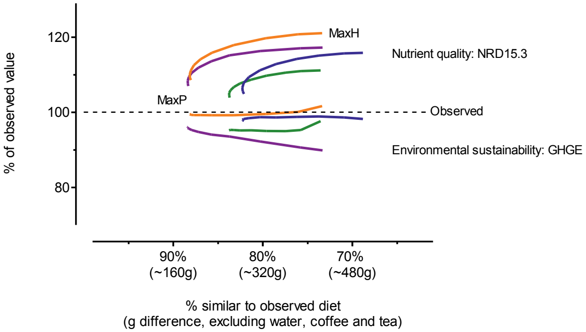
Table 2 General characteristics of the study sample and of the subjects with an identified healthier diet [a]

	Denmark (n = 1385)		**Czech Republic (n = 1386)**		**Italy (n = 1978)**		**France (n = 1713)**	
	Men (n=619)	Women (n=766)	Men (n=671)	Women (n=715)	Men (n=898)	Women (n=1080)	Men (n=713)	Women (n=1000)
N efficient diets	229 (37%)	240 (31%)	258 (39%)	324 (45%)	272 (28%)	245 (23%)	270 (38%)	281 (28%)
Age, years								
In total	44 (34; 55)	42 (32; 53)	43 (31; 54)	47 (32; 56)	44 (32; 54)	43 (32; 54)	45 (34; 54)	42 (32; 52)
In efficient diets	48 (37; 56)	45 (35; 56)	43 (31; 54)	48 (32; 56)	47 (35; 56)	44 (35; 56)	48 (37; 57)	46 (35; 54)
Low educational level								
In total	15%	11%	21%	22%	31% [b]	24% [b]	45% [c]	41% [c]
In efficient diets	12%	10%	16%	19%	22%	28%	44%	42%
Overweight,BMI≥25kg/m^2								
In total	50%	32%	58%	44%	45%	24%	45%	28%
In efficient diets	44%	29%	58%	43%	47%	26%	45%	26%

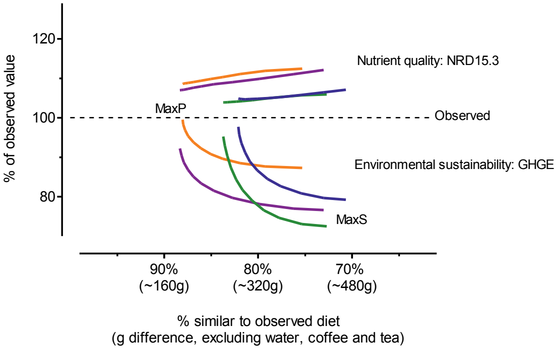
[a] Values are median and interquartile range, and percentage. [b] Data available for 851 men and 1028 women. [c] Data available for 711 men and 999 women.

Trade-off of dietary preferences against nutrient quality and environmental sustainability

Figure 1 shows the trade-off of dietary preferences against nutrient quality (1A) and environmental sustainability of the diet (1B), for all four countries, averaged for men and women. Of course, the MaxP diet remained closest to the observed diet (diet similarity index on average 85%) as compared to the MaxH diet and the MaxS diet (diet similarity index on average 72 and 73% respectively). Because of the FBDG-based modelling, the MaxP diet had already a 4-9% higher NRD15.3, whereas GHGE was only 0.5-5% lower than the observed country-specific diets. For the maxH diet, nutrient quality was increased at the expense of diet similarity and the NRD15.3 became 11-20% higher (Figure 1A). The GHGE of this diet was not sensitive to this trade-off except in Denmark where this lowered to about 10%. For the trade-off of environmental sustainability against dietary preferences (Figure 1B), the MaxS diet had a 13-28% lower GHGE, and the NRD15.3 appeared sensitive to this trade-off and became 6-12% higher. The shape of the trade-off curves for nutrient quality and environmental sustainability shows that the largest gains occurred in the first part of the curve, and were attenuated thereafter. Moreover, the maxH diet did only marginally affect GHGE and the maxS diet did reach only half the maximum for nutrient quality, indicating a trade-off between these objectives.



1A: Trade-off between dietary preferences and nutrient quality



1B: Trade-off between dietary preferences and environmental sustainability

Figure 1 Trade-offs of dietary preferences[a] against nutrient quality[b] (3A) and environmental sustainability of the diet[c] (3B).

— Denmark
— Czech Republic
— Italy
— France

[a] Dietary preferences were expressed as the diet similarity index, i.e. weight of foods in the modelled diet that corresponds to the observed diet, as a percentage of the latter. Total observed food weight (excluding water, coffee and tea) was around 1800g/2500kcal for men and around 1450g/2000kcal for women, respectively.

[b] Nutrient quality was calculated as NRD15.3 and expressed relative to its observed value for each population group (as %); observed NRD15.3 was 938 for Denmark, 812 for Czech Republic, 977 for Italy, and 831 for France.

[c] Environmental sustainability of the diet used GHGE as indicator and is expressed relative to its observed value (as %); observed GHGE in kgCO2eq/2,000kcal was 4.85 for Denmark, 4.42 for Czech Republic, 4.88 for Italy, and 6.08 for France.

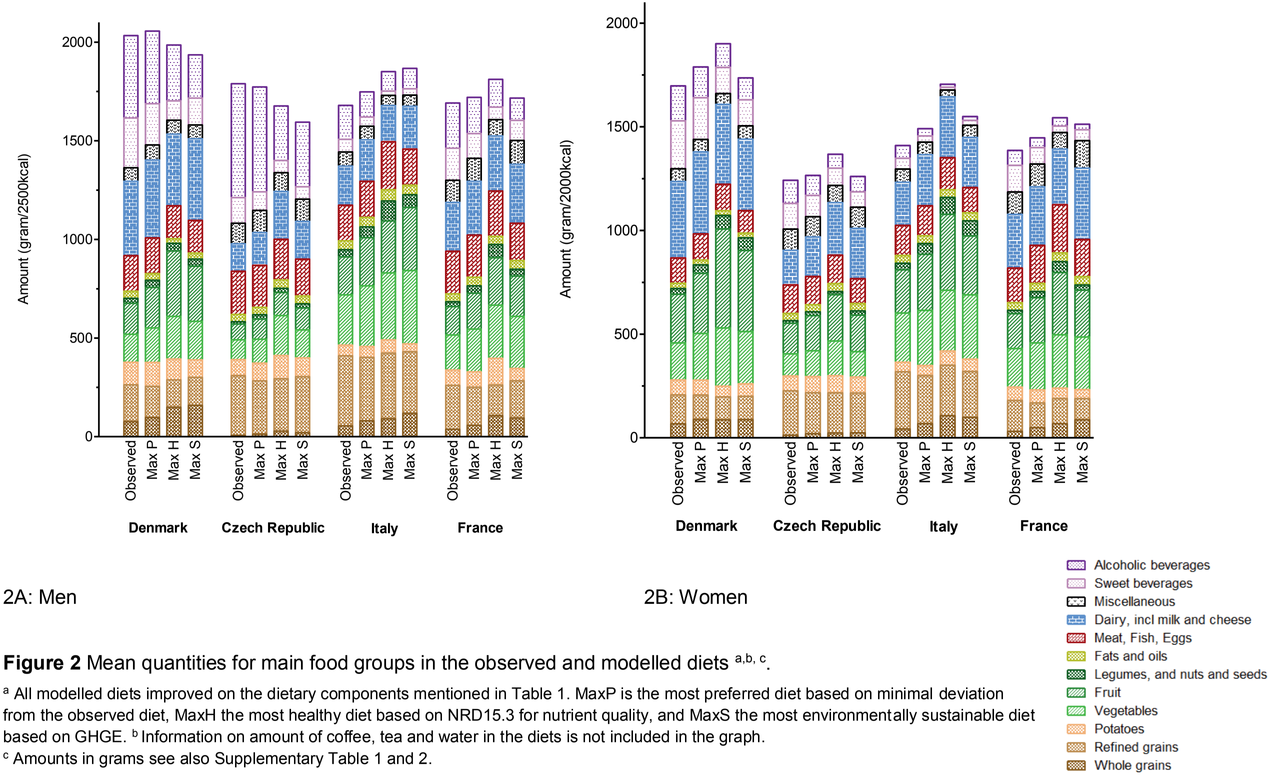
Food composition of observed and modelled diets

Figure 2 presents the total weight of the diet and the amounts consumed for each main food group, for the observed and modelled diets

In all countries, and for both genders, total weight of foods in the diet (including dairy, excluding coffee, tea, water, sweet and alcoholic beverages) was higher for the modelled diets. For the MaxP diet, this amounted to a higher diet weight of 65-130g/2500kcal (6-9% increase) for men and of 60-140g/2000kcal (6-11%) for women, followed by the MaxS diet where diet weight was around 122-288g/2500kcal (11-20%) higher for men and 106-248g/2000kcal (11-21%) higher for women, as compared to observed. The MaxH diet had the highest amount of foods, which was around 240-310g/2500kcal (18-24%) higher for men and 211-380g/2000kcal (20-29%) higher for women, as compared with the observed diet. For drinks (excluding water, coffee and tea), all models showed that alcoholic beverages and sweet drinks had to be substantially reduced, especially for the maxH and maxS diets among men (43 to 52% reduction).

Despite the higher food consumption, for all modelled diets the proportion of animal-sourced foods remained similar to the observed diets, i.e. approximately 35% of total weight (including dairy, excluding water, coffee and tea), but there were shifts within the animal and plant sourced food groups. Most marked were differences for the food groups that were incorporated in the model. The total amount of animal-sourced foods was higher in most modelled diets, except for MaxH in Danish men and MaxS in Danish women (Figure 3). The amount of meat from beef and pork was, however, lower in all modelled diets. The amount of poultry remained roughly similar, but amounts of fish, eggs and total dairy were higher in most of the modelled diets. Total dairy products (including cheese) were not entered in the model, and amounts slightly either de/increased (-8% to +74%) depending on the model and population subgroup. Taken together, for the MaxP diet, animal-sourced foods were on average 25g higher for men (+5%) and 40g higher for women (+8%) as compared with animal-sourced foods in the observed diet. Amounts were even higher for the MaxH diet for men (up to 60g (+16%); except for Danish men) and for the MaxS diet for Czech and French women (up to 79g (+21%)).

The total amount of plant-sourced food was also higher in all modelled diets (11%-36%). Especially, vegetables (+36%), fruits (+49%), legumes (+91%), and whole grains (+103%) increased, whereas refined grains decreased (-16%), and was the most clearly seen for the MaxH diet and the MaxS diet. The amount of nuts and seeds was only slightly higher than observed.



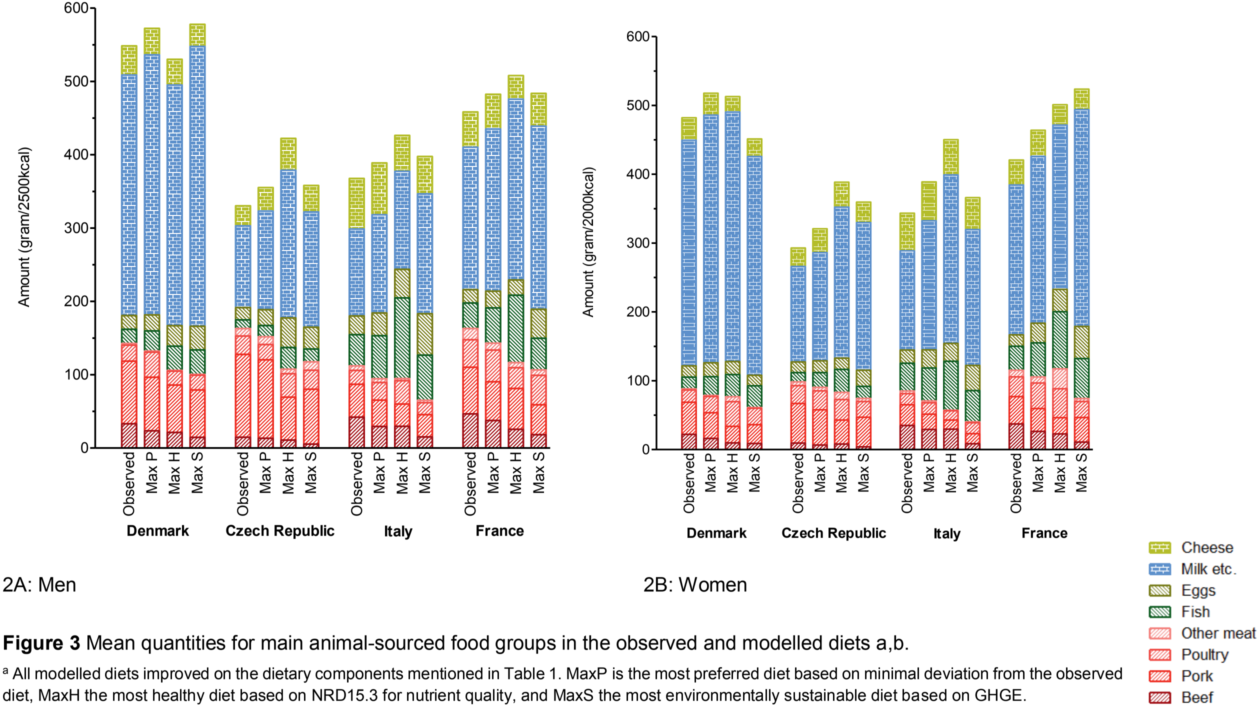
2A: Men

2B: Women

Figure 2 Mean quantities for main food groups in the observed and modelled diets [a,b, c].

[a] All modelled diets improved on the dietary components mentioned in Table 1. MaxP is the most preferred diet based on minimal deviation from the observed diet, MaxH the most healthy diet based on NRD15.3 for nutrient quality, and MaxS the most environmentally sustainable diet based on GHGE. [b] Information on amount of coffee, tea and water in the diets is not included in the graph.

[c] Amounts in grams see also Supplementary Table 1 and 2.



2A: Men

2B: Women

Figure 3 Mean quantities for main animal-sourced food groups in the observed and modelled diets a,b.

[a] All modelled diets improved on the dietary components mentioned in Table 1. MaxP is the most preferred diet based on minimal deviation from the observed diet, MaxH the most healthy diet based on NRD15.3 for nutrient quality, and MaxS the most environmentally sustainable diet based on GHGE.

[b] Amounts in grams see also Supplementary Table 1 and 2.

Results of the modelled diets differed by country and gender and were dependent on the trade-offs between dietary preferences, nutrient quality and environmental sustainability. For most population groups, the MaxH diet had the highest amount of fruit (+60%, except for Italian men), vegetables (+75%, except for Italy), legumes (+132%), and fish (+124%), and the lowest amount of sweet beverages (-60%, except for Czech women), as compared to the other diets. The amount of red and processed meat was lowest for the MaxS diet (-45%), followed by the MaxH diet (-36%), and closest to observed diets for the MaxP diet (-20%) (see Supplementary Table 1 and 2).

Nutrient quality of observed and modelled diets

In the detail for the nutrient quality, the nutrient improvements and/or deficiencies for each nutrient included in the NRD15.3, i.e. a summary measure for nutrient quality, are shown in Supplementary Table 3 and 4. In our data, the three modelled diets alleviated the nutrient inadequacies, but for dietary fibre, potassium, magnesium, vitamin E and vitamin D, the average intakes remained below recommended intake levels, although differences by modelled diet, country and gender. Nutrient inadequacies showed the most improvement for a MaxH diet, and the least for a MaxP diet. Next to nutrient to encourage, the NRD15.3 included three nutrients to limit. Compared to the observed diet, intakes in the modelled diets were improved (i.e. lower) for saturated fat in all four countries, and for added sugar in Denmark and Czech Republic, while intakes remained roughly the same for sodium in all four countries, and for added sugar in Italy and France. A note of caution is due here since sodium and added sugar were differently assessed in the countries. For example, in Italy, only the sodium intake from raw foods is included, which resulted in a sodium intake that is much closer to or even lower than the maximum reference value. In Italy and France, total sugar is assessed which resulted in less change as compared to added sugar that excludes sugars naturally occurring in fruit, vegetables and dairy.

DISCUSSION

This application of the DEA-model to dietary survey data from four European countries (Denmark, Czech Republic, Italy and France) showed that the most preferred diet had a larger impact on nutrient quality (on average 6% higher) than on GHGE (on average 4% lower). The diet with the highest nutrient quality (on average 16% higher NRD15.3), however, did not result in a lower GHGE, whereas the most environmentally sustainable diet (on average 21% less GHGE) had a higher nutrient quality (on average 9% higher NRD15.3) as compared with the observed diet. Although results differed by country and gender, the modelled diets had higher amounts of both plant-sourced and animal-sourced foods, but their relative amounts remained similar. Plant-sourced foods were highest in the diet with the highest nutrient quality, and red and processed meat was lowest in the most environmentally sustainable diet.

The modelled diets account for prevailing dietary preferences in the study populations. This is because the DEA-model preserves the existing interrelationships between food groups as it uses (linear combinations of) observed diets as benchmarks. These observed diets implicitly account for sensory preferences and culinary practices as well as availability, acceptability, and affordability of foods. We stratified our analyses for country and gender under the assumption that subjects in these strata share many unspecified variables, including educational level, overweight status and determinants of food choice. Indeed, the descriptive variables of the efficient diets compared well to the population segments they represent (Table 2). In our data, nutrient quality but not environmental impact of the diet was associated with gender and educational level [16, 38]. Future analyses might, however, also account for educational level or include indicators such as sensory profiles [39, 40] or food prices [41]. Such analyses in a more homogeneous population subgroup could identify solutions for dietary improvement that fit even better with subgroup-specific dietary practices and preferences. This way, DEA keeps the proposed diet realistic as they stay in the range of observed national diets.

To derive the most preferred diet, the DEA-model minimised the absolute value of the deviation between between the modelled and observed food intake, summed over all food groups. Our results suggest that a partial shift to poultry, fish and increased intake of legumes would be more preferred than a sole focus on reducing red and processed meat. Although the algorithm of minimal deviation might improve by using relative or squared differences instead, it is important to consider algorithms that can suggest likely steps to improve the diet, for example based on food replacements within meals and recipes instead of day menus. Although improvements in modelling would be possible, the DEA-model provides a first step to arrive at likely and realistic changes that could guide national policies towards improved dietary quality and environmental sustainability.

Data comparability between the countries was a challenge because food consumption data were obtained from different national dietary surveys. To enhance comparability, we expressed nutrients and GHGE relative to energy intake [16, 26] and used the NRD15.3 as a summary measure for nutrient quality. When the NRD15.3 is used to maximise nutrient quality, then it might be possible that the protein-rich foods, such as fish, eggs, dairy, legumes, and nuts and seeds, are chosen as a meat-replacement, because of the inclusion of protein, vitamins B1, B2 and B12, iron and zinc as nutrients to encourage in the NRD15.3. However, as sodium and added sugar are part of nutrients to limit in the NRD15.3, cross-country comparisons are hampered as they were differently assessed in the countries. We therefore expressed our results relative to the observed diet in each of the strata. For example, in Italy and France, total sugar is assessed which biases the NRD15.3 downwards as compared to Denmark or Czech Republic where added sugar is assessed. This may partially explain that in Italy intakes of fruit, vegetables and whole grains were not the highest for the diet that maximised NRD15.3. In Italy, only sodium intake from raw foods is assessed which biased the NRD15.3 upwards as compared to Denmark, Czech Republic and France where discretionary salt is assessed as well. Furthermore, environmental impact only included GHGE data averaged for the European context, and further refinement to national food systems is needed to incorporate differences between agricultural systems, including the influence of locally produced food and seasonality [42]. Moreover, pan-European standardised indicators of land and fresh water use, nitrogen and phosphorous flows and biodiversity could give a more balanced picture of environmental impact of the diet. Because of these imperfections in comparability of survey data and incompleteness of indicators, the observed and modelled diets differed by country, but the general pattern was similar, both in men and women, suggesting robustness of the findings.

The food consumption data were derived from national dietary surveys, and we used the average of two non-consecutive days for each individual which slightly reduces day-to-day variability [43]. The use of two averaged days for the benchmark diets exploits within- and between-subject variation within the demographic strata and creates a larger window of opportunity for improving diets than time-integrated long term dietary habits. Because part of the diets that is already efficient cannot be improved further, the modelled range of food and nutrient intake and GHGE was slightly lower than in the observed diets. Nevertheless, the range of solutions remained in the same order of magnitude (data not shown), which suggests that the results from the three models are realistic steps for dietary shifts at the population level. At the same time, the use of only two days raises questions on occasionally consumed foods, like fish, nuts and seeds, and legumes. Fish was of particular concern because its recommended consumption frequency is around one to two portions a week to avoid toxicological risks because of contaminants like (methyl)mercury [44]. Using this occasionally consumed high portion size of fish as a benchmark for an average diet, would allow the whole population to shift to these high intakes that are not representative for an usual day. This was tackled by capping fish intake at 1/7th of one portion, and by replacing upper intake levels by a lowest non-zero intake divided by two; the former was to not favour higher intakes than recommended, and to latter to put extreme upper intakes at a disadvantage, while benchmarking diets. Because of their small portion sizes and infrequent consumption, legumes, and nuts and seeds did not increase substantially in our diets. In other studies, food-based linear programming approaches have shown that these food groups can contribute to healthy and environmentally sustainable diet [45-47], as is also suggested by the healthy reference diet presented by the EAT-*Lancet* Commission [48]. Targeted efforts and/or product development would therefore be warranted to increase consumption of some foods beyond current national eating habits.

Results of our analyses depend on the choice of variables included in the model. In our modelling strategy, we aimed for diets that would increase adherence to FBDGs that are considered relevant to non-communicable disease risk (factor). After all, a healthy diet not only implies meeting food-based dietary guidelines, but also includes nutrient requirements, non-nutrients, bio-actives and direct physiological effects on hunger, digestion and satiation. Because of the underlying nutritional rationale, we replaced the guideline “use oils instead of hard fats” by unsaturated and saturated fats as “to increase” and “to decrease”, respectively. In all population groups the modelled diets performed the same or better for all nutrients, except in women from the Czech Republic. In these women, a substantial decrease in animal-sourced foods occurred which lowered intake of calcium, zinc, vitamin B2 and vitamin B12 (results not shown). To safeguard the intake of these nutrients, they were added to the DEA-model. Nevertheless, it must be realised that the modelled diets are based on calculated nutrient intake from dietary surveys, that do not account for bioavailability. We observed that the proportion of animal-sourced foods and the daily protein intake in modelled diets was essentially similar to observed diets.

However, bioavailability of protein and some minerals from plant-sourced foods is less than from animal-sourced foods, warranting physiological research into nutrients that can become critical for vulnerable population groups. For example, some plant compounds can inhibit the absorption of minerals, such as calcium, zinc and non-haem iron [49, 50], whereas vitamin C may increase the bioavailability from iron from plant foods [49].

In line with previous studies [47, 51-55], changing to a healthier diet implies higher amounts of fruits, vegetables and whole grains, whereas an environmentally sustainable diet implies an emphasis on lowering red and processed meat; legumes, nuts and seeds increased only mildly. Dairy products essentially remained in the diet, although results differed slightly by country and gender. Nevertheless the proportion of animal- and plant-sourced food in the modelled diets remained similar, but nutrient quality (NRD15.3) increased. Surprisingly, the total amount of foods (including dairy) increased by 5 to 30% for the modelled diets, most for the healthiest diet, and thus the overall energy density for these food groups decreased accordingly. At the same time, we observed that the modelled more healthy and environmentally sustainable diets had lower amounts of sweet and alcoholic beverages (especially in men), which might be implicated in improved weight control [56]. Earlier we have shown that – independent of nutrient quality – lowering BMI by circa 10% by reducing energy intake would reduce GHGE by circa 5% [38]. As overconsumption is a major driver of obesity [57, 58], these results suggest that the modelled diets not only help to improve nutrient quality and environmental sustainability, but also reduce energy density and contribute to a healthier body weight. These results show that at the national level important first steps can be made in nutritional policy, but the priorities will differently affect nutrient quality and environmental sustainability. However, on average, the proposed diets do not achieve the proposed global targets for healthy and environmentally sustainable diets and additional policy measures are warranted.

CONCLUSION

The DEA benchmarking diet model shows that generally accepted FBDGs and nutrient requirements can be used to model more healthy and environmentally sustainable diets based on dietary surveys from a set of diverse European diets. While improving the adherence to FBDGs, the most environmentally sustainable diet resulted in a win-win for both health and the environment, but did not reach the full health potential; focusing on health alone did not improve GHGE. For larger improvements in nutrient quality or environmental sustainability, larger dietary changes and/or complementary measures in agricultural production and processing [59], food loss and waste management, as well as an equitable distribution via the food supply chain [60] are required.

Funding

This work was supported by the European Union’s H2020 Programme under Grant Agreement number 633692 (SUSFANS: Metrics, models and foresight for European sustainable food and nutrition security); and TiFN under Project Agreement number 15SD01 (SHARP-BASIC). A. Kuijsten, J.M. Geleijnse, and PvtV received research funding from TiFN (grant 15SD01_SHARP).

REFERENCES

1. Forouzanfar MH, Alexander L, Anderson HR, Bachman VF, Biryukov S, Brauer M, Burnett R, Casey D, Coates MM, Cohen A: **Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013**. *The Lancet* 2015, **386**(10010):2287-2323.
2. Vermeulen SJ, Campbell BM, Ingram JSI: **Climate Change and Food Systems**. *Annu Rev Environ Resour* 2012, **37**:195.
3. Tubiello F, Salvatore M, Cóndor Golec R, Ferrara A, Rossi S, Biancalani R, Federici S, Jacobs H, Flammini A: **Agriculture, forestry and other land use emissions by sources and removals by sinks**. *Statistics Division, Food and Agriculture Organization, Rome* 2014.
4. Steinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M, de Haan C: **Livestock’s long shadow**. *Environmental issues and options FAO, Rome* 2007.
5. Buttriss JL, Briend A, Darmon N, Ferguson EL, Maillot M, Lluch A: **Diet modelling: How it can inform the development of dietary recommendations and public health policy**. *Nutrition Bulletin* 2014, **39**(1):115-125.
6. Gazan R, Brouzes CMC, Vieux F, Maillot M, Lluch A, Darmon N: **Mathematical Optimization to Explore Tomorrow's Sustainable Diets: A Narrative Review**. *Adv Nutr* 2018, **9**(5):602-616.
7. Dantzig GB: **The Diet Problem**. *INFORMS Journal on Applied Analytics* 1990, **20**(4):43-47.
8. van Dooren C: **A Review of the Use of Linear Programming to Optimize Diets, Nutritiously, Economically and Environmentally**. *Frontiers in nutrition* 2018, **5**:48-48.
9. Mertens E, van’t Veer P, Hiddink GJ, Steijns JM, Kuijsten A: **Operationalising the health aspects of sustainable diets: a review**. *Public health nutrition* 2017, **20**(4):739-757.
10. Smith VE: **Linear Programming Models for the Determination of Palatable Human Diets**. *American Journal of Agricultural Economics* 1959, **41**(2):272-283.
11. Kanellopoulos A, Gerdessen J, Ivancic A, van 't Veer P, Geleijnse JM, Bloemhof JM: **Designing Healthier and Acceptable Diets Using Data Envelopment Analysis**. *Public Health Nutr* 2019.
12. Pedersen A, Fagt, S., Groth, MV., Christensen, T., Biltoft-Jensen, A., Matthiessen, J., Andersen, NL., Kørup, K., Hartkopp, H., Ygil, K., Hinsch, HJ., Saxholt, E., Trolle, E. : **Danskernes kostvaner 2003-2008**. In.: DTU Fødevareinstituttet; 2009.
13. **Individual food consumption - the national study SISP04** [http://www.chpr.szu.cz/spotrebapotravin.htm]
14. Leclercq C AD, Piccinelli R, Sette S, Le Donne C and Turrini A: **The Italian national food consumption survey INRAN-SCAI 2005-06: main results in terms of food consumption**. *Publ Health Nutr* 2009, **12(12)**:2504 - 2532.
15. Agence Française de Sécurité Sanitaire des Aliments (AFSSA): **Report of the 2006/2007 Individual and National Study on Food Consumption 2 (INCA 2). Synthèse de l'étude individuelle nationale des consommations alimentaires 2 (INCA 2), 2006-2007**. In.; 2009: 1-44.
16. Mertens E, Kuijsten A, Dofkova M, Mistura L, D'Addezio L, Turrini A, Dubuisson C, Favret S, Havard S, Trolle E *et al*: **Geographic and socioeconomic diversity of food and nutrient intakes: a comparison of four European countries**. *Eur J Nutr* 2018.
17. EFSA (European Food Safety Authority): **The food classification and description system FoodEx2 (revision 2)**. *EFSA supporting publication 2015* 2015, **En-804**:90.
18. EFSA (European Food Safety Authority): **Use of the EFSA Comprehensive European Food Consumption Database in Exposure Assessment**. *EFSA Journal 2011* 2011, **9**(9):2097.
19. Møller A SE, Christensen AT, Hartkopp H. : **Fødevaredatabanken version 6.0**. In., 2005 edn. Afdeling for Ernæring, Danmarks: Fødevareinformatik; 2005.
20. Saxholt E, Christensen, A.T., Møller, A., Hartkopp, H.B., Hess Ygil, K., Hels, O.H.: **Fødevaredatabanken, version 7**. In., 2008 edn. Afdeling for Ernæring, Fødevareinstituttet, Danmarks Tekniske Universitet: Fødevareinformatik; 2008.

21. Czech Centre for Food Composition Database: **Czech Food Composition Database Version 6.16**. In. Prague, Czech Republic: Institute of Agricultural Economics and Information,; 2016.
22. Food Research Institute: **Slovak Food Composition Data Bank**. In. Bratislava, Slovak Republic: Department of Risk Assessment Food Composition Data Bank and Consumer's Survey VUP Food Research Institute,; 2016.
23. Istituto Nazionale di Ricerca per gli Alimenti e la Nutrizione (INRAN): **Banca Dati di Composizione degli Alimenti** In. Roma, Italy: Istituto Nazionale di Ricerca per gli Alimenti e la Nutrizione,; 2016.
24. Feinberg M FJ-CLC: **Répertoire général des aliments (General Inventory of Foods)**. In. Paris: Institut national de la recherche agronomique: Technique & Documentation - Lavoisier.; 1995.
25. Ireland J dCL, Oseredczuk M, et al **French Food Composition Table, version 2008**. In.: French Food Safety Agency (AFSSA); 2008.
26. Mertens E, Kuijsten A, van Zanten HHE, Kaptijn G, Dofková M, Mistura L, D'Addezio L, Turrini A, Dubuisson C, Havard S *et al*: **Dietary choices and environmental impact in four European countries**. *Journal of Cleaner Production* 2019, **237**:117827.
27. Willett WC, Howe GR, Kushi LH: **Adjustment for total energy intake in epidemiologic studies**. *The American journal of clinical nutrition* 1997, **65**(4):1220S-1228S.
28. Goldberg G, Black A, Jebb S, Cole T, Murgatroyd P, Coward W, Prentice A: **Critical evaluation of energy intake data using fundamental principles of energy physiology: 1. Derivation of cut-off limits to identify under-recording**. *Eur J Clin Nutr* 1991, **45**(12):569-581.
29. Black AE: **Critical evaluation of energy intake using the Goldberg cut-off for energy intake: basal metabolic rate. A practical guide to its calculation, use and limitations**. *Int J Obes Relat Metab Disord* 2000, **24**(9).
30. Cooper WW, Seiford LM, Kaoru T: **Data Envelopment Analysis**: Springer; 2007.
31. Forouzanfar MH, Alexander L, Anderson HR, Bachman VF, Biryukov S, Brauer M, Burnett R, Casey D, Coates MM, Cohen A *et al*: **Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013**. *The Lancet* 2015, **386**(10010):2287-2323.
32. Kromhout D, Spaaij CJ, de Goede J, Weggemans RM: **The 2015 Dutch food-based dietary guidelines**. *Eur J Clin Nutr* 2016, **70**(8):869-878.
33. EFSA (European Food Safety Authority): **Dietary Reference Values for nutrients: Summary report**. *EFSA supporting publication* 2017, **2017:e15121**:92 pp.
34. EFSA (Eurepean Food Safety Authority): **Statement on the benefits of fish/seafood consumption compared to the risks of methylmercury in fish/seafood**. *EFSA Journal* 2015, **13**(1):3982.
35. Zhu J, Cook WD: **Modeling data irregularities and structural complexities in data envelopment analysis**: Springer Science & Business Media; 2007.
36. Fulgoni VL, 3rd, Keast DR, Drewnowski A: **Development and validation of the nutrient-rich foods index: a tool to measure nutritional quality of foods**. *J Nutr* 2009, **139**(8):1549-1554.
37. Drewnowski A: **Defining nutrient density: development and validation of the nutrient rich foods index**. *J Am Coll Nutr* 2009, **28**(4):421S-426S.
38. Mertens E, Kuijsten A, van Zanten HHE, Kaptijn G, Dofkova M, Mistura L, D'Addezio L, Turrini A, Dubuisson C, Favret S *et al*: **Dietary choices and environmental impact in four European countries**. *Journal of Cleaner Production* 2019 [submitted].
39. van Langeveld AWB, Teo PS, de Vries JHM, Feskens EJM, de Graaf C, Mars M: **Dietary taste patterns by sex and weight status in the Netherlands**. *The British journal of nutrition* 2018, **119**(10):1195-1206.
40. van Bussel LM, Kuijsten A, Mars M, Feskens EJM, van 't Veer P: **Taste profiles of diets high and low in environmental sustainability and health**. *Food Quality and Preference* 2019, **78**:103730.
41. Wilson N, Nghiem N, Mhurchu C, Eyles H, Baker M, Blakely T: **Foods and dietary patterns that are healthy, low-cost, and environmentally sustainable: a case study of optimization modeling for New Zealand**. *PLoS One* 2013, **121**(21):2271 - 2283.

42. Notarnicola B, Sala S, Anton A, McLaren SJ, Saouter E, Sonesson U: **The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges**. *Journal of Cleaner Production* 2017, **140**:399-409.
43. Willett W: **Nutritional epidemiology**, vol. 40: Oxford University Press; 2012.
44. EFSA (European Food Safety Authority): **Statement on the benefits of fish/seafood consumption compared to the risks of methylmercury in fish/seafood**. *EFSA Journal* 2015, **13**(1):3982.
45. Maillot M, Vieux F, Amiot MJ, Darmon N: **Individual diet modeling translates nutrient recommendations into realistic and individual-specific food choices**. *Am J Clin Nutr* 2010, **91**(2):421-430.
46. Tyszler M, Kramer G, Blonk H: **Just eating healthier is not enoug: studying the environmental impact of different diet scenarios for the Netherlands by linear programming**. In: *9th International Conference LCA of Foods: 2014; San Francisco, USA*; 2014.
47. Green R, Milner J, Dangour AD, Haines A, Chalabi Z, Markandya A, Spadaro J, Wilkinson P: **The potential to reduce greenhouse gas emissions in the UK through healthy and realistic dietary change**. *Climatic Change* 2015, **129**(1):253-265.
48. Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A *et al*: **Food in the Anthropocene: the EAT-*Lancet* Commission on healthy diets from sustainable food systems**. *The Lancet* 2019, **393**(10170):447-492.
49. American Dietetic Association: **Position of the American Dietetic Association: Vegetarian Diets**. *Journal of the American Dietetic Association* 2009, **109**(7):1266-1282.
50. Gibson RS, Bailey KB, Gibbs M, Ferguson EL: **A review of phytate, iron, zinc, and calcium concentrations in plant-based complementary foods used in low-income countries and implications for bioavailability**. *Food and nutrition bulletin* 2010, **31**(2 Suppl):S134-146.
51. Macdiarmid JI, Kyle J, Horgan GW, Loe J, Fyfe C, Johnstone A, McNeill G: **Sustainable diets for the future: Can we contribute to reducing greenhouse gas emissions by eating a healthy diet?** *Am J Clin Nutr* 2012, **96**(3):632-639.
52. Horgan GW, Perrin A, Whybrow S, Macdiarmid JI: **Achieving dietary recommendations and reducing greenhouse gas emissions: modelling diets to minimise the change from current intakes**. *The international journal of behavioral nutrition and physical activity* 2016, **13**:46.
53. Vieux F, Perignon M, Gazan R, Darmon N: **Dietary changes needed to improve diet sustainability: are they similar across Europe?** *Eur J Clin Nutr* 2018, **72**(7):951-960.
54. Perignon M, Masset G, Ferrari G, Barre T, Vieux F, Maillot M, Amiot MJ, Darmon N: **How low can dietary greenhouse gas emissions be reduced without impairing nutritional adequacy, affordability and acceptability of the diet? A modelling study to guide sustainable food choices**. *Public Health Nutr* 2016, **19**(14):2662-2674.
55. Kramer GF, Tyszler M, Veer PV, Blonk H: **Decreasing the overall environmental impact of the Dutch diet: how to find healthy and sustainable diets with limited changes**. *Public health nutrition* 2017, **20**(9):1699-1709.
56. Poppitt SD: **Beverage Consumption: Are Alcoholic and Sugary Drinks Tipping the Balance towards Overweight and Obesity?** *Nutrients* 2015, **7**(8):6700-6718.
57. Rolls BJ: **The relationship between dietary energy density and energy intake**. *Physiology & behavior* 2009, **97**(5):609-615.
58. Vernarelli JA, Mitchell DC, Rolls BJ, Hartman TJ: **Dietary energy density and obesity: how consumption patterns differ by body weight status**. *European journal of nutrition* 2018, **57**(1):351-361.
59. Van Zanten HHE, Van Ittersum MK, De Boer IJM: **The role of farm animals in a circular food system**. *Global Food Security* 2019, **21**:18-22.
60. Rutten M, Achterbosch TJ, de Boer IJ, Cuaresma JC, Geleijnse JM, Havlík P, Heckelei T, Ingram J, Leip A, Marette S: **Metrics, models and foresight for European sustainable food and nutrition security: the vision of the SUSFANS project**. *Agricultural Systems* 2016.

SUPPLEMENTARY MATERIALS

Supplementary Table 1 Amount of foods by food group for the observed and modelled diets in men (g/2500kcal)

	Denmark				Czech Republic				Italy				France			
	Obs	MaxP	MaxH	MaxS	Obs	MaxP	MaxH	MaxS	Obs	MaxP	MaxH	MaxS	Obs	MaxP	MaxH	MaxS
Solid foods	1388	1515	1643	1616	1094	1169	1359	1235	1480	1629	1832	1797	1324	1448	1674	1536
Whole grains	77	98	150	159	7	13	28	20	55	80	91	119	37	58	107	95
Refined grains	186	158	138	142	302	270	265	284	355	322	333	311	223	193	155	189
Potatoes	114	121	106	89	81	90	118	95	55	55	67	40	78	78	135	62
Vegetables	142	175	216	196	101	121	202	142	255	308	340	372	178	217	270	264
Fruit	157	206	332	279	80	103	117	111	193	245	263	320	144	182	240	205
Legumes, nuts, seeds	25	36	39	36	11	22	21	21	36	55	102	64	24	38	67	34
Legumes	23	31	34	32	8	14	15	14	35	52	100	62	21	33	64	30
Nuts and seeds	3	5	5	4	4	7	6	8	1	2	2	1	3	5	4	4
Total dairy	377	394	364	414	140	166	243	192	198	210	183	217	248	273	279	299
Dairy	337	358	329	384	112	134	199	156	130	140	134	166	200	226	247	255
Cheese	40	36	35	30	27	32	43	36	69	71	49	51	48	47	32	45
Meat/Fish/Eggs	181	181	167	166	219	213	206	186	181	184	244	183	216	214	229	189
Meat	143	132	106	100	190	176	136	139	112	94	95	65	163	143	117	107
Red, processed meat	121	98	87	80	160	146	82	94	90	65	60	45	123	97	88	66
Beef	33	24	21	15	15	13	11	6	42	30	30	15	47	38	26	18
Pork	85	73	65	65	113	107	58	75	45	36	30	31	64	53	56	41
Other meat	2	2	1	1	10	11	6	12	6	5	3	3	15	9	7	7
Poultry	22	34	19	20	25	21	32	26	19	24	32	16	38	43	28	40
Fish	19	28	33	34	12	15	30	17	43	59	110	62	35	48	92	43
Eggs	19	22	28	32	17	22	40	30	26	31	39	56	18	23	21	39
Fats and oils	36	34	23	31	37	37	43	40	45	47	57	49	40	44	42	44
Soft fats and oils	3	3	3	4	17	21	29	27	41	45	54	48	19	23	25	24
Hard fats and butter	34	31	21	27	20	16	14	13	4	2	3	1	21	20	17	20
Miscellaneous	68	76	70	70	104	112	95	123	72	69	52	58	111	116	83	121
Drinks	2397	2486	2277	2113	1620	1612	1752	1472	1066	1098	1103	1236	1635	1699	2307	1582
Coffee, tea and water	1727	1908	1895	1758	913	986	1413	1082	830	924	983	1101	1243	1390	2102	1367
Sweet beverages	253	210	98	136	130	94	63	63	64	47	22	32	163	126	64	102
Alcoholic beverages	417	368	284	219	578	531	276	327	172	127	99	103	229	183	141	113
Total	3760	3964	3881	3693	2702	2758	3090	2686	2510	2672	2833	2970	2935	3110	3914	3084

Supplementary Table 2 Amount of foods by food group for the observed and modelled diets in women (g/2000kcal)

	Denmark				Czech Republic				Italy				France			
	Obs	MaxP	MaxH	MaxS	Obs	MaxP	MaxH	MaxS	Obs	MaxP	MaxH	MaxS	Obs	MaxP	MaxH	MaxS
Solid foods	1325	1480	1725	1565	1018	1084	1232	1132	1327	1477	1758	1581	1202	1349	1497	1486
Whole grains	67	88	87	88	12	20	23	24	42	68	107	99	31	49	68	87
Refined grains	140	117	110	112	215	198	194	191	276	232	244	221	149	119	121	102
Potatoes	71	72	51	60	71	78	82	77	46	49	68	59	64	63	50	44
Vegetables	180	226	281	252	107	125	168	123	238	266	293	310	186	227	258	254
Fruit	235	290	477	391	147	170	224	176	208	270	366	284	168	218	300	226
Legumes, nuts, seeds	27	41	66	60	12	18	15	20	31	52	81	73	16	29	53	24
Legumes	24	34	54	52	9	14	12	14	30	48	79	72	14	26	21	49
Nuts and seeds	4	7	12	8	3	4	3	6	1	4	3	1	2	3	3	3
Total dairy	369	396	386	345	167	191	253	242	208	246	294	242	259	283	268	344
Dairy	336	364	363	319	140	156	217	213	153	190	242	195	223	245	238	315
Cheese	33	32	23	26	27	35	36	30	55	57	51	47	36	38	30	30
Meat/Fish/Eggs	122	126	128	108	138	136	137	120	145	145	154	122	167	183	233	179
Meat	88	79	77	61	109	98	88	79	85	71	57	40	115	106	118	74
Red, processed meat	70	55	41	37	81	70	54	57	66	51	41	21	85	63	49	48
Beef	22	16	10	9	10	7	8	4	35	29	30	9	37	26	23	11
Pork	47	37	24	27	58	51	35	43	30	22	13	15	40	33	24	36
Other meat	2	1	7	1	5	5	10	5	4	3	1	1	10	9	29	4
Poultry	18	24	36	24	26	28	30	23	16	17	14	16	29	37	42	23
Fish	17	28	32	32	14	21	34	18	40	48	71	46	35	50	83	58
Eggs	16	20	19	15	16	17	16	23	19	26	26	37	17	28	32	47
Fats and oils	26	23	22	23	35	34	38	36	38	38	38	38	38	40	42	41
Soft fats and oils	2	3	3	4	16	19	22	21	35	36	35	37	19	22	22	22
Hard fats and butter	24	20	19	19	19	15	16	15	3	2	3	1	19	18	20	19
Miscellaneous	61	60	52	64	102	98	83	103	64	61	33	59	108	109	80	133
Drinks	2394	2528	2604	2526	1465	1645	1844	1430	977	995	908	867	1604	1907	1834	1642
Coffee, tea and water	1994	2178	2363	2295	1229	1446	1694	1283	864	930	880	825	1403	1780	1762	1563
Sweet beverages	231	201	127	125	124	103	83	74	52	30	14	24	128	79	31	52
Alcoholic beverages	169	149	114	106	111	96	67	74	61	35	14	18	73	47	40	27
Total	3691	3967	4264	4030	2471	2711	3062	2543	2273	2421	2585	2374	2789	3227	3306	3075

Supplementary Table 3 Evaluation of the environmental and the nutritional health impact under the observed and modelled diets, for men [a,b]

			15 nutrients to encourage as included in the NRD15.3 (+ magnesium)																3 nutrients to limit		
	GHGE	NRD15.3 [a]	MUFA	Protein	Dietary fibre	Calcium	Iron	Potassium	Vitamin A	Vitamin C	Vitamin E	Vitamin D	Zinc	Vitamin B1	Vitamin B2	Vitamin B12	Folates	Magnesium	SFA	Sodium	Added sugar
Denmark																					
Observed	100	100	128	195	89	148	192	106	233	113	59	24	163	191	139	156	133	112	69	61 [b]	117 [c]
MaxP	95	107	128	199	103	152	197	113	258	126	69	28	162	193	143	165	149	120	72	61 [b]	134 [c]
MaxH	88	115	123	197	128	158	209	117	294	137	78	34	164	201	137	161	165	129	84	64 [b]	208 [c]
MaxS	80	111	120	194	125	159	205	111	280	129	78	31	162	203	143	174	160	130	81	66 [b]	129 [c]
Czech Republic																					
Observed	100	100	151	186	72	94	209	73	132	81	105	24	118	182	98	146	95	97	75	45 [b]	151 [c]
MaxP	97	111	149	194	79	111	225	80	179	93	122	29	126	196	110	179	110	105	80	45 [b]	164 [c]
MaxH	94	124	152	208	90	152	245	90	231	117	150	51	135	190	123	171	142	119	85	47 [b]	221 [c]
MaxS	85	116	148	197	85	128	223	81	189	88	141	35	123	192	110	156	119	108	86	47 [b]	168 [c]
Italy																					
Observed	100	100	176	215	82	112	221	96	166	151	110	18	177	162	125	174	155	91	90	107 [b]	70 [c]
MaxP	95	105	175	219	94	123	240	104	233	183	123	22	182	175	141	198	180	97	95	105 [b]	66 [c]
MaxH	95	115	191	237	103	122	253	112	200	200	138	39	190	215	144	193	190	99	105	115 [b]	78 [c]
MaxS	75	106	180	211	105	126	242	111	215	192	133	23	167	155	140	157	202	101	102	102 [b]	65 [c]
France																					
Observed	100	100	134	223	76	132	252	93	226	102	86	18	165	188	161	162	121	92	66	70 [b]	61 [c]
MaxP	97	106	130	228	84	145	261	97	222	109	109	21	162	193	165	166	135	98	69	68 [b]	59 [c]
MaxH	100	114	127	243	109	160	303	111	260	129	121	27	159	225	173	255	178	117	76	70 [b]	64 [c]
MaxS	79	106	136	220	92	151	262	95	241	118	115	24	149	215	177	167	153	97	71	65 [b]	56 [c]

Supplementary Table 4 Evaluation of the environmental and the nutritional health impact under the observed and modelled diets, for women [a,b]

		15 nutrients to encourage as included in the NRD15.3 (+ magnesium)																	3 nutrients to limit		
	GHGE	NRD15.3 [a]	MUFA	Protein	Dietary fibre	Calcium	Iron	Potassium	Vitamin A	Vitamin C	Vitamin E	Vitamin D	Zinc	Vitamin B1	Vitamin B2	Vitamin B12	Folates	Magnesium	SFA	Sodium	Added sugar
Denmark																					
Observed	100	100	119	180	85	145	134	93	208	150	69	21	156	191	116	112	130	112	72	79 [b]	110 [c]
MaxP	97	111	119	193	100	157	143	103	233	172	91	31	162	207	127	132	164	126	78	77 [b]	141 [c]
MaxH	91	120	121	197	123	165	152	117	243	231	123	54	162	217	127	134	211	145	87	87 [b]	189 [c]
MaxS	80	116	117	194	119	159	150	113	217	205	136	41	162	220	118	121	240	141	86	84 [b]	151 [c]
Czech Republic																					
Observed	100	100	148	172	65	97	156	69	156	114	114	20	111	179	87	104	91	97	69	58 [b]	119 [c]
MaxP	102	114	148	182	70	114	173	75	271	133	132	26	117	189	106	151	111	106	73	58 [b]	143 [c]
MaxH	109	121	142	186	79	125	191	82	476	174	143	37	120	182	127	215	133	113	73	58 [b]	174 [c]
MaxS	90	115	150	176	73	118	169	76	311	135	140	23	112	189	114	148	114	104	75	61 [b]	143 [c]
Italy																					
Observed	100	100	180	202	73	102	160	85	181	165	117	17	179	177	113	145	141	89	88	145 [b]	61 [c]
MaxP	95	107	174	212	87	116	194	96	200	204	127	19	170	188	133	158	179	102	95	141 [b]	58 [c]
MaxH	100	112	163	224	107	125	225	114	235	299	139	40	211	212	155	153	220	127	104	152 [b]	58 [c]
MaxS	70	108	170	204	103	113	196	101	216	253	133	18	188	189	133	149	206	115	106	139 [b]	57 [c]
France																					
Observed	100	100	140	206	67	124	177	81	248	125	104	18	160	202	144	139	114	94	63	89 [b]	52 [c]
MaxP	98	109	140	207	76	144	186	89	304	140	130	24	162	220	156	175	133	106	66	88 [b]	51 [c]
MaxH	97	119	141	244	95	138	224	97	346	176	149	44	164	227	160	219	163	115	69	92 [b]	59 [c]
MaxS	79	110	143	211	84	147	172	90	287	137	131	24	151	241	159	159	139	104	69	89 [b]	51 [c]

[a] NRD15.3 - based on the principles of the Nutrient Rich Food Index, NRF [1, 2] - is the unweighted sum of percentage DRV for nutrients to encourage minus the sum of percentage MRV for nutrients to limit, calculated for a 2500-kcal diet for men and a 2000-kcal diet for women and capped at 100%DRV using percentage daily references values (DRV) for nutrients to encourage and percentage maximum recommended values (MRV) for nutrients to limit using DRVs of European Federation of Safety Authority (EFSA) [3], i.e. average requirement (AR) and adequate intake (AI) if AR cannot be set, and MRVs of World Health Organisation [4, 5] and Food and Agriculture Organisation [6].

. NRD15.3 included fifteen nutrients for which intake should be promoted (mono-unsaturated fatty acids (MUFA), protein, dietary fibre, calcium, iron, potassium, zinc, vitamin A, C, E, and D, B1, B2, B12, folates) and three nutrients for which intake should be limited (saturated fatty acids, added sugar and sodium).

[b] In Czech Republic, sodium intake included sodium intake from raw foods and discretionary salt, while in Italy discretionary salt was excluded, and in Denmark and France discretionary salt added at the table was excluded but discretionary salt added during cooking was included when a recipe was reported.

[c] In Denmark and Czech Republic, added sugar intake was calculated as total sugar intake minus the naturally occurring sugars from fruit, vegetables and dairy, while because of data availability total mono-and-disaccharides were used in Italy and France.

References

1. Drewnowski A: **Defining nutrient density: development and validation of the nutrient rich foods index**. *J Am Coll Nutr* 2009, **28**(4):421s-426s.
2. Fulgoni VL, 3rd, Keast DR, Drewnowski A: **Development and validation of the nutrient-rich foods index: a tool to measure nutritional quality of foods**. *J Nutr* 2009, **139**(8):1549-1554.
3. EFSA (European Food Safety Authority): **Dietary Reference Values for nutrients Summary report**. *EFSA Supporting Publications* 2017, **14**(12):e15121.
4. World Health Organisation (WHO): **Guideline: Sodium intake for adults and children.** In: *World Health Organisation (WHO)*. Geneva; 2012.
5. World Health Organisation (WHO): **Guideline: Sugars intake for adults and children**. In: *World Health Organisation (WHO)*. Geneva; 2015.
6. Food and Agriculture Organisation (FAO): **Fats and fatty acids in human nutrition. Report of an expert consultation**. *FAO Food and nutrition paper* 2010, **91**:1-166.

CHAPTER 8

General discussion

This thesis focussed on healthy and environmentally sustainable diets for European consumers. The main aim of this thesis was to develop a methodology for designing the first steps towards more healthy and environmentally sustainable diets that are acceptable for European consumers. First, methodologies for assessing health and environmental sustainability were operationalised (Chapter 2 and Chapter 3). After that, the current status of European diets was assessed in terms of health (Chapter 4) and environmental sustainability (Chapter 5). Finally, options for dietary improvement for European diets that integrate health, environmental sustainability and dietary preferences were identified using a benchmarking diet model (Chapter 6 and Chapter 7).

MAIN FINDINGS

Table 1 gives an overview of the main findings for the three objectives addressed in this thesis.

Objective 1: To operationalise the methodology for assessing health and environmental sustainability of European diets.

Results from the literature review showed that the method of dietary assessment plays a key role in integrating both health and environmental sustainability aspects of the diet (Chapter 2). When using national-level food supply data, the health aspect of the diet usually covers total energy and protein only. This is because the diet is described in a limited number of primary commodities that are available for human consumption. Individual-level dietary data reflect a wide variety of food choices in the consumer domain. These data allow studying diet in relation to health in terms of food groups and nutrient intakes, without directly hampering the linkage with environment impact indicators, using foods as common denominator.

Diet-related environmental impact was assessed using greenhouse gas emissions (GHGE) and/or land use (LU) in most studies (Chapter 2). As for assessment of nutrient and food intakes, environmental impact of the consumer diet was underestimated when using a food frequency questionnaire (FFQ) compared to 24-hour recalls (Chapter 3). In addition, calibration of the FFQ to 24-hour recalls increased the strength of the association with dietary quality. However, independent of the method of dietary assessment, associations between the healthiness and environmental impact of the diet appeared to be dependent on the definition of a healthy diet. In particular, the environmental impact of the diet was lower when adhering to food-based dietary guidelines, but not necessarily when complying with nutrient recommendations (Chapter 3). This highlights the need for an approach in which both foods and nutrients are taken into account to ensure both non-communicable disease risk reduction and nutrient adequacy. In addition, this is in line with the observation in the applied benchmarking diet model (Chapter 7); even when improving diets according to the food-based dietary guidelines, the diet solutions were still different depending on whether nutrient quality or environmental sustainability was maximised.

The complexity of a healthy and environmentally sustainable diet comprises both the amounts of food, energy consumed and the diet composition, i.e. energy-adjusted food and nutrient intakes, and environmental impact. For designing alternative diets, this may be captured in a reproducible and valid way using a diet model (Chapter 2). Such a diet model aims to compose a diet that satisfies objective criteria for a healthy diet, environmental impact and dietary preferences.

As an avenue for future research in designing alternative diets, Chapter 2 proposed the concept of a SHARP diet. This diet not only improves environmental **S**ustainability and nutritional **H**ealth, but also fits with existing food cultures, as reflected in the terms of **A**ffordability, **R**eliability and **P**references.

Table 1 Main findings of this thesis “Towards healthy and environmentally sustainable diets for European consumers”.

Chapter	**Study design**	**Main findings**	**Comments**
OBJECTIVE 1: METHODOLOGICAL ASPECTS OF ASSESSING HEALTH AND ENVIRONMENTAL SUSTAINABILITY OF DIETS			
2	Literature review	49 studies that combined the health and environmental aspects of consumer diets. Five approaches to operationalise the health aspect of the diet were identified: (i) food item replacements; (ii) dietary guidelines; (iii) dietary quality scores; (iv) diet modelling techniques; and (v) diet-related health impact analysis.	In the design of improved diets, current approaches lack to account for dietary preferences in a reproducible and valid way, by implicitly keeping basic interrelationship between foods intact.
3	Validation study	The FFQ underestimates environmental impact when compared to the 24-hour recall. Diet-related environmental impact was inversely associated with a food-based diet score, while associations with a nutrient-based diet score were inconsistent.	Both foods and nutrients need to be taken into account to ensure both non-communicable disease risk reduction and nutrient adequacy.
OBJECTIVE 2: HEALTH AND ENVIRONMENTAL SUSTAINABILITY OF EUROPEAN DIETS [a]			
4	Descriptive analyses	Overweight was the most prevalent in Czech Republic (52%), followed by Denmark (43%) and France (39%), and was the least in Italy (36%). Expressed per 2,000 kcal, in all countries, mean daily intakes were low for legumes (<19g/d), and for nuts and seeds (<15g/d), but high for red and processed meat (>71g/d). Ruminant meat as a proportion of red and processed meat was the lowest in Czech Republic (13%), followed by Denmark (29%), and France (48%), and the highest in Italy (55%).	It is possible to assess diet-related health and environmental sustainability in a comparable way across countries by harmonisation and standardisation of available dietary data and using a common set of reference values for health.
5	Descriptive analyses	A 200-kcal higher total energy intake was associated with a 9% higher daily GHGE and 10% higher daily LU. Expressed per 2,000 kcal, a 5 energy percent (50g/2,000 kcal) higher meat intake was associated with a 10% and a 14% higher GHGE and LU. Ruminant meat was the main contributor, as a 10% higher proportion of ruminant to total meat was associated with a 5% and a 7% higher GHGE and LU.	Addition of e.g. fresh water use, nitrogen and phosphorus flows, biodiversity loss and land-system change, and country-specific LCA data for foods would give a more balanced picture of environmental impact in different countries.

Chapter	Study design	Main findings	Comments
OBJECTIVE 3: DIETARY IMPROVEMENT OPTIONS FOR EUROPEAN DIETS [a]			
6	Description	A benchmarking diet model starts from all observed diets within a population sample and identifies efficient diets, i.e. diets that have the most “dietary components to increase” for the least “dietary components to decrease” as compared to the other diets, or vice versa. Subsequently, this set of existing efficient diets is used to generate linear combinations of diets for dietary improvement of others. The benchmarking diet model thus provides different solutions for an improved diet within the range of observed diets by using peer resemblance. In this way, modelled diets are first steps for dietary improvement and they are assumed to be realistic and feasible for the population under study.	A benchmarking diet model allows for the identification of existing better diets and provides a framework for the improvement of diets. As compared to the food-based diet optimisation model, the advantage of benchmarking diets is that the improved diets are a combination of existing diets, and thus they implicitly account for intrinsic relationships between foods in the diet.
7	Diet modelling	When dietary preferences were prioritised, NRD15.3 was ~6% higher, GHGE was ~4% lower than observed and ~85% of food group intake remained similar to the observed diets. When nutrient quality was prioritised, NRD15.3 was ~16% higher, GHGE was ~3% lower, and ~72% of food group intake remained similar. When environmental sustainability was prioritised, NRD15.3 was ~9% higher, GHGE was ~21% lower, and ~73% of food group intake remained similar.	Maximum solutions for health and environmental sustainability cannot be achieved simultaneously by dietary choices alone.

Abbreviations: FFQ food frequency questionnaire; GHGE greenhouse gas emissions; LCA Life Cycle Analyses; LU land use; NRD nutrient rich diet

[a] Denmark: DANSDA (2005-2008), based on seven-day diet records on consecutive days [1]; Czech Republic: SISP04 (2003-2004), based on two 24-hour recalls spaced over three to five months [2]; Italy: INRAN-SCAI (2005-2006), based on three-day diet records on consecutive days [3]; and France: INCA-2 Study (2006-2007), based on seven-day diet record on consecutive days [4]. For each country, we sampled two non-consecutive days.

Objective 2: To assess European diets in terms of health and environmental sustainability

The assessment of the current status of European diets was based on available individual-level dietary survey data from four European countries, i.e. Denmark, Czech Republic, Italy and France. To enable cross-country comparison, dietary data were harmonised using the FoodEx2 classification system of the European Food Safety Authority (EFSA), and standardised for the number of days and reported energy intakes. Moreover, to assess adherence to food-based dietary guidelines, a common set was constructed using existing guidelines from European countries as a reference (Chapter 4). To assess GHGE and LU of the diet, the *SHARP-Indicator Database (SHARP-ID)* was constructed, i.e. a standardised life cycle assessment (LCA) database for each food consumed, as coded by FoodEx2 (Chapter 5, Appendix).

Results showed that cultural and individual dietary preferences play an important role in dietary choice, resulting in substantial variation among consumers in both nutritional health (Chapter 4) and diet-related environmental impact (Chapter 5). Within countries, the healthiness of a diet varied by age, gender and educational level, but not by overweight status (Chapter 4). These demographics were of minor importance for explaining the environmental impact of the diet across countries (Chapter 5).

One-quarter to half of the populations of the four selected countries were overweight (i.e. BMI ≥ 25 kg/m^2) (Chapter 4). Moreover, the observed variation in daily environmental impact of a consumer diet was mainly explained by the amount of energy consumed (~35%) (Chapter 5). It was estimated that if these overweight subjects would be able to reduce body weight (to a mean BMI of 22.5 kg/m^2) and adapt their energy intake accordingly, then they could reduce their daily GHGE and LU by about 12%.

For food groups, adherence to food-based dietary guidelines was in general low at the population level in all four countries (Chapter 4). Intakes of fruit and vegetables showed considerable geographical variation. Intake of dairy, excluding cheese and butter, was relatively high in Denmark, as was the case for sweet and alcoholic beverages. Italy and France had the highest intake of fish. In all countries, however, intakes were low for legumes, and nuts and seeds. Intake of red and processed meat was high in all countries (84-94g/day).

Intake of red and processed meat contributed to 70-80% of the total meat intake (Chapter 4), comprising mainly of meat from pork in Denmark and Czech Republic, and from beef in Italy and France (Chapter 5). In addition, of all food groups, the intake of total meat – especially the proportion of ruminant meat – explained most of the variation (~15 and 20%, respectively) in the environmental impact of consumer diets (Chapter 5).

For nutrients, inadequate intake of dietary fibre was highly prevalent in all four countries (Chapter 4). Intakes of potassium and folate were the most inadequate in Czech Republic, magnesium in Italy, and vitamin E in Denmark When changing diet composition for improving environmental sustainability, the food group meat, and in particular the proportion of ruminant meat, was the most important. Milk was relatively neutral, while grain products were associated with a lower environmental impact. However, a theoretical shift from meat to plant products resulted in lower intakes of vitamin B2 and B12 (Chapter 5).

Objective 3: To identify dietary improvement options in Europe that integrate health, environmental sustainability and dietary preferences

Dietary improvement options that integrate health and environmental sustainability were identified using a benchmarking diet model (Chapter 6). When benchmarking diets, part of the observed diets were identified as efficient diets, and they were not improved further by the model, but were used as examples for improving the diets of others. In Chapter 7, diets were compared with each other based on an *a priori* defined set of food-based dietary guidelines, and basically they were efficient if the ratio of "dietary components to increase" to "dietary components to decrease" was higher. Modelled diets by definition were more in line with the food-based dietary guidelines and either had the least deviation from the observed diet (*Max P*, for the most preferred diet), the highest nutrient quality (*Max H*, for the healthiest diet), or the lowest environmental impact (*Max S*, for the most environmentally sustainable diet).

An important aspect of the benchmarking diet model is that improved diets are a combination of other existing diets as observed in the population under study, hence population-specific options for dietary improvement. As a visual representation of the results in Chapter 7, Figure 1 summarises the relative improvement on nutrient quality and environmental sustainability for the modelled diets as compared to the observed gender- and country-specific diets. The modelled diets were compared with the observed diet and each other with respect to healthiness (Y-axis; using percentage change in the Nutrient Rich Diet (NRD) score 15.3) and environmental sustainability (X-axis; using percentage change in GHGE). Maximal feasible improvement for nutrient quality was the highest in Czech Republic, followed by Denmark, France and the lowest in Italy; this ranking was related to the ranking on nutrient quality of the observed diets where nutrient quality was the highest in Italy, followed by France, Denmark, and the lowest in Czech Republic (Chapter 4). Ranking of the countries on their maximal feasible improvement for environmental sustainability was, however, not in line with ranking on their observed diet-related environmental impact. Maximal feasible improvement for this was the highest in Italy, followed by Denmark, France and the lowest in Czech Republic. This high reduction potential of Italy was related to a steep decrease in the proportion of beef, while that of France failed to materialise probably due to dietary choices within a food group (Chapter 5).

Dietary improvement options, proposed by a benchmarking diet model, are in general based on partial replacement of food groups. In this thesis, the healthier diets showed substantially higher levels of fruit and vegetables, and alleviated nutrient inadequacies. Within the range of observed diets, it was possible to shift from red and processed meat to fish, eggs, poultry and/or dairy, depending on the observed diet and national dietary habits, while room for improvement in legumes, and nuts and seeds was limited. When taking this first step towards a healthier diet (*Max P diet*), on average 85% of the food group intake could remain similar as the observed diet, but more changes were needed for a further improvement in nutrient quality or environmental sustainability.

When nutrient quality was prioritised (the *Max H* diet), the improved diet had even higher amounts of fruit, vegetables, fish and legumes, and lower amounts of sweet and alcoholic beverages. Surprisingly, when environmental sustainability was prioritised (the *Max S* diet), the improved diet had still a similar proportion of animal- to plant-sourced foods as the observed diet, but with shifts within the group of animal-sourced foods as explained earlier. Moreover, the *Max H* diet did only marginally affected GHGE, whereas the *Max S* diet did still reach half the maximum for nutrient quality. For both improvement options, on average only ~73% of the food group intake remained similar as the observed diet. This indicates a trade-off between health, environmental sustainability and dietary preferences.

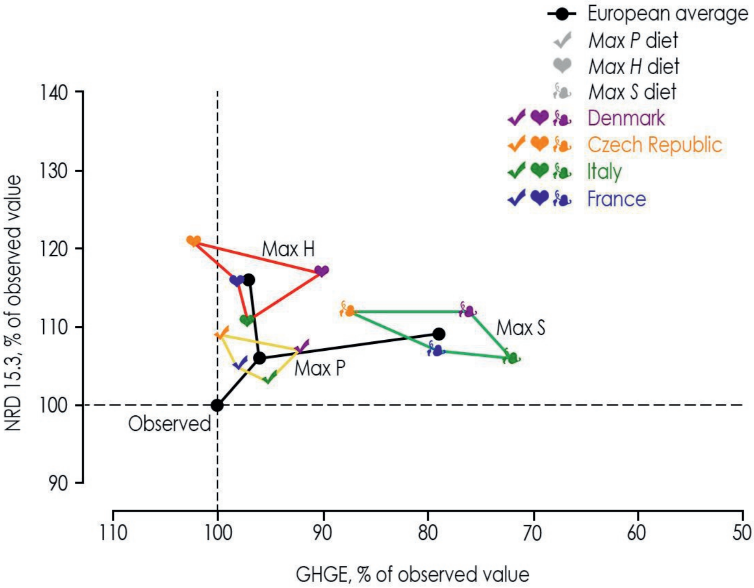


Figure 1 Evaluation of the nutrient quality and the environmental sustainability of the modelled diets according to a benchmarking diet model [ab]

[a] All modelled diets have an improved adherence to food-based dietary guidelines. *Max P* is the most preferred diet based on minimal deviation from the observed diet, *Max H* the most healthy diet based on NRD15.3 for nutrient quality, and *Max S* the most environmentally sustainable diet based on GHGE.

[b] Dots represent the averages from the analyses reported in Chapter 7, and the country-specific results are presented by a check mark for the *Max P* diet, a heart for the *Max H* diet, and a leaf for the *Max S* diet.

METHODOLOGICAL AND CONCEPTUAL CONSIDERATIONS

Methods of dietary assessment

Findings described in Chapter 4, Chapter 5 and Chapter 7 apply to consumer diets in Europe using national dietary surveys carried out at the individual level. This thesis makes use of survey data from Denmark (2005-2008), Czech Republic (2003-2004), Italy (2005-2006), and France (2006-2007). Because of differences in survey methodologies, available dietary data were harmonised and standardised to enable comparisons between countries.

Harmonisation of the food classification and food group categorisation

EFSA has developed the FoodEx2 classification [5], and data providers code all foods and beverages in their national dietary survey accordingly [6]. The total number of foods reported in these surveys differed between the countries, possibly reflecting differences in the variety of foods available in these countries and/or a level of detail for reporting of foods in the different surveys. This, however, did not influence the results, as foods were categorised into food groups. Foods within a health-based food group are – roughly – comparable for health, but not necessarily for environmental sustainability. This in particular explains why the categorisation for meat products, and fats and oils was different for assessing health (in Chapter 4) and environmental sustainability of the diet (in Chapter 5). For health, these foods were categorised based on their non-communicable disease risk (factor) reduction, i.e. for meat a categorisation into red, processed and white meat, and for fats and oils a categorisation based on fatty acid composition. For environmental sustainability, categorisation was based on food source, i.e. meat from beef, pork or poultry, and fats and oils from animal or plant sources. The use of one common food classification system, as applied in the present thesis, was therefore an important step in the alignment of dietary surveys, increasing the comparability of food group categorisation between countries. To maintain comparability in a diet model, the deviations from observed diets were also quantified at the level of food groups (Chapter 7).

Furthermore, both the health and environmental evaluations (Chapter 4 and Chapter 5) and the diet models (Chapter 7) are dependent on how well the method of dietary assessment can describe the diet. In this thesis, for example, for food group adherence, the level of detail in the dietary surveys did not allow for a differentiation between sugar- and artificially-sweetened beverages and therefore the intake of ‘sweet beverages’ was reported instead of ‘sugar-sweetened beverages’ for the four countries. However, given the increasing trend of consuming artificially-sweetened beverages, this differentiation becomes more important for future research [7, 8]. Other sources of dietary data uncertainties in this thesis are the intake of whole grain products and salt. Issues for the quantification of whole grains (and types of dietary fibre) and salt relate to the high variability in nutrient content of foods between the countries and this is not accurately captured in the national food composition tables. In particular for salt, a better assessment of sodium from discretionary sources and processed foods and/or population-wide assessment of 24-hour urinary sodium excretion is warranted in diet surveys to better inform public health and provide dietary advice on the modelled diets [9]. In this thesis, the design of healthy, environmentally sustainable diets for European consumers is therefore hampered by inaccurate data on the consumption of sugar-sweetened beverages (added sugar intake), whole grains (dietary fibre) and salt, and this has probably led to an underestimation of their impact on health and environmental sustainability.

Sugar, dietary fibre and salt are major determinants of taste and texture of foods, and therefore their influence on dietary preferences of consumers should not be ignored when designing more healthy and environmentally sustainable diets.

Dietary habits are different in each country, depending on food availability and dietary preferences. This accounts for part of the difference in nutrient intakes and environmental impacts of the diet across the countries (Chapter 4 and Chapter 5). The use of a country-specific versus standardised database for food composition and environmental indicators would also influence estimations of nutrient intakes and environmental impacts from foods, respectively. In the present thesis, nutrient intakes were estimated using a country-specific database (Chapter 4), and diet-related environmental impacts using a standardised database for Europe (Chapter 5). The advantage of using country-specific databases is that the variables of interest are more accurately estimated for that particular country, while a standardised database ignores any country-specific differences in food composition and/or food supply systems. Both have thus their own advantages, i.e. a country-specific database provides a better match to national food habits and survey methods, whereas a standardised database is more readily available and could suffice for conclusion at the EU-level, but lacks specificity for the national food production system. The relevance of our analyses for national food policy might be improved if the LCA-data would account for the national mix of food production systems [10].

Standardisation for energy intake

To ensure a fair comparison of diets in this thesis, diets were standardised for energy intake using the density method [11]. Densities of intakes maintain the relative consumption quantities of foods in the diet, and permit disentangling diet composition from systematic errors in reporting the overall quantity of food and energy intake.

In this thesis, diets were standardised for energy intake using the density method. Using densities is very useful to describe dietary patterns in a comparable way, and densities of intake can easily be translated to dietary advice in a public health setting. However, the use of energy-standardised diets disregards the impact of overconsumption on health and the environment.

Dietary changes by individuals and populations may be considered as iso-caloric, provided that body weight and physical activity remains constant. This highlights the need to keep energy constant when comparing diets between groups. Consistent with the literature [12-14], Chapter 3 found that using energy-adjusted values resulted in a higher group mean bias and a lower correlation between FFQ and 24-hour recall, but there was less attenuation. As measurement errors in the assessment of the quantity of food are strongly correlated with errors in the measurement of total energy intake, the same is expected to hold when comparing 24-hour recalls with diet records. Replicates of a 24-hour recall in general show higher intakes of total energy as compared to diet records [15-17], as also seen in Chapter 4 and Chapter 5, but their group-mean bias is expected to be lower as with an FFQ. The reason for this is that they share a larger amount of correlated errors as compared with an FFQ, since both are short-term open-ended methods of dietary assessment that allow greater specificity for describing foods and food preparation methods [17]. Thus, 24-hour recalls and diet records are both suitable methods to provide more objective food intake data that also captures day-to-day variation, as will be explained later on in this discussion.

In addition, using densities is considered as a way to compensate for non-differential under- or over-estimation of food intakes [11]. When assessing the healthiness (Chapter 4) and environmental impact of the diet (Chapter 5), we did not exclude under- and over-reporters, because some of the mis-reporters may truly be consuming a low- or a high-energy diet on those specific days. Their intake data were, however, not likely to reflect a representative day of intake, and because of that they were excluded from the benchmarking diet model (Chapter 7). After all, the benchmarking diet model is based on the normal range of variation in dietary habits and not on exceptional days, because such days should not be 'copied' by others. Therefore, the variation should be in the range of reasonable intakes for each food group. This is certainly not the case for under-reporters and their (upscaled) energy-standardised intakes leading to extremely high amounts of any particular food group. Although excluding mis-reporters limited the internal consistency with the previous chapters (Chapter 4 and 5), mean intakes on the population level were barely affected and distributions of intake were only slightly shrunk towards the group mean.

Standardisation for the number of days

Related to the time integration of dietary exposure, the average of two non-consecutive days for each individual was used in this thesis. This number of days was standardised, but not the time span between the two assessment days, i.e. one day in between for Italy, one to five days for Denmark and France, and three to five months for Czech Republic. Because of within-subject day-to-day variation, this raised questions on occasionally consumed foods and the usual intake distribution.

Statistical methods correcting for the intake distribution for within-subject day-to-day variation require the availability of one or more non-consecutive 24-hour recalls or diet records. In literature, it has been acknowledged that consecutive days, including days spaced over a week time-interval, as compared to random days spaced over a longer time-period, are more dependent on each other, e.g.: leftovers and eating more on one day and less the next day [18]. Relying on nearby days is therefore likely to affect the within-subject day-to-day variation [19-21]. This phenomenon was, however, not supported in the present thesis where the intra-class correlation coefficients of the two days were comparable in the four countries. More research is needed to study the role of time span between the assessment days on the estimations of the within-subject day-to-day variation. Moreover, removing this within-subject variation to obtain usual intake is more difficult in the case of densities, and in particular for densities of episodically consumed foods where no standard statistical packages are available. Not removing the within-subject day-to-day variation would not affect the observed mean intake of the population, but would widen the intake distribution [22]. This widened intake distribution gave rise to biased estimates for nutrient inadequacy and food-group adherence (Chapter 4), and attenuated associations (Table 5 of Chapter 5) (Figure 2). The latter was confirmed in Chapter 3, showing stronger associations between the healthiness and environmental impact of the diet after removing within-subject variation. Nevertheless, using the average of two days is regarded as a simple way to partly account for within-subject day-to-day variation, and leads to only a partial shrinkage of the intake distribution as compared to one single day [23].

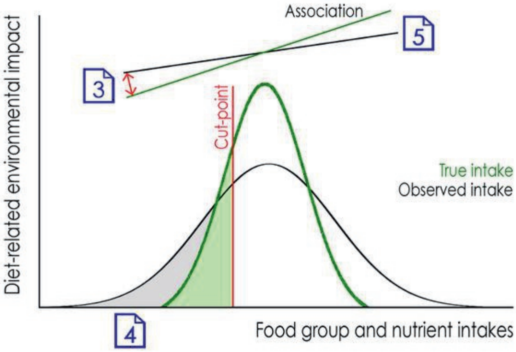


Figure 2 A widened population intake distribution affects the estimated prevalence of inadequate intakes [a] and attenuates the associations with diet-related environmental impact [b].

[a] Percentage of the population below or above a cut-point was calculated in Chapter 4.

[b] Associations of diet-related environmental impact with diet scores were calculated in Chapter 3 using repeated 24-hour recalls as observed and corrected for within-subject variation, and with diet composition in Chapter 5 using two assessment days as observed.

Time-integration of dietary exposure in a benchmarking diet model

In the benchmarking diet model, the diet of each individual, as averaged from the two assessment days, was regarded as an example of an existing daily menu, whereby some daily menus perform better than others (Chapter 7). A combination of these better performing daily menus would thus result in a better weekly menu. However, to obtain a weekly menu in accordance with a healthy diet, the combination of daily menus must be interpreted with caution, because for some food groups recommendations are not based on daily but weekly consumption, such as one portion of fish a week. In the present thesis, this issue was tackled by capping fish intake at sufficient intake levels, and by replacing upper intake levels by a marginal small amount; the former was done to not favour higher intakes, and the latter to put upper intakes at a disadvantage while benchmarking diets. In this way, a combination of different efficient sample daily menus, i.e. of fish, meat, poultry, legumes, etc. was used to guide dietary improvement at population level.

In this thesis, the dietary exposure in the benchmarking diet model covered two assessment days for each individual, as an example of an average daily menu. The use of these daily menus in the benchmarking diet model created a larger window of opportunity for dietary improvement than when using habitual intakes. This is because daily menus capture a substantial amount of variation in dietary practices to identify the most efficient diets, but warrant attention for food groups with a recommended weekly consumption.

This issue of weekly consumption instead of daily consumption can also be accounted for by closer approximating the habitual intake of an individual, e.g. by using the average of seven days, as representative for a week menu, rather than using the average of two days or just one day. Improved diets are in this way a combination of better performing week menus, and thus represent a better habitual diet. This in turn suggests the use of habitual intakes over a longer period of time. Habitual intake is the long-term average daily intake that accounts for both consumption and non-consumption days, and can be assessed by using a FFQ or repeated individual-level 24-hour recalls and diet records over a longer period of time. However, as compared to 24-hour recalls and diet records, a FFQ may introduce a substantial amount of measurement error, in particular person-specific problems with estimating frequencies and portion sizes of grouped food items instead of a single food item [24]. This person-specific bias would cause misreported dietary habits to be used in benchmarking. In addition, averaging individual-level 24-hour recalls and diet records over a longer period of time may reduce benefitting from the between-subject variation in diets. In the benchmarking diet model, this between-subject variation is the major factor to inspire dietary improvements and accounts for implicit associations between food groups for the two assessment days, but not for long term diet patterns at the level of the individual. Therefore, averaging over more than two days could lead to improved acceptability when individual advice is aimed at, but might be less important at the population level.

Healthy diets

The present thesis made use of energy-standardised diets, and therefore energy balance, as one of the aspects of a healthy diet, has been separated from diet composition. For studying diet composition, both food- and nutrient-based approaches were considered to ensure non-communicable disease risk (factor) reduction and nutrient adequacy. Food-based dietary guidelines and nutrient recommendations were used for evaluating the diet in Chapter 3 and Chapter 4, and for the design of dietary improvement in Chapter 7.

This thesis focuses on dietary quality rather than quantity of diets in Europe. Caloric intake, however, is also important. Energy imbalance, as reflected in the BMI of individuals and populations, has a major impact on both health and environmental sustainability, and should be considered in policy scenarios.

Energy balance

Using energy-standardised diets as starting point for the benchmarking diet model implies that options for dietary improvement only consider an iso-caloric substitution between food groups, as they are a combination of existing energy-standardised diets (Chapter 7). Thus, all improved diets are healthier options with regard to their diet composition, but they do not tackle overconsumption and its associated overweight/obesity burden as such. Nevertheless, these energy-standardised improved diets can be re-scaled to the desired level of energy intake, according to energy needs. By proportionally lowering or increasing the intake from each food group, the diet composition, as proposed by the benchmarking diet model, remains the same for a different level of energy intake. Next to the health improvement, reducing energy intake is also an effective strategy for lowering the environmental impact of the diet (Chapter 5).

Dietary variable selection

Population adherence to food-based dietary guidelines for the Netherlands, as described in Chapter 3, was captured by using a summary measure, i.e. the Dutch Healthy Diet index 15 [25]. The use of such a summary measure was not possible in Chapter 4, because food-based dietary guidelines are country or region specific. Nutrient adequacy at population level in Chapter 3 and Chapter 4 was captured by using a summary measure, i.e. the Nutrient Rich Diet score (NRD) 9.3 that includes nine nutrients to encourage and three nutrients to limit [26, 27], and Chapter 4 additionally included an extended version, i.e. NRD 15.3 that captures more nutrients that are potentially relevant for European populations switching towards a more plant-based diet. In contrast to the individual components, summary measures, however, are important information tools to take diet quality at face value, but interpretation is limited by score-related limitations, e.g. the inclusion of a selected number of dietary components, arbitrary penalties for unmet criteria, and the failure of the overall score to identify dietary components of public health importance.

For the design of dietary improvements in Chapter 7, the starting point for identifying healthier diets were the dietary components that serve as a basis for establishing food-based dietary guidelines in the four countries (Box 1). All generic key elements of a healthy diet, i.e. food groups and nutrients that have consolidated knowledge on diet and health, were included as model variables for the diet comparison in the benchmarking diet model, except sodium because of known inaccuracy in intake assessment [9]. When modelling on the quantifiable generic key elements of a healthy diet, a substantial decrease in animal-sourced foods occurred, and this resulted in a lower intake of several key nutrients that are mainly derived from animal-sourced foods. This was in particular of concern in women from Czech Republic, where in the context of observed diets no appropriate plant-based alternatives could compensate for this. For the identification of existing efficient healthier diets in Chapter 7, food-based dietary guidelines were, therefore, complemented by several key nutrients, i.e. calcium, zinc, vitamin B2 and B12, to ensure nutrient adequacy. Although food-based dietary guidelines and these key nutrients were used to identify the set of efficient healthier diets, health implications of dietary improvements as such were not considered. To improve modelling healthier diets, population impact fractions for individual dietary risks might therefore serve as evidence-based weights for the individual dietary components included in the model to identify efficient existing diets. Adding weights based on public health impact to the individual dietary components might thus prioritise some dietary improvements above others.

Box 1 Dietary components to identify existing healthier diets according to food-based dietary guidelines, using Data Envelopment Analyses.

↑ Fruit, vegetables, legumes, nuts and seeds, fish, whole grains, unsaturated fat, calcium*, zinc*, vitamin B2* and B12*

↓ Red and processed meat, refined grains, sweet beverages, alcohol and saturated fat

* Apart from food-based dietary guidelines, key nutrients are added for safeguarding nutrient quality.

Reference values

In all health evaluations, the chosen reference values play a key role in assessing food group adherence and nutrient intake adequacy. For food group adherence, the amounts presented in food-based dietary guidelines give an indication on how much from a certain food group an individual should include in the daily menu. Although the food groups were rather similar in the food-based dietary guidelines of European countries, the reference values differed between countries [28, 29]. In Chapter 4, the less restrictive reference values for an individual's diet was used for assessing adherence at population level across countries. It might, however, be questioned whether such reference values are suitable for evaluating adherence to food-based dietary guidelines on the population level. This issue has been acknowledged for nutrient evaluations, where several indicators and cut-points of the nutrient level are available [30, 31]. Although the probability method is considered theoretically the best choice for evaluating nutrient adequacy [32], the AR cut-point method was adopted as a feasible and acceptable alternative [32, 33],and applied for the nutrient evaluation in Chapter 4. There is currently no such framework for adherence to food-based dietary guidelines. It is unlikely that the assumptions underlying the AR cut-point method also apply to the skewed intake distribution of food groups; the results of this evaluation of adherence should therefore be viewed as comparative descriptors rather than as valid estimates of adherence for the population.

When designing healthier diets, dietary reference values serve as a guide for safeguarding diet quality, and they are important for monitoring the nutritional status of individuals and populations. Most food-based diet optimisation models rely on dietary reference values that are included in the model as constraints in order to compose a healthy diet from all foods available [34]. In contrast, in a benchmarking diet model, there is no need to specify any dietary reference value, as the healthiness of a diet is principally determined by the ratio of “dietary components to increase” to “dietary components to decrease” (Chapter 6 and Chapter 7).

This thesis shows that improved diets for consumers may be designed by a benchmarking model that is commonly used in economics. With the econometric frontier approach – data envelopment analyses (DEA) – diets are efficiently maximised for their benefits, i.e. “dietary components to increase”, against minimal costs, i.e. “dietary components to decrease”, without specifying any dietary reference value.

While benchmarking diets, a diet is thus efficient when the benefit-cost-ratio of “dietary components to increase” to “dietary components to decrease” is higher. To allow for fair comparison between the diets, diets were standardised for their energy intake. In diet planning, the estimated average energy requirement associated with gender, age, height, weight and physical activity level of the population can be used as a reference energy intake [31]. The average energy requirement is estimated to be 2,500 kcal for men and 2,000 kcal for women, and subsequently in the benchmarking diet model, diets were standardised to 2,500 kcal for men and 2,000 kcal for women (Chapter 7). This, however, limited the internal consistency for men with Chapter 4 where their diets were standardised to 2,000 kcal, though a 2,500-kcal diet represents a more realistic assumption of energy intake for men.

Moreover, in practice, “dietary components to increase” are only beneficial up to a certain level, whereby intakes higher than this level may not offer additional health benefit. To account for this while benchmarking diets, a capping value at the level of the reference intake was applied for each of the dietary components to increase, except for the infrequently consumed food groups like legumes, and nuts and seeds (Chapter 7). All diets with an intake at the level of the capping value or higher are for the diet benchmark considered equivalent for health with regard to the intake of that particular dietary component. Using capping values affects the number of efficient diets, leading to a larger set of efficient diets that not only includes diets with extreme high intakes for a particular food group. This in turn results in improved diets that are closer to the observed diet, and thus are assumed to be more realistic and feasible.

Environmentally sustainable diets

Assessment of environmental impact of consumer diets

Diet-related environmental impacts of consumer diets are commonly assessed using attributional LCA that describes the environmental impacts throughout all the stages of a product's life cycle under the current architecture of the food system [35]. The assessment of the diet-related environmental impact is, however, hampered by uncertainties involved in the environmental impact analyses based on attributional LCA. This results in a large variation in available LCA data, due to differences in model choice and assumptions underlying the LCA method. In the present thesis, LCA data used in Chapter 3 (Blonk Consultants data set version 2016 [36]) differed from those used in Chapter 5 and Chapter 7 (the *SHARP-ID* constructed in this thesis). The Data provided by Blonk Consultants are specific for the Dutch context and were used for the assessment of the environmental impact of diets in the Netherlands in Chapter 3. The data in the *SHARP-ID* represent a broader European context, and therefore ignores variation originating from nationally different food supply systems, and these data were used for the assessment of environmental impact of diets across Europe (Chapter 5 and Chapter 7). Comparison of both LCA-databases revealed that although absolute impact values for foods were different, the contribution by food group and the hierarchy in impact per amount of food group as consumed was approximately the same [37]. This further supports the idea that for most foods the largest environmental burden in food production originates from the primary production phase, involving crop production and animal breeding [38]. Adding impacts from the other stages of a product's life cycle adds thus to the precision of the estimate [10], and any differences in these stages has until now limited influence on the ranking in the diet as a whole. Nevertheless, with increasing data availability on LCA and on dietary practices, such as packaging, home preparation, and food waste at home, these aspects of food consumption are likely to affect the environmental impact of a specific food with an food group to a greater extent [10, 39] and to increase the precision of the estimate. As the aim of Chapter 5 and Chapter 7 was to advance dietary advice for consumers, it could be relevant to separate out the role of food choice between and within food groups at the consumer level.

This thesis makes use of a standardised database for environmental impact indicators of GHGE and LU, i.e. the *SHARP-ID*, to assess the environmental impact of European diets. The *SHARP-ID* allows for direct comparison of dietary patterns, but precludes comparison of national food supply systems. In addition, including environmental impact indicators on fresh water use, nitrogen and phosphorus flows, biodiversity loss and land-system change would give a more balanced picture of environmental footprints.

Broad spectrum of environmental impact indicators

In this thesis, GHGE, LU and fossil energy use (FE) were used as indicators for environmental impact assessment. GHGE is the most commonly used indicator for environmental impact [40, 41], although a narrow focus on this ignores many other ecosystems that are affected by diets and agri-food systems. This can be illustrated by the contribution of food groups to diet-related environmental impact, which ranks differently per indicator (Chapter 3 and Chapter 5). Foods like fruit, vegetables and fish have a lower contribution to LU as compared to GHGE, which implies higher amounts of these foods for an environmentally sustainable diet when using LU instead of GHGE as an indicator (Chapter 3 and Chapter 5). On the other hand, instead of GHGE and LU, using FE is likely to result in an environmentally sustainable diet that includes lower amounts of vegetables, fruit, fish, grains and beverages, because of their higher contribution to FE as compared to GHGE and LU (Chapter 3). Impacts thus differ by environmental domain, and that is why the broad spectrum of environmental impact indicators should be considered when evaluating and modelling environmentally sustainable diets. Provided that LCA data are available for a large number of indicators, summary measures can be used, as applied in Chapter 3 for the Dutch diet, but not for the diet modelling in Chapter 7. However, such summary measures limit interpretations, as explained earlier in the case of diet scores.

Moreover, next to considering trade-offs between the different environmental impact indicators, it is important to incorporate the supply chain of a food when modelling environmentally sustainable diets for consumers. This is because of the production interdependencies between foods, for example when considering side streams of production, both milk and meat from dairy cattle need to be included in an environmentally sustainable diet [42]. In Chapter, 7, the modelled diet high in environmental sustainability therefore needs to be interpreted with caution, because of the use of attributional LCA. The food group substitutions for this modelled diet are based on the fact that under the current production and consumption practices the consumption of one food is better than that of another one. In practice, however, it is not that simple, as each change in food production and consumption is likely to affect the environmental impact of all foods in the long run. Using consequential LCA or food systems models instead allows to account for potential changes in environmental flows as a response to such changes in food production and/or consumption [43].

In addition, options for a diet that minimise the environmental impact of food production and consumption differ by region. In particular, replacing animal-sourced foods with plant-sourced ones would in high-income countries reduce some environmental impacts, in particular GHGE, but increase fresh water use, and would additionally increase cropland use, nitrogen and phosphorous application in low-income countries [44]. In addition, as a result of globalising food markets, food consumption demands of Europe may put pressure on the environment elsewhere in the world [45]. Thus, ideally, the broad spectrum of GHGE, cropland and freshwater use, nitrogen and phosphorous applications, and biodiversity should be considered from both a country-specific and a global perspective when evaluating and designing diets.

Dietary choices

The context of observed diets

This thesis addressed dietary choices in the context of observed diets, and these observed better dietary choices allow to provide a wide range of improvement options that are assumed to be realistic and feasible for the population under study (Chapter 7). The assumption underlying this is that peer group behaviour may be seen as a key feature of human dietary behaviour [46, 47], whereby valid information about appropriate eating is provided by similar others or those with whom they affiliate.

In this thesis, the benchmarking diet model aimed for moderate dietary improvements in the subgroup of the population with inefficient diets. These dietary improvements were calculated based on the efficient diets in the population, and thus individuals with an efficient diet act as role models for dietary improvement. The use of this ‘peer resemblance’ approach provides options for dietary improvement that are realistic and feasible, as they are within the boundaries of observed dietary practices.

In addition to peer resemblance, a consumer dietary choice is also dependent on individual characteristics, such as demographics, taste, convenience, price, etc. [48, 49]. Therefore, the modelled dietary improvement options can still be disputed. In one of the models of Chapter 7, the improved diet should stay as close as possible to the observed diet (the *Max P* diet). Such a preferred healthier diet was modelled by minimising the sum of positive and negative deviations in food group intake. Using these absolute differences in consumption amount between food groups assumes that each dietary improvement is equally likely to occur, whereas in practice some are more likely than others. Previous studies have tried to capture the likelihood of dietary improvement by using penalty weights that are directionality-dependent and proportional to food popularity [50]. This algorithm for the likelihood of dietary improvement assumes that consumers do not like dietary changes, but if needed, they rather prefer an increase in the amounts of foods consumed than a decrease or an introduction of foods that were not consumed before [50]. Collecting and including information on individual food preferences and aversions will therefore obviously enhance the modelling of more realistic and feasible options for dietary improvement for each consumer. It is, however, hard to know how the modelled diets are affected by the different measures of deviations.

Quantifying how much a modelled diet is in line with dietary preferences is challenging. Therefore, Chapter 7 introduced a simple description of the overall similarity between the observed and alternative healthier diet, a so-called diet similarity index.

In this thesis, a diet similarity index was calculated as the summed amount of each food group amount that remains the same in the modelled diet as compared to the observed diet divided by total diet weight of the observed diet. It is, however, still hard to judge how much diet similarity is needed for a dietary improvement option that is likely to occur.

This measure of diet similarity assumes that, in the course of dietary improvement, consumers are willing to increase consumption of a consumed food without considering this as a change, and if needed they rather partly give up a consumed food than totally eliminating this from the diet or introducing a new food. Although the diet similarity index estimates the proportion of food intake that remains unchanged, it is still hard to say at what order of magnitude in diet similarity a dietary improvement is more or less likely to occur. There is thus a need for studying consumer perception, such as food preferences and aversions, price, taste and texture, personal interest in health or environmental sustainability etc. on the suggested improvement. If such indicators on consumer perception become available for each consumer, incorporating them to the indicators and adding them to the benchmarking diet model will help to further tailor dietary advice to the individual consumer.

In this context, a previous observational study conducted in five urban regions across Europe showed that barriers of perceived “lack of willpower”, “time constraints” and “taste preferences” are strongly related to dietary behaviours in adults [51]. In particular the barrier of “lack of willpower” and “time constraints” appeared to be especially important for the consumption of home-cooked meals and a frequent consumption of breakfast. Accounting for such barriers of dietary behaviour in the diet model relates to the previous discussion on time integration of dietary exposure. This implies that a meal-oriented approach rather than a daily menu-oriented approach might increase the understanding of dietary choices towards improved diets by means of improved meals.

Towards healthy and environmentally sustainable diets

Chapter 2 describes two approaches for designing alternative diets, i.e. food item replacements and diet models. For the design of diets towards improved health and environmental sustainability, it is particularly important to satisfy nutrient recommendations and food-based dietary guidelines, and to minimise environmental impact, while still accounting for dietary preferences.

Food item replacement

Food item replacement is a simple approach for designing alternative diets, and for the design of environmentally sustainable diets, the main interest is replacing animal-sourced foods by plant-sourced ones. In the literature review of Chapter 2, it is found that diets with less meat may have a lower environmental impact up to 50% of the observed impact depending on the amount and type of meat included in the observed diet and the substitution food [52, 53]. In such replacement studies, the intake of meat was often stepwise lowered until full elimination, and was replaced by one food group or a combination of different food groups, either on a food weight, a protein or an energy basis (Chapter 2).

Chapter 5 introduced a regression-based substitution to simulate a food item replacement that accounts for total energy intake and the underlying type of data, i.e. observed dietary practices. In particular, a 50% replacement of the energy from meat by grains or by fruit, vegetables, legumes and nuts decreased environmental footprints by 12% for GHGE and 17% for LU. Although these simple replacement messages are straight-forward, the implementation in practice may face some challenges. Plant-based alternatives may not fit within dietary preferences of consumers, because of different taste profiles. i.e. taste of salt/umami/fat for meat, neutral for bread, vegetables, legumes and nuts, and sweet/sour taste for fruit [54]. In addition, it has been shown that a more healthy and environmentally sustainable diet includes lower amounts of foods with a taste of salt/umami/fat and of bitter, and higher amounts of foods with a neutral taste [55]. Next to taste differences, a transition towards a more plant-based diet can also put critical nutrient intake under pressure in the population. Critical nutrients in this thesis were vitamins B2 and B12 when replacing meat (as found by the regression-based substitution; Chapter 5), and additionally included calcium and zinc when replacing both meat and dairy (as earlier discussed; Chapter 7). Such simple food item replacements do thus modify the diet as a whole, but they do not capture the complexity of the dietary pattern.

Diet models – in general

Transparent and reproducible integration of health and environmental sustainability aspects of a diet requires mathematical modelling. Diet models have been used to design either population or individual diets that are more optimal according to certain criteria [34, 56]. The usefulness and validity of the results obtained with diet models is, however, dependent on how well the model generates realistic and feasible diets, and on the quality of the underlying data.

This thesis shows the application of a benchmarking diet model for the design of dietary improvement options. The great advantage of using a benchmarking diet model is that the diet solutions fit in the context of observed diets and that it implicitly accounts for dietary preferences by keeping the basic relationships between foods intact.

While common diet optimisation models starts from a set of available foods with data on food composition and environmental impact, the benchmarking diet model identifies existing healthier diets within a population and uses them as example for dietary improvement (Chapter 6). The main difference for dietary improvements is thus the decision-making unit which is a basket of foods in a diet optimisation model and a set of observed diets in a benchmarking diet model. This difference influences the generation of diets in two ways. First, in diet modelling ensuring realism and acceptability of the modelled diet requires introducing additional constraints on food associations, such as bread and butter, oil and green salad, milk and cereals, while there is no need for in a benchmarking diet model. This is because the resulting diet is a combination of other existing diets, and thus describes a first step for dietary improvement, or in other words the maximal feasible solutions for dietary improvement within the range of observed diets, instead of an optimised diet. Second, an increase in the amount of infrequently consumed foods, such as nuts and seeds, is hampered by a benchmarking diet model (Chapter 7), although these foods fit in a healthy and environmentally sustainable diet, as suggested by food-based diet optimisation models. Nevertheless, results of the benchmarking diet model suggest a need for targeted efforts and/or product development to increase consumption of some foods beyond observed dietary practices. Moreover, observed individual dietary practices are partly shaped by the food environment [57, 58] that is, however, subjected to changes, such as the introduction of new foods on the market and price fluctuations, which in turn can influence dietary intake. This supports the idea of adding recommendation algorithms that include both peer resemblance of the diet as well as product characteristics. Recommendation algorithms such as “people like you often use this product to arrive at a healthier and more environmentally sustainable diet” can thus complement the modelled diets by providing additional suggestions for dietary improvement. Such suggestions can be seen as a second step that helps to pave the way for more healthy and environmentally sustainable diets.

This thesis provides examples for the first steps towards improvement of diets for health and environmental sustainability, within the framework of food-based dietary guidelines, and with solutions that are close to observed diets in Europe. Such dietary improvement options, as explored by the benchmarking diet model, are highly dependent on the dietary variables used to identify efficient diets and the set of observed diets.

Diet models – assumptions

Several assumptions that underlie most diet models could be questioned, including the indicators for health, environment and dietary preferences, as discussed above. In a benchmarking diet model based on data envelopment analyses (DEA), particularly, the indicators used to identify efficient diets are of major importance for the direction of dietary improvement. A previous benchmarking diet model using a nutrient-based approach did not capture the full spectrum of a healthy diet, since not all modelled food group amounts were in line with food-based dietary guidelines [59]. This is because in the context of observed diets, subjects with a higher nutrient quality do not necessarily have a higher adherence to food-based dietary guidelines. In a cohort of 1,169 Dutch highly educated adults (NQplus study), for example, only 57% of the population that scored highly on a nutrient-based diet score had a high food-based diet score (Chapter 3). This suggests that subjects can cover nutrient intakes without necessarily fully adhering to food-based dietary guidelines. On the other hand, food-based dietary guidelines provide a basic framework when planning daily menus, and are supposed to cover 100% of the nutrient recommendations [60]. That is why in Chapter 7, the identification of efficient diets was based on an *a priori* defined set of food-based dietary guidelines. There appeared to be no need to add nutrients to the DEA-model, except for Czech Republic where no appropriate plant-based alternatives could compensate for a substantial decrease in animal-sourced foods and their key nutrients, as discussed above.

It was therefore important to incorporate several nutrients, next to the food-based approach to prevent that the healthier diet in the context of observed diets negatively affects nutrient adequacy of the diets in these populations.

Modelled diets are in general influenced by the order of modelling steps, since options for dietary improvement are dependent on the set of existing efficient diets that are identified by the model variables. In the case of Chapter 7, indicators for a healthy diet were used to identify efficient diets. Options for dietary improvement are thus in Chapter 7 first of all derived from food-based dietary guidelines, and after that additional constraints on dietary preferences, nutrient quality and environment are included. When instead of health, the environment is the main reason for dietary improvement, the set of existing efficient diets would be identified by using indicators for environmental sustainability. Diets with a lower environmental impact are then used as examples for dietary improvement of others. In this way, such modelled diets are expected to have a much larger improvement for environmental sustainability than the *Max S* diet as found in Chapter 7, but a lower improvement for health even after adding additional constraints on health. This implies that the maximum solutions for health and environmental sustainability cannot be achieved simultaneously by dietary choices alone. This also confirms the weak associations between healthiness and environmental impact of the diet (Chapter 3). That is why public health and agri-food policies and research programmes should be integrated in the design of future consumer diets, and not as an add-on of each other.

DISCUSSION OF THE MAIN FINDINGS

Results of the diet model presented in this thesis shows that dietary solutions that benefit both human health and the environment promote a higher intake of plant-sourced foods and a lower intake of meat, in particular beef, along with tackling overconsumption.

Overconsumption

Obesity (i.e. BMI ≥ 30 kg/m^2) ranks among the leading five risk factors for early death and disability in Europe [61, 62], and is highly prevalent (10-15%) across the four countries. Nevertheless, this burden of disease is potentially preventable. A modest weight loss of 5-10% significantly improves metabolic and cardiovascular health, with more improvement for greater weight loss [63]. Caloric restriction is one of the key features for achieving weight loss that would also benefit the environment (Chapter 5). When energy intake was reduced to meet energy needs for a 5-10% lower body weight, then the diet-related GHGE and LU would decrease by 3-5%, without changing diet composition.

Diet composition – national benchmarking

Diet-related environmental impact can be further reduced by changing diet composition. In Chapter 7, improved diets within the framework of food-based dietary guidelines and in the range of observed diets were identified using a benchmarking diet model. A total of 6,462 individual diets across Europe were benchmarked, of these diets 4,344 (67%) could be improved for their adherence to food-based dietary guidelines by other national diets within a country-and-gender-specific context of observed diets. In particular, dietary improvement was modelled for 66% of the diets in Denmark, 58% of the diets in Czech Republic, 74% of the diets in Italy, and 68% of the diets in France. In line with the food group adherence (Chapter 4), the solution space to improve inefficient diets was the lowest in Czech Republic, followed by Denmark and France, and the highest in Italy. This is because this solution space is dependent on the number of efficient diets that in turn is dependent on to what extent individuals in a population meet food-based dietary guidelines. When a number of individuals in the population meet only a part of the food-based dietary guidelines, then many of this number of individuals are included in the set of efficient diets, hence less improvement on a population level, and vice versa.

Diet composition - European benchmarking

On top of this, a further improvement of diet composition is possible when using European benchmarking, as elaborated in this discussion section; instead of a national benchmarking as applied in Chapter 7. When allowing for one food market for Europe, and hereby allowing for exchange of dietary habits across European countries, 5,293 (82%) of the diets could be improved within a European-gender-specific context. This implies that the dietary practices of the different countries provide more opportunities to achieve dietary improvements than the dietary practices of one single country. As expected from the food group adherence (Chapter 4), it is apparent that the diets from Italy are included most frequently in the set of efficient diets in a European-wide context (44%), followed by diets from France (32%) and Denmark (15%), and the least frequently included are the diets from Czech Republic (9%).

Diet composition – the EAT-Lancet reference diet

In the context of integrating health and the environment, the EAT-*Lancet* Commission has proposed the global adoption of a healthy reference diet [64]. This healthy reference diet includes the same food groups as the food-based dietary guidelines in the European countries, but amounts of some food groups differ substantially. It is thus regarded as a future diet to strive for rather than a feasible solution for dietary improvement at this moment.

Figure 3 shows the results on nutrient adequacy and environmental sustainability for the modelled diets as compared to the observed diet, and Figure 4 shows the food group composition of the observed and modelled diets. Modelled diets were based on a country-and-gender-specific context, a European-gender-specific context, and the EAT-*Lancet* reference diet.

This thesis provides examples for the first steps towards further improvement of diets for health and environmental sustainability, within the framework of food-based dietary guidelines, and with solutions that are in the range of the observed diets.

- The *Max P* diet is a modelled diet with improved adherence to food-based dietary guidelines and is the most preferred, based on minimal absolute deviation from the observed diet.
- The *Max H* diet is a modelled diet with improved adherence to food-based dietary guidelines and is the most healthy, based on the NRD 15.3 for nutrient quality.
- The *Max S* diet is a modelled diet with improved adherence to food-based dietary guidelines and is the most environmentally sustainable, based on GHGE.

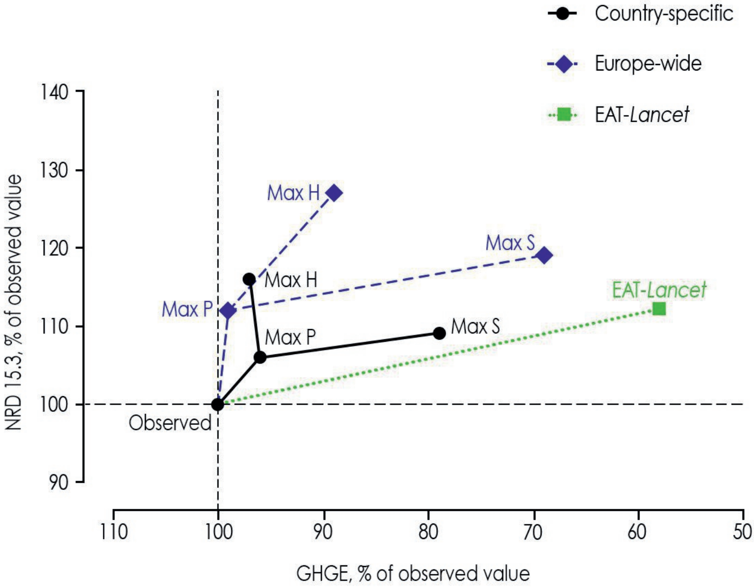


Figure 3 Evaluation of the nutrient quality and the environmental sustainability of the modelled diets according to a benchmarking diet model [ab] and the EAT-*Lancet* diet [64].

[a] All modelled diets have an improved adherence to food-based dietary guidelines. *Max P* is the most preferred diet based on minimal deviation from the observed diet, *Max H* the most healthy diet based on NRD15.3 for nutrient quality, and *Max S* the most environmentally sustainable diet based on GHGE.

[b] Using a country-specific versus a Europe-wide benchmarking diet model.

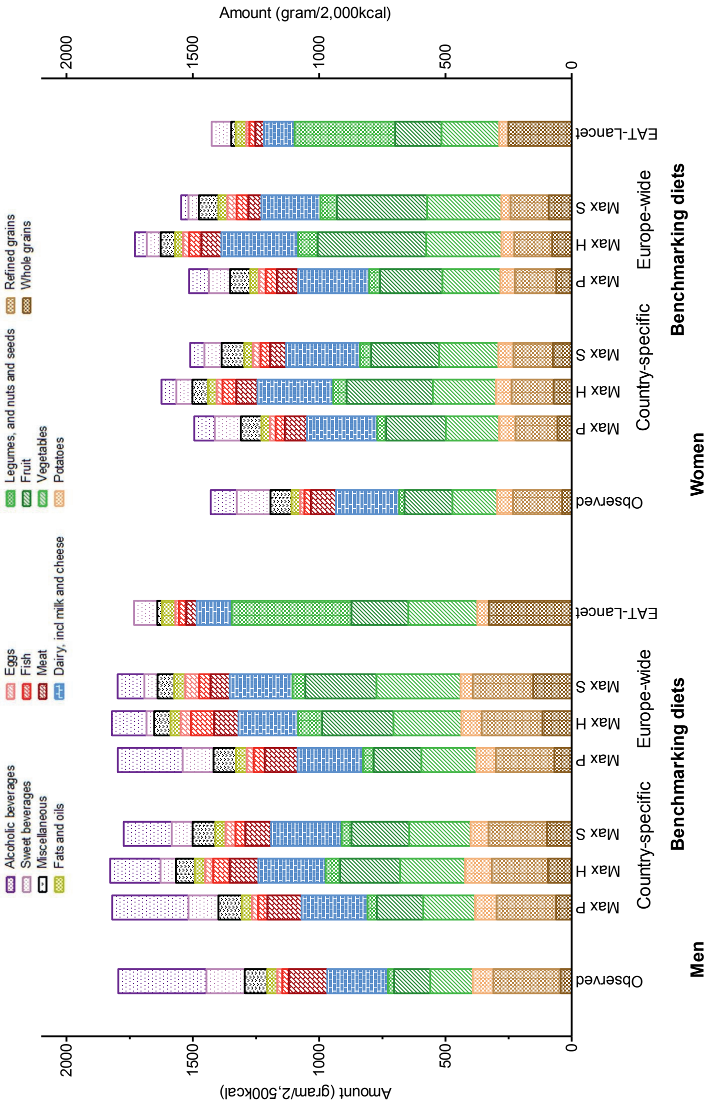


Figure 4 Food group composition of the observed, healthier diets, as modelled by a country-specific and a Europe-wide benchmarking diet model, and the EAT-*Lancet* diet [64]

[a] Average amount of food consumed by the population in gram per 2,500 kcal for men, and gram per 2,000 kcal for women..

Improved diet that is the closest to the observed diet – Max P diet

A first step towards healthier diets within specific European countries can be achieved while preserving on average 85% of the observed diets. When allowing for exchange of food habits across countries, healthier diets were on average for 80% similar to the observed diet. In the Europe-wide context, the improvement in nutrient adequacy was twice as large as in the country-specific context. For the *Max P* diet, environmental impact was not improved in the Europe-wide context, but was on average 4% lower as observed in the country-specific context. Because of the modelling based on food-based dietary guidelines, compared to the observed diet, the *Max P* diet has higher amounts of whole grains, fruit, vegetables, legumes and fish, and lower amounts of meat, sweet and alcoholic beverages. In the Europe-wide context, the amount of sweet beverages was lower for women and that of alcoholic beverages was lower for men as compared to the *Max P* diet in the country-specific context.

Improved diet that has the highest nutrient quality – Max H diet

In a next step, nutrient adequacy was prioritised on top of improved adherence to food-based dietary guidelines. However, prioritising nutrient adequacy occurred at the expense of dietary preferences, i.e. only 72% of the food group intake remained similar in the country-specific context and 61% for the Europe-wide context. In this Europe-wide context, the improvement in nutrient adequacy was larger than in the country-specific context, i.e. on average 27% versus 16%. For the *Max H* diet, environmental impact was on average 11% lower in the Europe-wide context, with hardly any improvement in the country-specific context. The *Max H* diet had even higher amounts of whole grains, fruit, vegetables, legumes and fish, and lower amounts of sweet and alcoholic beverages. In the Europe-wide context, the amount of fruit, vegetables, and legumes was even higher, and the amount of sweet and alcoholic beverages was even lower as compared to the *Max H* diet in the country-specific context.

Improved diet that has the highest environmental sustainability – Max S diet

As for nutrient quality, environmental sustainability was prioritised on top of improved adherence to food-based dietary guidelines. Prioritising environmental sustainability also occurred at the expense of dietary preferences, i.e. only 73% of the food group intake remained similar in the country-specific context and 64% for the Europe-wide context. Again, in this Europe-wide context, the improvement in nutrient adequacy was twice as large as in the country-specific context, i.e. on average 19% versus 9%. Environmental impact of the *Max S* diet was on average 21% lower in the country-specific context and on average 31% lower in the Europe-wide context. Compared to the observed diet, the *Max S* diet in the country-specific context had a higher amount of animal-sourced foods, but protein sources shifted from red and processed meat to poultry, fish, eggs and/or dairy. In the Europe-wide context, the amount of meat was even lower, while dairy was not chosen as a replacement food for meat. This finding is related to the fact that dietary improvement options are more frequently derived from Italian diets where dairy intake, excluding cheese and butter, is relatively low as compared to dairy intake in France and Denmark (Chapter 4).

The EAT-Lancet reference diet

The healthy reference diet, as presented by the EAT-*Lancet* Commission, is mainly characterised by relatively low amounts of meat (43g/2,500kcal), and higher amounts of legumes (75g/2,500kcal), nuts and seeds (50g/2,500kcal) and whole grains (332g/2,500kcal) [64]. It would require much more changes in the observed diet than the diets for Europe as modelled in this thesis, as it was only for 39% similar to the observed diet. Moreover, the EAT-*Lancet* diet would have the largest improvement in environmental impact, on average 42%, while the improvement in nutrient adequacy was on average only 12%.

> This thesis shows that dietary improvements for more healthy and environmentally sustainable diets requires sacrifices in terms of dietary preferences. Moreover, in the context of observed diets in four European countries, the maximal solutions for health compromise the maximal solutions for environmental sustainability in the design of realistic and feasible diets, and vice versa.

A tailored approach, as applied in the benchmarking diet model, accounts for the large variation of individual dietary patterns, and thereby performs better regarding acceptability and realistic dietary improvements. The diets modelled in this thesis represent the maximal feasible solutions for dietary improvement within the range of observed diets, i.e. not the ultimate (better) solutions that can go beyond observed diets. The national country-specific diet model gives solutions for realistic and likely short-term directions of dietary improvements, while long-term directions, which are the exchange of food habits across countries, are represented by the Europe-wide diet model. To further improve both modelling approaches, there is a need to not only include the consumer focus, but also the involvement of supporting (national) policies on consumer diet and agri-food production systems to strengthen the concept of food system thinking that encompasses the activities associated with producing, processing, distributing, purchasing and consuming food.

The EAT-*Lancet* diet outlines a global average and ranges of food group intakes that would benefit human health within the safe planetary boundaries for food production [64]. The EAT-*Lancet* Commission acknowledged that given the ranges of intake included, there are possibilities for local interpretation and adaptation of this diet, with foods and amounts consistent with cultural preferences and habits [64]. Such a national and regional interpretation and adaptation will take time, as the EAT-*Lancet* diet represents an ultimate goal that goes beyond the current dietary practices and even beyond food-based dietary guidelines and food-based diet optimisation models. This highlights the added value of a benchmarking diet model that finds realistic and feasible solutions for dietary improvement within the context of current dietary practices. As the dietary practices are likely to change over time, re-applying such a benchmarking diet model with updated dietary data will provide next steps for moving towards the ultimate goal of healthy and environmentally sustainable diets.

IMPLICATIONS

Research implications

Modelling in this thesis was based on data from four countries from different European regions, i.e. Denmark (Scandinavia), Czech Republic (Central Eastern Europe), Italy (Mediterranean region) and France (Western Europe). Eastern Europe, where a third of all deaths may be caused by unhealthy diets [65], is not well represented in this thesis. Dietary patterns in several Eastern European countries may resemble that of Czech Republic. However, outcomes from this thesis may not merely be extrapolated to the whole of Europe. For future modelling and an integrated food and health policy in Europe, more national dietary surveys in the Eastern European region, preferably linked to the FoodEx2 food classification system [66], are needed. Also for other regions, regular monitoring of dietary intakes should be guaranteed for evidence-based food and health policy.

Scenarios used in food and health policy often rely on macroeconomic models that are based on agricultural commodities and aggregate food consumption data (e.g. by household, *per capita*). This thesis emphasises the value of individual-level dietary data. Observed consumer diets can serve as a starting point for a demand-driven (rather than production-driven) journey towards healthier and more environmentally sustainable diets. The benchmarking approach applied in this thesis can be used within and across European countries, and even globally, provided that representative national dietary intake data are available. While the health impact of foods is rather comparable across different European countries, this is probably not the case for the environmental impact of foods. The latter depends, amongst others, on local production, transport and food waste practices by consumers. For a better estimation of national or regional environmental sustainability of diets, more environmental impact indicators and country-specific harmonised LCA data for foods are needed.

Because this thesis relies on observed diets for modelling dietary improvements, it implicitly accounts for cultural preferences, sensory aspects and culinary practices, as well as affordability and availability of foods in the different countries. Nevertheless, a more sophisticated approach to capture dietary preferences may be considered for future modelling, including the use of food attributes (e.g. taste, texture, and liking) linked to food composition tables, clustering of foods within meals and over time, and prices of foods. Apart from that, more attention could be paid to the reliability aspect of European diets, e.g. food safety and the stability of food supply. Ultimately, this may lead to an extended benchmarking diet model that captures all dimensions of the SHARP diet, i.e. a diet that is environmentally Sustainable, Healthy, Affordable, Reliable and Preferred by consumers.

The benchmark diet model targets the design of improved consumer diets, but not the wide range of interconnected factors related to the food supply chain and its mutual interaction with food consumption. This highlights the importance of coupling a diet model, with macro-level agricultural, trade, and environmental impact analyses for strengthening the achievement of more healthy and environmentally sustainable diets within a sustainable food system. As explored in the SUSFANS project [67]), such a toolbox of interrelated models with harmonised data could become a European wide reference for advancing evidence-based health and food policy in Europe, and for monitoring and evaluating food production and consumption practices in a comparable way at the national level. To ensure comparability at the European level, the diet model could eventually be used on comparable data across Europe, whereas the implementation of food-based dietary guidelines could remain in the national policy remit, as the diet model will provide consumer-oriented dietary guidance considering regional food cultures and challenges.

Public health implications

'Benchmarked' diets, as presented in this thesis, are easier to implement and to communicate to the public than 'optimal' diets. Such optimal diets are (still) beyond reach for large segments of the population, especially for those with less health literacy and/or a lower socioeconomic position [68, 69]. To illustrate, this thesis shows that replacement of ruminant meat with other animal-sourced foods (e.g. fish, white meat, eggs or dairy) is a valuable first step towards more healthy and sustainable diets. This message is probably more acceptable to many European consumers than the commonly conveyed message to replace animal-sourced with plant-sourced foods. The latter will lead to more health and environmental gains, but it ignores the dietary preference aspect. When the public rejects the message of an 'optimal' diet, there will ultimately be less health and environmental gains than when the public accepts a more modest 'benchmarked' diet.

OVERALL CONCLUSION

This thesis provides the methodology and examples for the integration of health, environmental sustainability and dietary preferences in the design of improved healthy and environmentally sustainable diets for consumers in Europe.

National dietary surveys carried out at the individual level serve as an evidence base to assess the healthiness and environmental impact of consumer diets. Direct cross-country comparison is, however, challenged by the methodological differences in national dietary surveys collected at the individual level. This thesis demonstrates that available dietary surveys can be aligned to enable cross-country comparison. In this way, it is possible to assess diet-related health and environmental sustainability in a comparable way across countries by using a common set of reference values for health and a standardised LCA database for environmental sustainability.

This thesis shows that a benchmarking diet model allows designing healthier and more environmentally sustainable diets that are close to dietary preferences of consumers and national dietary practices. This extends the relevance of national dietary surveys from surveillance to public health and agri-food policies at the European level. Within the framework of food-based dietary guidelines and the context of observed diets, dietary solutions presented in this thesis showed similar proportions of animal- and plant-sourced foods as observed diets, but with less beef and more fruit and vegetables, that contributes to nutrient-dense diets with lower energy density. Maximising health and environmental sustainability, however, comes with a trade-off against current dietary preferences. To simultaneously achieve maximal improvement in health and environmental sustainability, current food supply chains need to be rethought and dietary preferences need to be inspired by the rich diversity of European diets.

REFERENCES

1. Pedersen A, Fagt, S., Groth, MV., Christensen, T., Biltoft-Jensen, A., Matthiessen, J., Andersen, NL., Kørup, K., Hartkopp, H., Ygil, K., Hinsch, HJ., Saxholt, E., Trolle, E. : **Danskernes kostvaner 2003-2008**. In.: DTU Fødevareinstituttet; 2009.
2. **Individual food consumption - the national study SISP04** [http://www.chpr.szu.cz/spotrebapotravin.htm]
3. Leclercq C AD, Piccinelli R, Sette S, Le Donne C and Turrini A: **The Italian national food consumption survey INRAN-SCAI 2005-06: main results in terms of food consumption**. *Publ Health Nutr* 2009, **12(12)**:2504 - 2532.
4. Agence Française de Sécurité Sanitaire des Aliments (AFSSA): **Report of the 2006/2007 Individual and National Study on Food Consumption 2 (INCA 2). Synthèse de l'étude individuelle nationale des consommations alimentaires 2 (INCA 2), 2006-2007**. In.; 2009: 1-44.
5. European Food Safety Authority (EFSA): **The food classification and description system FoodEx 2 (revision 2)**. *EFSA Supporting Publications* 2015, **12**(5):804E.
6. European Food Safety Authority (EFSA): **Use of the EFSA Comprehensive European Food Consumption Database in Exposure Assessment**. *EFSA Journal* 2011, **9**(3):2097.
7. Pereira MA: **Diet beverages and the risk of obesity, diabetes, and cardiovascular disease: a review of the evidence**. *Nutr Rev* 2013, **71**(7):433-440.
8. Hu FB: **Resolved: there is sufficient scientific evidence that decreasing sugar-sweetened beverage consumption will reduce the prevalence of obesity and obesity-related diseases**. *Obesity reviews : an official journal of the International Association for the Study of Obesity* 2013, **14**(8):606-619.
9. Freedman LS, Commins JM, Moler JE, Willett W, Tinker LF, Subar AF, Spiegelman D, Rhodes D, Potischman N, Neuhouser ML *et al*: **Pooled results from 5 validation studies of dietary self-report instruments using recovery biomarkers for potassium and sodium intake**. *Am J Epidemiol* 2015, **181**(7):473-487.
10. Notarnicola B, Sala S, Anton A, McLaren SJ, Saouter E, Sonesson U: **The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges**. *Journal of Cleaner Production* 2017, **140**:399-409.
11. Willett WC, Howe GR, Kushi LH: **Adjustment for total energy intake in epidemiologic studies**. *The American journal of clinical nutrition* 1997, **65**(4):1220S-1228S.
12. Kipnis V, Subar AF, Midthune D, Freedman LS, Ballard-Barbash R, Troiano RP, Bingham S, Schoeller DA, Schatzkin A, Carroll RJ: **Structure of dietary measurement error: results of the OPEN biomarker study**. *American journal of epidemiology* 2003, **158**(1):14-21.
13. Freedman LS, Schatzkin A, Midthune D, Kipnis V: **Dealing with dietary measurement error in nutritional cohort studies**. *Journal of the National Cancer Institute* 2011, **103**(14):1086-1092.
14. Schatzkin A, Kipnis V, Carroll RJ, Midthune D, Subar AF, Bingham S, Schoeller DA, Troiano RP, Freedman LS: **A comparison of a food frequency questionnaire with a 24-hour recall for use in an epidemiological cohort study: results from the biomarker-based Observing Protein and Energy Nutrition (OPEN) study**. *International journal of epidemiology* 2003, **32**(6):1054-1062.
15. De Keyzer W, Huybrechts I, De Vriendt V, Vandevijvere S, Slimani N, Van Oyen H, De Henauw S: **Repeated 24-hour recalls versus dietary records for estimating nutrient intakes in a national food consumption survey**. *Food & nutrition research* 2011, **55**.
16. Holmes B, Dick K, Nelson M: **A comparison of four dietary assessment methods in materially deprived households in England**. *Public Health Nutr* 2008, **11**(05):444-456.
17. Bingham S, Gill C, Welch A, Day K, Cassidy A, Khaw K, Sneyd M, Key T, Roe L, Day N: **Comparison of dietary assessment methods in nutritional epidemiology: weighed records v. 24 h recalls, food-frequency questionnaires and estimated-diet records**. *Br J Nutr* 1994, **72**(04):619-643.

18. Larkin FA, Metzner HL, Guire KE: **Comparison of 3 Consecutive-Day and 3 Random-Day Records of Dietary-Intake**. *J Am Diet Assoc* 1991, **91**(12):1538-1542.
19. Tarasuk V, Beaton GH: **Statistical Estimation of Dietary Parameters - Implications of Patterns in within-Subject Variation - a Case-Study of Sampling Strategies**. *Am J Clin Nutr* 1992, **55**(1):22-27.
20. Tarasuk V, Beaton GH: **The Nature and Individuality of within-Subject Variation in Energy-Intake**. *Am J Clin Nutr* 1991, **54**(3):464-470.
21. Ellozy M: **Dietary Variability and Its Impact on Nutritional Epidemiology**. *J Chron Dis* 1983, **36**(3):237-249.
22. Dodd KW, Guenther PM, Freedman LS, Subar AF, Kipnis V, Midthune D, Tooze JA, Krebs-Smith SM: **Statistical methods for estimating usual intake of nutrients and foods: a review of the theory**. *J Am Diet Assoc* 2006, **106**(10):1640-1650.
23. Guenther PM, Dodd KW, Reedy J, Krebs-Smith SM: **Most Americans Eat Much Less than Recommended Amounts of Fruits and Vegetables**. *J Am Diet Assoc* 2006, **106**(9):1371-1379.
24. Park Y, Dodd KW, Kipnis V, Thompson FE, Potischman N, Schoeller DA, Baer DJ, Midthune D, Troiano RP, Bowles H *et al*: **Comparison of self-reported dietary intakes from the Automated Self-Administered 24-h recall, 4-d food records, and food-frequency questionnaires against recovery biomarkers**. *Am J Clin Nutr* 2018, **107**(1):80-93.
25. Looman M, Feskens EJ, de Rijk M, Meijboom S, Biesbroek S, Temme EH, de Vries J, Geelen A: **Development and evaluation of the Dutch Healthy Diet index 2015**. *Public Health Nutrition* 2017:1-11.
26. Fulgoni III VL, Keast DR, Drewnowski A: **Development and validation of the nutrient-rich foods index: A tool to measure nutritional quality of foods**. *J Nutr* 2009, **139**(8):1549-1554.
27. Drewnowski A: **Defining nutrient density: development and validation of the nutrient rich foods index**. *J Am Coll Nutr* 2009, **28**(4):421s-426s.
28. Montagnese C, Santarpia L, Buonifacio M, Nardelli A, Caldara AR, Silvestri E, Contaldo F, Pasanisi F: **European food-based dietary guidelines: a comparison and update**. *Nutrition* 2015, **31**(7-8):908-915.
29. Bechthold A, Boeing H, Tetens I, Schwingshackl L, Nothlings U: **Perspective: Food-Based Dietary Guidelines in Europe-Scientific Concepts, Current Status, and Perspectives**. *Advances in nutrition (Bethesda, Md)* 2018, **9**(5):544-560.
30. Murphy SP, Barr SI, Poos MI: **Using the New Dietary Reference Intakes to Assess Diets: A Map to the Maze**. *Nutrition Reviews* 2002, **60**(9):267-275.
31. EFSA Panel on Dietetic Products N, Allergies: **Scientific Opinion on establishing Food-Based Dietary Guidelines**. *EFSA Journal* 2010, **8**(3):1460.
32. Institute of Medicine **Dietary Reference intakes: Applications in Dietary Assessment**. In. Washington (DC): National Academies Press; 2000.
33. de Lauzon B, Volatier JL, Martin A: **A Monte Carlo simulation to validate the EAR cut-point method for assessing the prevalence of nutrient inadequacy at the population level**. *Public Health Nutr* 2004, **7**(7):893-900.
34. Gazan R, Brouzes CMC, Vieux F, Maillot M, Lluch A, Darmon N: **Mathematical Optimization to Explore Tomorrow's Sustainable Diets: A Narrative Review**. *Adv Nutr* 2018, **9**(5):602-616.
35. Ekvall T, Azapagic A, Finnveden G, Rydberg T, Weidema BP, Zamagni A: **Attributional and consequential LCA in the ILCD handbook**. *The International Journal of Life Cycle Assessment* 2016, **21**(3):293-296.
36. Blonk H, Ponsioen T, Kool A, Marinussen M: **The Agri-Footprint Method. Methodological LCA framework, Assumption and Applied Data**. In. Edited by Blonk Milieuadvies. Gouda; 2011.
37. Vellinga R, Kuijsten A, Temme EH: **A comparison between Dutch and European Life Cycle Assessment to estimate diet-associated environmental impact**. In. Bilthoven, the Netherlands; 2018.

38. Notarnicola B, Tassielli G, Renzulli PA, Castellani V, Sala S: **Environmental impacts of food consumption in Europe**. *Journal of Cleaner Production* 2017, **140, Part 2**:753-765.
39. Garnett T: **Cooking Up a Storm. Food, Greenhouse Gas Emissions and Our Chaning Climate**. In. Edited by Food Climate Research Network Centre for Environmental Strategy University of Surrey. Guildford; 2008.
40. Heller MC, Keoleian GA, Willett WC: **Toward a life cycle-based, diet-level framework for food environmental impact and nutritional quality assessment: a critical review**. *Environ Sci Technol* 2013, **47**(22):12632-12647.
41. Jones AD, Hoey L, Blesh J, Miller L, Green A, Shapiro LF: **A Systematic Review of the Measurement of Sustainable Diets**. *Adv Nutr* 2016, **7**(4):641-664.
42. Rohmer S, Gerdessen J, Claassen G, Bloemhof J, van't Veer P: **A nutritional comparison and production perspective: Reducing the environmental footprint of the future**. *Journal of Cleaner Production* 2018, **196**:1407-1417.
43. Keating BA, Herrero M, Carberry PS, Gardner J, Cole MB: **Food wedges: Framing the global food demand and supply challenge towards 2050**. *Global Food Security* 2014, **3**(3):125-132.
44. Springmann M, Wiebe K, Mason-D'Croz D, Sulser TB, Rayner M, Scarborough P: **Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail**. *The Lancet Planetary health* 2018, **2**(10):e451-e461.
45. Berkhout P, Achterbosch T, Van Berkum S, Dagevos H, Dengerink J, Van Duijn A, Terluin I: **Global implications of the European Food System: a food systems approach**. In.: Wageningen Economic Research; 2018.
46. Cruwys T, Bevelander KE, Hermans RC: **Social modeling of eating: a review of when and why social influence affects food intake and choice**. *Appetite* 2015, **86**:3-18.
47. Higgs S: **Social norms and their influence on eating behaviours**. *Appetite* 2015, **86**:38-44.
48. Leng G, Adan RAH, Belot M, Brunstrom JM, de Graaf K, Dickson SL, Hare T, Maier S, Menzies J, Preissl H *et al*: **The determinants of food choice**. *The Proceedings of the Nutrition Society* 2017, **76**(3):316-327.
49. Renner B, Sproesser G, Strohbach S, Schupp HT: **Why we eat what we eat. The Eating Motivation Survey (TEMS)**. *Appetite* 2012, **59**(1):117-128.
50. Kramer GF, Tyszler M, Veer PV, Blonk H: **Decreasing the overall environmental impact of the Dutch diet: how to find healthy and sustainable diets with limited changes**. *Public Health Nutr* 2017, **20**(9):1699-1709.
51. Pinho MGM, Mackenbach JD, Charreire H, Oppert JM, Bardos H, Glonti K, Rutter H, Compernolle S, De Bourdeaudhuij I, Beulens JWJ *et al*: **Exploring the relationship between perceived barriers to healthy eating and dietary behaviours in European adults**. *European journal of nutrition* 2018, **57**(5):1761-1770.
52. Hallström E, Carlsson-Kanyama A, Börjesson P: **Environmental impact of dietary change: a systematic review**. *J Clean Prod* 2015, **91**(0):1-11.
53. Seves SM, Verkaik-Kloosterman J, Biesbroek S, Temme EH: **Are more environmentally sustainable diets with less meat and dairy nutritionally adequate?** *Public Health Nutr* 2017, **20**(11):2050-2062.
54. Langeveld Av, Teo P, Pol-van der Vaart K, Siebelink A, Vries Jd, Graaf dC, Mars M: **Profiling the basic tastes and fat sensation of commonly consumed Dutch foods**. In: *EuroSense: 2016; Dijon, France*; 2016.
55. van Bussel LM, Kuijsten A, Mars M, Feskens EJM, van 't Veer P: **Taste profiles of diets high and low in environmental sustainability and health**. *Food Quality and Preference* 2019, **78**:103730.
56. Buttriss JL, Briend A, Darmon N, Ferguson EL, Maillot M, Lluch A: **Diet modelling: How it can inform the development of dietary recommendations and public health policy**. *Nutrition Bulletin* 2014, **39**(1):115-125.

57. Pinho M, Mackenbach JD, Oppert JM, Charreire H, Bardos H, Rutter H, Compernolle S, Beulens J, Brug J, Lakerveld J: **Exploring absolute and relative measures of exposure to food environments in relation to dietary patterns among European adults**. *Public Health Nutr* 2019, **22**(6):1037-1047.
58. Mackenbach JD, Lakerveld J, Van Lenthe FJ, Teixeira PJ, Compernolle S, De Bourdeaudhuij I, Charreire H, Oppert JM, Bardos H, Glonti K *et al*: **Interactions of individual perceived barriers and neighbourhood destinations with obesity-related behaviours in Europe**. *Obesity reviews : an official journal of the International Association for the Study of Obesity* 2016, **17 Suppl 1**:68-80.
59. Kanellopoulos A, Gerdessen J, Ivancic A, van 't Veer P, Geleijnse JM, Bloemhof JM: Designing Healthier and Acceptable Diets Using Data Envelopment Analysis. Public Health Nutr 2019
60. Stichting Voedingscentrum Nederland: **Richtlijnen Schijf van Vijf**. In. Den Haag, Nederland; 2016.
61. GBD 2017 Risk Factor Collaborators: **Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017**. *The Lancet* 2018, **392**(10159):1923-1994.
62. Tobias DK, Hu FB: **The association between BMI and mortality: implications for obesity prevention**. *The lancet Diabetes & endocrinology* 2018, **6**(12):916-917.
63. Brown JD, Buscemi J, Milsom V, Malcolm R, O'Neil PM: **Effects on cardiovascular risk factors of weight losses limited to 5-10**. *Transl Behav Med* 2016, **6**(3):339-346.
64. Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A *et al*: **Food in the Anthropocene: the EAT-*Lancet* Commission on healthy diets from sustainable food systems**. *The Lancet* 2019, **393**(10170):447-492.
65. Afshin A, Sur PJ, Fay KA, Cornaby L, Ferrara G, Salama JS, Mullany EC, Abate KH, Abbafati C, Abebe Z *et al*: **Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017**. *The Lancet* 2019, **393**(10184):1958-1972.
66. European Food Safety Authority (EFSA): **Guidance on the EU Menu methodology**. *EFSA Journal* 2014, **12**(12):3944.
67. Rutten M, Achterbosch TJ, de Boer IJ, Cuaresma JC, Geleijnse JM, Havlík P, Heckelei T, Ingram J, Leip A, Marette S: **Metrics, models and foresight for European sustainable food and nutrition security: the vision of the SUSFANS project**. *Agricultural Systems* 2016.
68. Irala-Estevez JD, Groth M, Johansson L, Oltersdorf U, Prattala R, Martinez-Gonzalez MA: **A systematic review of socio-economic differences in food habits in Europe: consumption of fruit and vegetables**. *Eur J Clin Nutr* 2000, **54**(9):706-714.
69. Darmon N, Drewnowski A: **Does social class predict diet quality?** *Am J Clin Nutr* 2008, **87**(5):1107-1117.

English summary

In Europe, overconsumption and unhealthy diets cause a massive triple burden of diseases, including obesity, non-communicable diseases and nutrient deficiencies. Apart from that, our diet not only impacts health, but also the environment. Currently, the land area needed to produce an average European diet is roughly around half a football pitch per person per year. There is thus an urgent need to transform both food production systems and food consumption patterns.

This thesis develops a methodology to design the first steps towards more healthy and environmentally sustainable diets that are acceptable for European consumers. To achieve this, this thesis operationalised health of the diet using a food- and a nutrient-based approach, and the environmental sustainability of the diet was assessed using greenhouse gas emissions (GHGE) and land use (LU).

We first reviewed how nutritional health was operationalised in published research on healthy and environmentally sustainable diets (Chapter 2), and we conducted a validation study on the assessment of diet-related environmental impact using individual-level dietary data (Chapter 3). Further, the current status of European diets was described in terms of health (Chapter 4) and environmental sustainability (Chapter 5) using data from four European countries, i.e. Denmark, Czech Republic, Italy and France. Subsequently, health and environment were integrated in a benchmarking diet model (Chapter 6), which provides more healthy and environmentally sustainable diets that fit within the dietary preferences of European consumers (Chapter 7). The final chapter (Chapter 8) discusses the main findings and their implications.

PART I: Methodological aspects of assessing health and environmental sustainability of diets

In the past decade, various studies have optimised diets for environmental sustainability. How health aspects were operationalised in those studies was described a literature review of 49 studies (Chapter 2). Five different approaches were identified: three following a descriptive outline that compared diets with each other based on dietary guidelines, dietary quality scores or diet-related health-impact, and two following an analytical outline for the design of alternative diets using food item replacement or diet modelling. In particular, for the design of alternative diets, the complexity of the diet can be captured in a reproducible and valid way by using a diet model. Such a diet model aim to compose a diet that satisfies nutrient recommendations and/or food-based dietary guidelines, amongst other diet-related factors, such as minimising environmental impact and maximising dietary preferences. As an avenue for future research in designing alternative diets, we proposed the concept of a diet that is SHARP: environmentally Sustainable, Healthy, Affordable, Reliable and Preferred. The operationalisation of such a diet requires further exploration of mapping all diet-related dimensions into quantifiable indicators.

Like the assessment of nutrient and food intakes, the assessment of diet-related environmental impact is dependent on the method of dietary assessment. In a validation study, the performance of a food frequency questionnaire (FFQ) for assessing diet-related environmental impact was compared to the 24-hour recall (24hR). In addition, it was assessed whether the method of dietary assessment affects the association that is observed with diet quality (Chapter 3). Analyses were based on 1,169 men and women, who participated in the NQplus study in the Netherlands, and completed a 216-item FFQ and two replicates of a web-based 24hR. Life cycle assessments of 207 foods taken from Blonk Consultants were used to assess diet-related GHGE, LU and fossil energy use of a Dutch diet. After energy-adjustment, the FFQ underestimated diet-related environmental impact by 7-10% as compared to the reference 24hR. Energy-adjustment by the residual method of observed values showed covariate-adjusted attenuation coefficients that vary between 0.48-0.60, and the attenuation was lower for density residuals (with covariate-adjusted attenuation coefficients varying between 0.57-0.69). Diet-related environmental impact was inversely associated with a food-based diet score for both FFQ and 24hR, while associations with a nutrient-based diet score were inconsistent. This implies that in the context of observed diet, a healthy diet is not necessarily an environmentally sustainable diet.

PART II: Health and environmental sustainability of European diets.

European food consumption patterns were described in terms of food groups and nutrients using national survey data carried out at the individual level in four countries, i.e. Denmark, Czech Republic, Italy and France (Chapter 4). Intakes of food groups showed large deviations from food-based dietary guidelines in all countries, in particular low intakes for legumes (<20g/d), and nuts and seeds (<5g/d), and high intakes for red and processed meat (>80g/d). Intakes of fruit and vegetables showed considerable geographical variability. Intake of dairy, excluding cheese and butter, was relatively high in Denmark, as was the case for sweet and alcoholic beverages. Italy and France had the highest intake of fish. For nutrients, intakes were inadequate for dietary fibre in all countries. Intakes of potassium and folate were the most inadequate in Czech Republic, magnesium in Italy, and vitamin E in Denmark. Within countries, dietary intakes also varied by age, gender and educational level, but not by overweight status.

The environmental impact associated with observed consumer diets across four European countries was assessed (Chapter 5). Dietary intake data from Denmark, Czech Republic, Italy and France were linked to a newly developed pan-European environmental sustainability indicator database that contains GHGE and LU values for ~900 foods. Energy intake explained 41% and 33% of the variation in daily GHGE and LU, respectively, and a 200-kcal (10%) higher intake was associated with a 9-10% higher daily GHGE and LU. Expressed per 2,000 kcal, mean GHGE ranged from 4.4 to 6.3 kgCO_2eq, and LU ranged from 5.7 to 8.0 m^2/year. Country explained 49% and 45% of this variation in GHGE and LU, respectively, while age, gender, educational level and overweight status were of minor importance. In all four countries, the main contributors to total GHGE and LU were meat products with a relative contribution for total meat varying between 36 and 38 percent for GHGE and between 45 and 52 percent for LU. Once country and reported energy intake were accounted for, dietary choices of meat – especially the proportion of ruminant meat to total meat – explained most of the variation in GHGE, i.e. 11% for meat and 17% for the proportion of ruminant meat. A 5 energy percent (50g/2,000-kcal) higher meat intake was associated with a 10% higher GHGE, and a 20% higher proportion of ruminant to total meat with a 10% higher GHGE. Similar results were found for LU.

PART III: Identification of dietary improvement options for European consumers that integrate health, environmental sustainability and dietary preferences

To facilitate the transition to healthy and environmentally sustainable diets, the first steps for dietary improvement needs to be identified. Examples for such first steps can be provided by a benchmarking diet model (Chapter 6). A benchmarking diet model composes diets that are not only healthier and more environmentally sustainable, but also implicitly fit dietary preferences. Dietary survey data of 6,462 adults from Denmark, Czech Republic, Italy and France were used for benchmarking diets with respect to adherence to food-based dietary guidelines (Chapter 7). After that, these diets were optimised for dietary preferences, nutrient quality and environmental sustainability. When dietary preferences were prioritised, the nutrient rich diet (NRD) 15.3, i.e. a diet score for nutrient quality, was ~6% higher, GHGE was ~4% lower as compared to the observed diet, and ~85% of food group intake remained similar to the observed diets. When nutrient quality was prioritised, NRD15.3 was ~16% higher, GHGE was ~3% lower, and ~72% of food group intake remained similar. When environmental sustainability was prioritised, NRD15.3 was ~9% higher, GHGE was ~21% lower, and ~73% of food group intake remained similar. Thus, the maximal solutions for nutrient quality and environmental sustainability occurred at the expense of dietary preferences, and they cannot be achieved simultaneously. Compared to the observed diet, all improved diets are mainly characterised by higher amounts of fruit, vegetables, whole grains, fish, and lower amounts of meat, and sweet and alcoholic beverages. Still, the proportion of animal- to plant-sourced foods was similar in the observed diet and in the modelled diets, but animal-sourced foods shifted from red and processed meat (in particular beef) to fish, poultry, eggs and/or dairy.

CONCLUSION

In conclusion, as described in Chapter 8, this thesis provides the methodology and examples for the integration of health, environmental sustainability and dietary preferences in the design of improved diets for consumers in Europe.

National dietary surveys carried out at the individual level serve as an evidence base to assess the healthiness and environmental impact of consumer diets. This thesis demonstrates that available dietary surveys can be aligned to enable cross-country comparison. In this way, it is possible to assess diet-related health and environmental sustainability in a comparable way across countries by using a common set of reference values for health and a standardised LCA database for environmental sustainability. The addition of indicators for environmental sustainability and country-specific harmonised LCA data for foods are, however, needed to obtain a more balanced picture of the diet-related environmental impact in a particular country.

More importantly, this thesis shows the possibility of designing more healthy and environmentally sustainable diets that are close to dietary preferences of consumers and national dietary practices by using a benchmarking diet model. This extends the relevance of national dietary surveys from surveillance to public health and agri-food policies at the European level. The benchmarking diet model proposed here provides examples for the first steps towards improved diets in the framework of food-based dietary guidelines, including options that remain as close as possible to the observed diet, are the most healthy or the most environmentally sustainable. Next steps in the design of alternative diets are required to explore the full spectrum of the SHARP diet dimensions, i.e. environmentally Sustainability, Health, Affordability, Reliability and dietary Preferences.

While improving adherence to food-based dietary guidelines within the range of observed diets, modelled diets had a similar proportion of animal- and plant-sourced foods as the observed diets, but energy density of these diets was lower. Maximal solutions for health and environment, however, come with a trade-off against current dietary preferences. To simultaneously achieve maximal improvement in health and environmental sustainability, current food supply chains need to be rethought and dietary preferences need to be inspired by the rich diversity of European diets.

Dankwoord | Acknowledgements

Mijn tijd in Wageningen zit erop! Wat een bijzondere reis was de afgelopen vier jaar. Nu ben ik zeer trots op het einde van deze reis: MIJN PROEFSCHRIFT. Graag wil ik iedereen bedanken die hieraan heeft bijgedragen.

Allereerst grote dank aan mijn promotors en co-promotor. Ontzettend bedankt voor de uitdaging om het thema voeding en duurzaamheid verder uit te diepen. Ik heb enorm veel van jullie geleerd. Marianne, dank je wel voor je vertrouwen in mij om dit project uit te voeren. Ik bewonder jouw kritische blik en jouw ‘helicopter view’. Pieter, jouw onuitputtelijke creativiteit betreffende statistische analyses is bewonderenswaardig. Bedankt voor de inspirerende discussies en voor het roodkleuren van mijn manuscripten. Anneleen, jouw betrokkenheid bij mijn onderzoek en jouw scherpziende kanttekeningen heb ik erg gewaardeerd.

I would like to thank the promotion committee Dr. Monika Zurek, Dr. Corné van Dooren, Prof. Jack van der Vorst and Prof. Kees de Graaf for reading my thesis and being present at my defence.

Mijn paranimfen, Liesbeth en Vera. Wat ben ik ontzettend blij dat jullie deel uitmaken van mijn reis in Wageningen. Liesbeth, mijn overbuur! Bedankt voor je gezelligheid, je luisterend oor en je babbeltjes, de gezellige momenten van puzzelen in de winter tot wandelen over de dijk en ijsjes eten in de zomer. Vera, mijn kamer 1061-roomie! Bedankt voor je gezelligheid, je babbeltjes, het organiseren van uitjes, het samen leegdrinken van een pot thee of twee per dag.

To all partners of the SUSFANS project, Ellen, Marcela, Lorenza, Laura, Aida, Carine, Sandra, and Sabrina, thank you very much for giving me the opportunity to apply the benchmarking diet model to your dietary survey data, and thank you for your valuable ideas and concerns regarding handling the dietary data. To all team members of the TiFN project SHARP-BASIC, thank you very much for the nice collaborations and inspiring discussions. To all co-authors, thank you for providing me with valuable feedback on the manuscripts.

Gerdine, dank je wel voor je bijdrage aan de SHARP-ID, met deze data zetten wij milieu-impact van het voedingspatroon op de kaart. Herinneringen aan een onvergetelijke tijd. Je stond altijd paraat voor een gezellige babbel. Argyris, it was a great privilege to work with you. Thank you for the close collaboration on the benchmarking diet model. Never forget to celebrate all kind of victories, even the little ones.

Alle (oud-) collega's van de afdeling Humane Voeding en Gezondheid, bedankt voor de leuke tijd, de lunchwandelingen en de PhD reis door de UK. Also, a special thanks to my roommates of room 1061 at Helix, Vera, Gerdine, Desiree, Ruoxuan, Marie-Luise, Ilse, Pol and Apple. I have had a memorable time while working with you in the office: a lot of talks and laughs, making decorations for Easter and Christmas, but also hard work. Thank you for your understanding when I was talking to SAS or Xpress. I am going to miss all of you.

Lieve Nicole, Famke, Liesbeth, Vera, Ellen, Mariëlle, Anniek, Lisa, Lieve, Hanne, Evelien en Stefanie. Dank jullie wel voor de gezelligheid de afgelopen jaren. Het is altijd fijn om met jullie te babbelen en zalig te ontspannen. Herinneringen aan leuke momenten van avondeten, wandelen, gezelschapspelletjes, en whisky- en bieravonden. Bedankt voor jullie geduld wanneer ik nog even de pot wou uitscharen en wanneer ik te enthousiast was bij winst of heel stilletjes bij verlies. Ook dank u wel aan Anne, wat ben ik trots dat ik jouw "Elly-to-the-rescue" kan zijn. Jouw inzet, jouw moed en jouw gedrevenheid blijven me buitengewoon inspireren. Ik denk nog vaak aan wat een plezier wij hadden met het uitpluizen van bf160 bier en bf133 taart en gebak.

Allerliefste mama en papa, ik prijs me gelukkig met jullie. Bedankt voor jullie steun en interesse in mijn onderzoek. Het is heerlijk om elk weekend weer thuisthuis te komen in Merksplas (BE) om gewoon bij jullie te zijn. Dank jullie wel voor de goede zorgen en de autoritjes naar Wageningen en Tilburg station.

Mijn lieve zus, Lena, wat denk ik vaak dat wanneer ik je zie, ik in een spiegel kijk. Wij lijken veel op elkaar. Zo hebben we allebei 'een piek om te pieken' en wandelen we samen 100km op pure doorzettingskracht. Maar toch, als ik beter kijk, dan zie ik dat we elk heel uniek zijn. Ik ben super trots op wat jij doet als leerkracht Wiskunde – Economie. Bedankt voor het samen avondeten via Skype en ook voor de autoritjes naar Wageningen en Tilburg station.

Mijn Michiel dank ik als laatste, zonder jou stond ik hier niet! Wat vind ik het geweldig dat jij dag en nacht mijn luisterend oor bent. Dank je wel voor mij te laten stomen en nadien weer te laten lachen. Zalig genoten van jouw telefoontjes, al jouw massa's bezoekjes in Wageningen en niet te vergeten de Magnum-dates! Weet zolang jij bij mij bent, verveel je je nooit.

ELLY.

About the author

CURRICULUM VITAE


© Bart van Overbeeke Fotografie

Elly Mertens was born on March 26, 1992 in Turnhout, Belgium. After completing secondary school at Instituut Spijker in Hoogstraten in 2010, she started studying Nutrition and Dietetics at Plantijn Hogeschool in Antwerp. She obtained her Bachelor's degree <*magna cum laude*> in 2013 and continued her education in Nutrition and Health at Wageningen University, the Netherlands. In 2015, Elly completed her MSc thesis entitled: "Association between blood pressure trajectories and dietary protein intake in the Zutphen Study". Thereafter, she was an intern at the Hugh Sinclair Unit of Human Nutrition at the University of Reading where she investigated the association between diet as a whole and cardiovascular incidence and risk markers in the Caerphilly Prospective Study. She won an award (by NVVL Network for Food Experts) for the best MSc internship report. In 2015, Elly obtained her Master's degree <*cum laude*> with a specialisation in Nutritional Epidemiology and Public Health. After graduating, she started her PhD training in healthy and environmentally sustainable diets for European consumers at the Division of Human Nutrition and Health of Wageningen University. With this PhD project, she aimed to bridge the gaps between 'food', 'nutrition', 'health', and 'environmental sustainability', and she took the challenge to familiarise herself with a benchmarking diet model for the design of improved diets. In her project, she actively involved stakeholders from public health and food industry. During her PhD training, Elly was involved in teaching at the BSc and MSc level, and she was a member of the organising committee of the PhD study tour to the United Kingdom in 2017. She attended several (international) conferences and courses within the educational programme of VLAG. She won a runner-up award (by the Dutch Nutrition Society, NAV) for the best research publication in 2016. Moreover, she was selected as a participant of the 49th ten-day International teaching Seminar on Cardiovascular disease Epidemiology and Prevention in Kuala Lumpur, Malaysia. In 2019, she was selected to participate in the 25th seminar of the European Nutrition Leadership Platform in Luxembourg. For four months, Elly continued her work in the field of healthy and environmentally sustainable diets as postdoctoral researcher at the division of Human Nutrition and Health of Wageningen University.

LIST OF PUBLICATIONS

Published abstracts
Mertens E, Tielemans S, Soedamah-Muthu S, Geleijnse J: Pulse pressure trajectories in relation to cardiovascular mortality and dietary protein intake: the Zutphen Study. *Proceedings of the Nutrition Society* 2015, 74(OCE5).

Peer reviewed publications
Mertens E, Markey O, Geleijnse JM, Givens DI, Lovegrove JA: Dietary Patterns in Relation to Cardiovascular Disease Incidence and Risk Markers in a Middle-Aged British Male Population: Data from the Caerphilly Prospective Study. *Nutrients* 2017, 9(1).

Mertens E, Markey O, Geleijnse JM, Lovegrove JA, Givens DI: Adherence to a healthy diet in relation to cardiovascular incidence and risk markers: evidence from the Caerphilly Prospective Study. *European journal of nutrition* 2018, 57(3):1245-1258.

Mertens E, Van't Veer P, Hiddink GJ, Steijns JM, Kuijsten A: Operationalising the health aspects of sustainable diets: a review. *Public Health Nutr* 2017, 20(4):739-757.

Mertens E, Kuijsten A, Geleijnse JM, Boshuizen HC, Feskens EJM, Van't Veer P: FFQ versus repeated 24-h recalls for estimating diet-related environmental impact. *Nutrition journal* 2019, 18(1):2.

Mertens E, Kuijsten A, Dofkova M, Mistura L, D'Addezio L, Turrini A, Dubuisson C, Favret S, Havard S, Trolle E *et al*: Geographic and socioeconomic diversity of food and nutrient intakes: a comparison of four European countries. *European journal of nutrition* 2019, 58(4):1475-1493.

Mertens E, Kuijsten A, van Zanten HHE, Kaptijn G, Dofková M, Mistura L, D'Addezio L, Turrini A, Dubuisson C, Havard S *et al*: Dietary choices and environmental impact in four European countries. *Journal of Cleaner Production* 2019, 237:117827.

Mertens E, Kaptijn G, Kuijsten A, van Zanten H, Geleijnse JM, van 't Veer P: SHARP-Indicators Database towards a public database for environmental sustainability. *Data in Brief* 2019, 27:104617.

Expected publications
Mertens E, Kuijsten A, Kanellopoulos A, Dofkova M, Mistura L, D'Addezio L, Turrini A, Dubuisson C, Havard S, Trolle E *et al*: Improving health and environmental sustainability of European diets using a benchmarking approach. *(submitted)* 2019.

OVERVIEW OF COMPLETED TRAINING ACTIVITIES

Discipline specific activities
Multivariate analyses for food data/sciences – VLAG (Wageningen, 2016)
Exposure Assessment in Nutrition Research – VLAG (Wageningen, 2016)
Mixed Models – VLAG (Wageningen, 2017)
49th ten-day International teaching Seminar on Cardiovascular disease Epidemiology and Prevention –ISCEP (Kuala Lumpur, 2017)
Healthy and Sustainable diets: synergies and trade-offs– VLAG (Wageningen, 2017)
Modelling of habitual intake using SPADE – VLAG/RIVM (Wageningen, 2017)
Dutch Nutritional Science Days – NAV (Kapellerput Heeze, 2015-2019)
3rd Wageningen PhD Symposium "Diversity in Science"– WU (Wageningen, 2016)
Dutch Epidemiological Conference, WEON – VvE (Wageningen, Utrecht, Groningen, 2016, 2018, 2019)
Congres Zuivel & Duurzaamheid – Friesland Campina Instituut (Rotterdam, 2016)
FOOD2030 Towards sustainable agri-food systems – University of Hohenheim (Stuttgart, 2018)
13th European Nutrition Conference FENS 2019 – Nutrition Society (Dublin, 2019)

General courses
PhD week – VLAG *(Baarlo, 2015)*
Orientation on teaching for PhD candidates – Educational Staff Development *(Wageningen, 2016)*
Efficient Writing Strategies – Wageningen in'to Languages *(Wageningen, 2017)*
Teaching and Supervising Thesis students – Educational Staff Development *(Wageningen, 2017)*
25th European Nutrition Leadership Programme | Essentials – ENLP (*Luxembourg, 2019)*
Writing Grant Proposals – Wageningen Graduate School *(Wageningen, 2018)*
Career Perspectives – Wageningen Graduate School *(Wageningen, 2019)*

Optionals
Preparing PhD research proposal – WU *(Wageningen, 2015)*
ORL-20306 Decision Science 1 – WU *(Wageningen, 2015)*
ESA-20806 Principles of Environmental Sciences – WU *(Wageningen, 2016)*
PhD study tour Division of Human Nutrition and Health – WU *(UK, 2017)*
Staff seminars, group meetings, paper clubs – WU *(Wageningen, 2015-2019)*

COLOPHON

The research described in this thesis was financially supported by the European Union’s H2020 Programme under Grant Agreement number 633692 (SUSFANS: Metrics, models and foresight for European sustainable food and nutrition security); and TiFN (Wageningen), a public-private partnership on pre-competitive research in food and nutrition, under Project Agreement number 15SD01 (SHARP-BASIC).

Financial support from Wageningen University and TiFN for printing this thesis is gratefully acknowledged.

Cover design by Mercedes Benjaminse, ProefschriftMaken
Printed by ProefschriftMaken, Wageningen.