More sustainable European diets based on self-selection do not require exclusion of entire categories of food

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Abbreviations:

AHC: agglomerative hierarchical clustering
ANOVA: Analysis of variance
EFSA: European Food Safety Authority
FAO: Food and Agriculture Organization of the United Nations
FINDIET: Finnish national dietary survey
FOODEX: Food classification system derived by the EFSA
GHGE: greenhouse gas emissions
INCA2: second French Individual and National Dietary Survey
INRAN-SCAI: Italian National Food consumption survey
LCA: life cycle assessment
MAR: Mean Adequacy Ratio
MER: Mean Excess Ratio
MFA: multiple factorial analysis
NDNS: United Kingdom national diet and nutrition survey
RIKSMATEN: Swedish national dietary survey
SED: solid energy density
Kcal: kilocalories
g=grams
d=day

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Abstract

Sustainable diets are nutritious, culturally acceptable and have low environmental impact. The aim of this study was to identify sustainable diets among actual self-selected diets based on five national dietary surveys (Finland, France, Italy, Sweden, the United Kingdom), without ex ante assumptions concerning the food content of diets. Using nutrient intakes and dietary greenhouse gas emissions as active variables, energy-adjusted multiple factor analysis and agglomerative hierarchical clustering were applied to identify clusters of diets. The cluster with the lowest dietary GHGE had the lowest nutritional quality. Another cluster displayed a good compromise between nutritional quality and dietary GHGE (21% lower than the average of observed diets) and was therefore considered as more sustainable than the other clusters. Compared to the rest of the sample, diets in the more sustainable cluster were characterized by a larger quantity of plant-based products and lower quantities of meats, soft drinks and alcoholic beverages. The average diet in this cluster contained approximately 1000 grams per day (g/d) of plant-based products (including 400 g/d of fruit and vegetables, 100 g/d of juices and 500 g/d of other plants) and 400 g/d of animal-based products (including 100 g/d of meat/fish/eggs of which livestock meat represented 20 g/d, 50 g/d of animal-based composite dishes, 30 g/d of cheese and 220 g/d of other dairy products). We concluded that exclusion of entire food categories (e.g., meat) is not necessary to improve the sustainability of European diets.

Keywords: Nutrition, greenhouse gas emissions, multicriteria analysis, meat, environment, flexitarian

Highlights:

Self-selected diets were studied because they are likely to be culturally acceptable.

European diets with the best environmental and nutritional compromise were identified.

The greenhouse gas emissions were 21 % lower than the average of observed diets.

The diets contained 1 kg of plant-based products and 400 g of animal-based products.

Exclusion of entire categories of food is not a necessity to improve sustainability.

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1. Introduction

In response to the growing evidence that food consumption patterns, due to negative health and environmental impacts, are fundamentally unsustainable globally the Food and Agriculture Organization of the United Nations (FAO) defined sustainable diets as environmentally respectful, nutritionally adequate and healthy, economically fair and affordable and culturally acceptable (FAO, 2010). In the process of establishing the food content of such diets, the compatibility between environmental impact and healthiness has received increasing attention, especially in European countries (Aleksandrowicz et al., 2016; Mertens et al., 2017; Perignon et al., 2017). Most studies are based on comparisons between current and theoretical diets (Aleksandrowicz et al., 2016; Mertens et al., 2017; Nelson et al., 2016), with the latter derived based on either simulations or mathematical optimization. Simulations have included scenarios based on adherence to dietary guidelines (Tukker et al., 2011; Wolf et al., 2011), traditional food patterns (e.g. Mediterranean, Nordic) (Sáez-Almendros et al., 2013; Saxe et al., 2012; Tukker et al., 2011), exclusion of entire food categories (e.g. pescatarian, vegetarian, vegan diets) (Baroni et al., 2007; Berners-Lee et al., 2012; Kim et al., 2019; Springmann et al., 2018; Tilman and Clark, 2014), and replacement of specific food items (e.g. meat/dairy being replaced by plant-based products) (Seves et al., 2017; Temme et al., 2013; van de Kamp et al., 2018a, 2018b; Vieux et al., 2012). A limitation of simulation studies is that they are based on preconceived views concerning the food content of a sustainable diet. Another limitation is that nutritional and environmental indicators are outputs of the scenarios, meaning that they do not necessarily improve and may even worsen in some scenarios (Payne et al., 2016; Seves et al., 2017; Vieux et al., 2012). In contrast, mathematical optimization integrates nutritional and environmental constraints in the model thereby guaranteeing that the diets modeled are both nutritionally adequate and reduce environmental impacts (Donati et al., 2016; Green et al., 2015; Horgan et al., 2016; Macdiarmid et al., 2012a; Perignon et al., 2016b; van Dooren et al., 2015; Vieux et al., 2018). By deriving optimized diets which are as close as possible to observed population averages (Macdiarmid et al., 2012b; Perignon et al., 2016b) or individual diets (Horgan et al., 2016) the cultural dimension is taken into account. However, the findings remain theoretical as the modeled diets are never tested in the real word and hence it is questionable whether consumers would accept these diets.

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Thus, there is a need to more directly take into account the notion of cultural acceptability and consumer preferences (Irz et al., 2016). It seems reasonable to assume that self-selected diets are more culturally appropriate than theoretical diets as, by definition, they are already consumed by at least some individuals (Aleksandrowicz et al., 2016; Perignon et al., 2017). However, epidemiological studies analyzing the sustainability of self-selected diets have found that lower greenhouse gas emissions (GHGE) are not necessarily associated with higher nutritional quality and vice versa (Biesbroek et al., 2017; Payne et al., 2016; Perignon et al., 2016a; Sjors et al., 2017; Vieux et al., 2013a). Investigating the impact of dietary recommendations based on a behavioral consumer choice model (Irz et al., 2016) reached a similar conclusion. This can be explained by a quantity vs quality dichotomy, with the environmental impact being closely and positively linked to both physical quantities and calories ingested (Vieux et al., 2012). At a given level of caloric intake, low quality diets, due to high energy density, are consumed in smaller quantities and thus often have low GHGE (Vieux et al., 2013a). Furthermore, some foods, such as high-sugar foods and refined cereals, display both low GHGE and low nutritional quality (Masset et al., 2014a; Payne et al., 2016). As sustainability dimensions may not be compatible with one another, one-dimensional analyses are inappropriate in identifying more sustainable food choices.

Multicriteria analyses applied to self-selected diets, overcoming the quantity vs quality dichotomy, are urgently needed in order to identify realistic sustainable diets that are culturally acceptable. The objective of the present study was therefore to apply such energy-adjusted multicriteria approaches, without ex ante assumptions concerning the food content, to identify which current self-selected diets are relatively more sustainable in five European countries, namely Finland, France, Italy, Sweden and the UK. Our contribution is both methodological and empirical. We develop and test a new method for identification of sustainable diets and the results have broad policy implications. We conclude that significantly lower GHGE from diets with high nutritional quality and already adopted by a large share of the European population is possible. The relatively more sustainable diets do not exclude entire categories of foods (e.g. meat), which suggests that flexitarian diets should be promoted in order to improve the sustainability of European diets.

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2. Material and Methods

2.1. Dietary surveys and nutritional and environmental indicators

2.1.1. Study population

Dietary intake data were derived from five national food consumption surveys, i.e. the Finnish 2012 national dietary survey (FINDIET) based on one 48h recall (n=1708) (Helldan et al., 2013); the French 2006–2007 individual and national dietary survey (INCA2) based on 7-day dietary records (n=4079) (AFSSA, 2009); the Italian 2005-2006 national food consumption survey (INRAN-SCAI) based on 3-day dietary records (n=3323) (Leclercq et al., 2009); the Swedish 2010 national dietary survey (Riksmaten) based on 4-day dietary records (n=1797) (Amcoff et al., 2012); and the 2008–2012 rolling national diet and nutrition survey (NDNS) in the UK based on 4-day dietary records (n=4156) (NatCen Social Research et al., 2015). Detailed information of each survey is available in supplementary data. Individuals younger than 18 years old and older than 64 years old, consumers of dietary supplements and one outlier (Franklin et al., 2001) were excluded. The final sample consisted of 8302 individuals including 568 men and 679 women in Finland, 930 men and 1323 women in France, 967 men and 1105 women in Italy, 588 men and 764 women in Sweden and, 627 men and 751 women in the UK. Age, and socio-demographics information of each selected sample are available in supplementary data.

2.1.2. Individual dietary intakes

Each national institute provided individual energy and nutrient intakes as well as the consumed quantities of 151 food items. The food items were derived from the FoodEx food classification system (European Food Safety Authority, 2011) and grouped into 6 food groups and 27 food sub-groups. Information on folates was not available in the Italian survey and was assumed to be the same as for the corresponding French food items (The French Information Center on Food Quality, 2013). Information on free sugars (monosaccharides and disaccharides added to foods by the manufacturer, cook or consumer, plus the sugars that are naturally present in honey, syrups and fruit juices) was not available in the Swedish, Finish and Italian surveys. It was assumed that the content of intrinsic sugar (naturally present in food) was the same as for the corresponding French food items (Lluch et al., 2017) and the level of free sugars was calculated as the difference between total sugar content (according to the national surveys) and intrinsic sugar content.

2.1.3. Nutritional quality indicators

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Three nutritional quality indicators (Vieux et al., 2013b) were estimated for each individual: The Mean Adequacy Ratio (MAR), the Mean Excess Ratio (MER) and the Solid Energy Density (SED). Briefly, the MAR was calculated for the diet of each individual as the mean percentage of European Food Safety Authority (EFSA) dietary reference values (European Food Safety Authority, n.d.) for 17 beneficial nutrients. It was used as an indicator of good nutritional quality and varied between 0 (low quality) and 100 (high quality) with a daily intake of each nutrient higher than the dietary reference value capped at 100. The MER was similarly constructed but included nutrients to be restricted (sodium, free sugars, saturated fatty acids). It was used as an indicator of poor nutritional quality with a minimum value of 100 when none of the nutrients exceeded the maximum recommended value in the diet. SED, calculated as the energy from solid foods (all food groups except hot drinks, sugary and non-sugary beverages, milk, juices, water, alcohol) divided by the quantity provided by solid foods, was used as another indicator of poor nutritional quality as lower SED is recommended by several public health authorities (World Cancer Research/American Institute for Cancer Research, 2007; World Health Organization, 2003) to prevent obesity and obesity-related diseases (Ledikwe et al., 2006).

2.1.4. GHGE associated with food consumption

A GHGE coefficient, expressed in grams of CO_2 equivalents (g CO_2eq), derived from life cycle assessment (LCA) literature studies was assigned to each of the 151 food items as described by Hartikainen and Pulkkinen (Hartikainen and Pulkkinen, 2016). The reader should be aware that there are major uncertainties related to GHGE coefficients aggregated from the LCA literature (Clune et al., 2017; Kendall and Chang, 2009) but that it is still the best available alternative. For each individual, the consumption of 151 food items was matched to their respective GHGE in order to calculate dietary GHGE, i.e. the GHGE related to the daily food consumption of the individual. Dietary GHGE were used as indicators of the environmental impacts of diets.

2.2. Identification of “More-Sustainable” cluster and class

We hypothesized that some diets combine cultural acceptability (because they are self-selected), good nutritional quality and low environmental impact. Diets that relative to other diets were more sustainable were identified using two approaches: a new clustering approach

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specifically developed for this study (described in 2.2.1) and a previously described classification approach (Masset et al., 2014b). The methods were used to identify a collection of self-selected diets called the “More-Sustainable” cluster and the “More-Sustainable” class, respectively.

Both approaches were applied without ex ante assumptions concerning the food content of sustainable diets. Adjustments were made for energy intakes to take into account the well-documented and strongly positive relationship between dietary GHGE and energy intakes (Monsivais et al., 2015; Saxe et al., 2012; Vieux et al., 2012).

2.2.1. Clustering of diets and identification of the “More-Sustainable” cluster

The “More-Sustainable” cluster was identified as the cluster with the best compromise between high nutritional quality and low dietary GHGE. Clustering was conducted in two consecutive steps. In a first step, multiple factorial analysis (MFA) (Tucker, 2010) was applied to the 8302 individual diets, using nutrient intakes (representing the nutritional dimension) and dietary GHGE (representing the environmental dimension) as active variables and intake by food sub-group, diet quality indicators (SED, MAR and MER), number of food items consumed and other characteristics (total energy, total quantity, age) as illustrative variables. The illustrative variables are useful in interpreting the results but do not influence the principal component analysis. Because the environmental dimension was represented by only one variable while the nutritional dimension included 28 nutrients, dietary GHGE were weighted to be as important as nutritional intakes. All variables included in the MFA were adjusted for total energy intake (using residuals of each linear regression between the variable considered and the total energy intake) and scaled to the standard deviation in order to avoid bias due to different units. In a second step, a partition of diets was carried out by agglomerative hierarchical clustering (AHC) using Euclidean distances between individuals, based on their coordinates on the first component, i.e. the new variables derived by the MFA which summarize the largest variability of the raw data (Contreras and Murtagh, 2015; Cornillon et al., 2012). Individuals were in this second step grouped into clusters. The number of clusters was chosen using two criteria: the gain of inter/intra cluster inertia ratio and the interpretability of clusters. Comparisons of characteristics across clusters, especially regarding dietary GHGE and nutritional quality indicators, were used to name clusters and to identify which of the clusters defined by AHC that was the “More-Sustainable”.

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2.2.2. Classification of diets and identification of the "More-Sustainable" class

The approach used to identify a class of more sustainable diets was based on the methodology suggested by Masset et al (Masset et al., 2014b). Briefly, this approach was used to define individual diets as belonging to "More-Sustainable" class if the diet had a MAR above, a MER below, and dietary GHGE (all being adjusted for energy) below the energy-adjusted gender-specific median.

2.3. Statistical analysis

Correlations between the first two components from the MFA and the active and illustrative variables were computed and represented on a correlation circle. Each cluster was described in terms of individual characteristics (nationality, gender, age) and diet characteristics. Differences of means between clusters were tested by analysis of variance (ANOVA) adjusted as appropriate (Fisher, 1925). Post-hoc comparisons between means using Tukey correction were performed. Differences in the distribution of nationalities across the different clusters were analyzed with a chi-squared test. The "More-Sustainable" cluster was isolated and nutritional intakes as well as consumption (in percentage of total diet weight) of food groups and sub-groups were compared to the rest of the sample by ANOVA after adjusting for total energy intake. The "More-Sustainable" class was similarly compared to the rest of the sample. This made it possible to qualitatively identify the main differences between the "More-Sustainable" cluster and the "More-Sustainable" class.

Statistical softwares SAS version 9.4 (SAS Institute, Cary, NC, USA) and R version 3.3.0 (Base and FactoMineR packages) were used to perform the statistical analysis. A 5% level of statistical significance was used for all tests.

3. Results

The two first components of the MFA accounted for 23% and 15% of the variability (Figure 1). The MFA showed that dietary GHGE were inversely correlated with carbohydrates and sugar intakes, including free sugars (Figure 1, panel A). Vitamins and minerals were highly correlated with each other but not with dietary GHGE. Graphically representing consumption of food groups in the map defined by MFA (Figure 1, panel B) revealed that consumption of livestock meat was strongly correlated with dietary GHGE while consumption of fruits and vegetables as well as dairy were positively correlated with vitamins and minerals.

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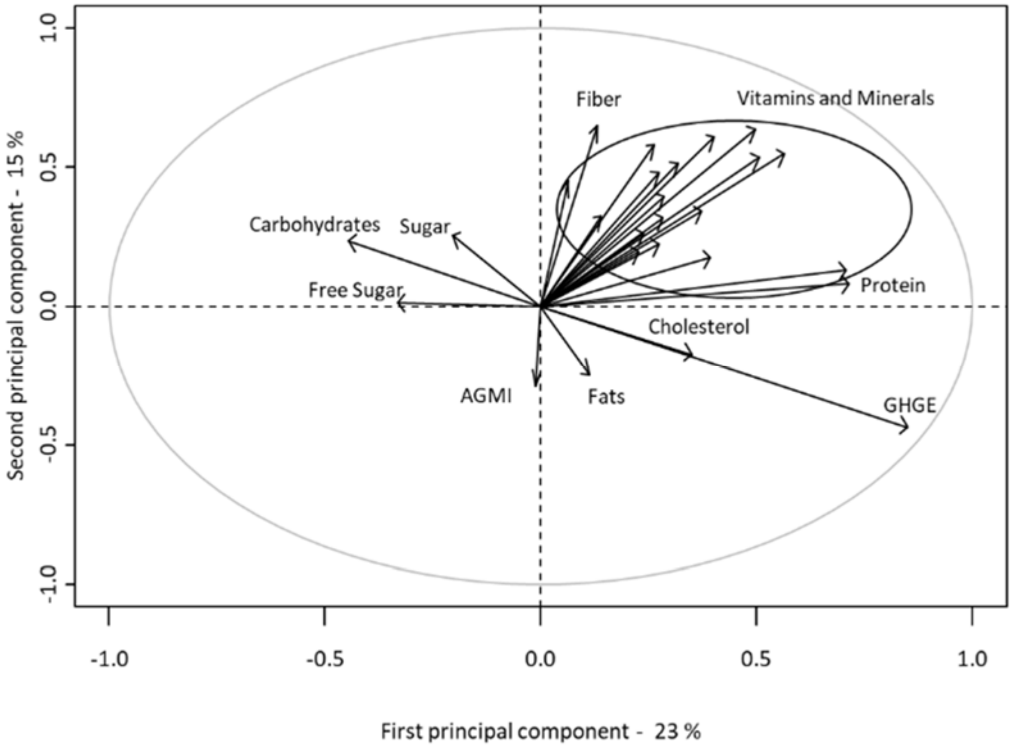
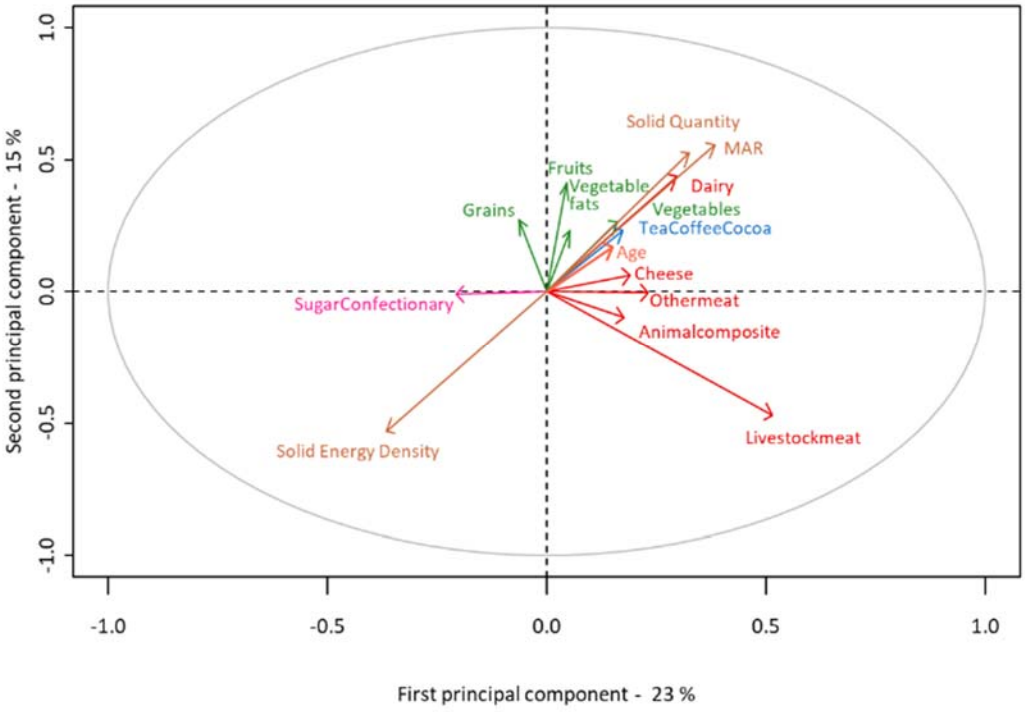
Figure 1: Correlation circles derived from the Multiple Factorial Analysis (MFA)

PANEL A: Active variables



PANEL B: Illustrative variables[1]



[1] *Only illustrative variables with an Euclidean distance from the center higher than 0.05 were represented.*

MAR denotes Mean Adequacy Ratio, GHGE denotes greenhouse gas emissions.

Individuals were grouped into six clusters by applying hierarchical clustering and studying the inertia gain and the interpretability of clusters. The characteristics of the overall sample and the six clusters are shown in Table 1. Mean energy intake varied from 1916 kilocalories (kcal) per day, in cluster 3, to 2152 kcal per day, in cluster 4. Cluster 1 had the lowest dietary GHGE (3551 g CO_2eq/d) and low nutritional quality, as indicated by the highest SED (191 kcal/100g), the lowest MAR (77 %) and the second highest MER (133 %). It was also characterized by the lowest mean age. Cluster 5 had the highest dietary GHGE (7034 g CO_2eq/d) and nutritional quality similar to the overall sample average. Clusters 4 and 6 also had high dietary GHGE (>5000 g CO_2eq/d). Cluster 4 was characterized by the lowest SED (141 kcal/100g) and the highest MAR (93 %) but the highest MER (140 %). Cluster 6 was the smallest cluster (<1 % of the sample) and had the highest mean age. Cluster 3, representing 33% of the whole sample, had intermediate dietary GHGE (4327 g CO_2eq/d) but the second lowest MAR (80 %). Finally, cluster 2, representing 18 % of the sample, displayed the second lowest dietary GHGE (3834 g CO_2eq/d, 21 % less than the sample average), the lowest MER (121 %), the second lowest SED (143 kcal/100g), and its MAR was relatively high (88 %). This cluster was therefore considered to be relatively more sustainable because none of the other clusters featured a better combination of low dietary GHGE and high nutritional quality. Names were also attributed to the other clusters according to their main specific characteristics. The percentage of individuals belonging to the “More-sustainable” cluster was 25.1 % in Finland, 11.6 % in France, 16.6 % in Italy, 19.7 % in Sweden and 23.4 % in the UK (data not shown).

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Table 1. Characteristics of the overall sample and the six clusters [1]

	All	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
N (%)	8302	2020 (24.33%)	1498 (18.04%)	2749 (33.11%)	809 (9.74%)	1151 (13.86%)	75 (0.90%)
Age (y)	42.57 (12.77)	38.51 (12.94)	45.78 (12.21)^{a}	42.55 (12.52)^{b}	46.29 (11.63)^{a}	42.53 (12.50)^{b}	48.72 (11.47)^{a}
Women (%)	55.67%	57.77%	61.95%	58.86%	49.32%	41.18%	48.00%
Energy (kcal/d)	2003.91 (634.4)	2059 (680.4)^{a}	1939 (579.1)^{b}	1916 (599.3)^{b}	2152 (659.2)^{c}	2091 (638.5)^{ac}	2084 (697.3)^{abc}
Energy from solid foods[2]	1797 (579.6)	1827 (636.5)^{a}	1742 (532.3)^{b}	1752 (547.0)^{b}	1900 (594.9)^{c}	1851 (577.0)^{ac}	1868 (653.4)^{abc}
Total quantity (g/d)	2587.80 (878.5)	2352 (800.6)^{a}	2886 (783.0)^{b}	2327 (790.2)^{a}	3359 (837.8)	2676 (882.2)^{c}	2876 (1076)^{bc}
Solid quantity	1083 (349.7)	969.0 (326.2)^{a}	1236 (339.1)^{b}	984.1 (282.3)^{a}	1375 (388.3)	1109 (320.0)^{c}	1202 (380.8)^{bc}
GHGE (g CO2 eq/d)	4516 (1789)	3551 (1315)	3834 (1188)	4327 (1254)	5187 (1538)^{a}	7034 (1891)	5191 (1794)^{a}
SED (kcal/100g)	170.3 (380.0)	191.0 (360.0)	142.8 (310.0)^{a}	179.4 (320.0)	140.9 (320.0)^{a}	169.2 (330.0)^{b}	158.8 (380.0)^{b}
MAR (%)	82.84 (12.37)	77.36 (13.89)	88.55 (8.04)^{a}	79.92 (12.34)	93.02 (5.49)^{b}	84.34 (9.91)	90.37 (7.08)^{ab}
MER (%)	128.08 (33.01)	132.74 (36.96)^{a}	121.42 (28.27)^{b}	124.43 (28.9)^{c}	139.7 (39.68)^{d}	129.0 (32.14)^{e}	128.99 (32.43)^{abcde}
Distinguishing features of cluster		Lowest GHGE, Highest SED Lowest MAR, 2nd highest MER	2nd lowest GHGE 2nd lowest SED High MAR (88%) Lowest MER	2nd lowest MAR	Lowest SED Highest MAR Highest MER	Highest GHGE	Highest intakes of offals*
Cluster Name		*«Lowest-GHGE»*	*«More-Sustainable»*	*«Smallest-Quantity»*	*«Largest-Quantity»*	*«Highest-GHGE»*	*« Others »*

[1] Results are presented as means (standard deviation) or percentages; statistical tests of differences in means between clusters, based on ANOVA and chi-square, were all statistically significant (p<0.01).

[2] Solid foods are all foods except liquids; liquids were defined as hot drinks, sugary and non-sugary beverages, milk, juices, water, and alcoholic beverages.

[a,b,c,d,e] Non-significant 2 by 2 post-hoc comparisons (using Tukey correction) have the same letter.

* This cluster was characterized by the highest mean intake of Offals/Other meats (see table 2).

The “Highest-GHGE” cluster (Cluster 5) was characterized by a high intake of livestock meat, animal fats and alcoholic beverages and low intakes of meat imitates, vegetable fats and plant-based composite dishes (Table 2). The ”Lowest-GHGE” cluster (Cluster 1) had the highest consumption of soft drinks, sugar/confectionaries, and snack/desserts. The “Others” cluster (Cluster 6) was characterized by high intakes of offal/other meats.

The diets in the “More-Sustainable” cluster included all food groups and sub-groups. The cluster was characterized by a high consumption of fruits, vegetables, legumes/nuts/oilseeds, juices, and a low consumption of alcoholic beverages, animal-based composite dishes and animal fats. Furthermore, it contained more animal-products imitates than in other clusters although quantities remained small (<11 g/d of meat and milk products imitates).

The diets in the cluster on average contained approximately 1000 g/d of plant-based products including 400 g/d of fruit and vegetables, 100 g/d of juices and 500 g/d of other plant-based products (such as 200 g/d of composite dishes and 20 g/d of legumes/nuts/oilseeds). Furthermore, they contained approximately 400 g/d of animal-based products including 100 g/d of meat/fish/eggs of which 20 g/d was livestock-meat, 50 g/d of composite dishes and 250 g/d of dairy products of which 30 g/d was cheese.

Figure 2 compares the “More-Sustainable” cluster to the rest of the sample. Individuals from the cluster consumed a larger total quantity which can be explained by the relatively low energy density of plant foods representing half of the quantity consumed (Figure 2 panel A). Among drinks (Figure 2 panel B), alcoholic beverages and soft drinks were the only sub-groups consumed in smaller quantities than in the rest of the sample.

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Table 2. Mean consumption, grams per day, by food group and sub-group in the overall sample and in the six clusters [1]

	All	"Lowest-GHGE"	"More-Sustainable"	"Smallest-Quantity"	"Largest-Quantity"	"Highest-GHGE"	"Others"
Plant foods	**519.9 (241.8)**	**478.85 (215.37)**	**691.48 (250.1)**	**431.58 (181.8)**	**631.91 (284.6)**	**496.2 (219.5)**	**587.75 (285.4)**
Grains	209.83 (119.0)	221.97 (117.85)	229.27 (122.7)	182.02 (96.29)	259.67 (156.6)	194.97 (115.0)	204.55 (126.7)
Vegetables	102.29 (91.55)	77.49 (71.74)	146.11 (113.2)	88.77 (71.4)	119.45 (108.0)	106.88 (93.62)	134.57 (142.6)
Starchy roots	49.00 (59.66)	46.50 (53.71)	56.54 (69.57)	41.81 (49.47)	54.13 (80.52)	56.67 (58.50)	55.93 (57.70)
Legumes/Nuts/Oilseeds	16.16 (28.4)	15.20 (27.79)	20.90 (35.13)	13.71 (22.86)	12.83 (29.26)	19.68 (29.87)	18.92 (27.83)
Fruits	142.60 (142.7)	117.69 (116.7)	238.66 (180.4)	105.27 (97.61)	185.83 (175.3)	118.02 (125.8)	173.77 (180.1)
Meat/Fish/Eggs	**121.44 (74.19)**	**88.10 (56.7)**	**102.25 (60.82)**	**124.07 (62.2)**	**148.24 (101.9)**	**177.57 (78.08)**	**155.93 (83.15)**
Livestock meat	33.43 (38.57)	17.74 (23.0)	19.22 (25.19)	33.10 (28.75)	25.39 (40.61)	86.20 (47.26)	29.52 (36.88)
Poultry	21.26 (32.9)	19.41 (28.94)	19.68 (29.63)	21.71 (31.65)	24.82 (45.44)	23.29 (35.63)	15.98 (31.58)
Processed meat	28.98 (35.11)	23.92 (28.31)	24.47 (30.43)	30.73 (32.29)	42.76 (60.02)	29.39 (30.59)	35.91 (41.47)
Meat imitates	0.41 (4.81)	0.45 (5.15)	1.17 (7.97)	0.20 (3.42)	0.28 (3.49)	0.00 (0)	0.00 (0)
Offals/Other meat	3.10 (13.19)	0.99 (5.57)	1.29 (6.97)	2.57 (8.76)	4.60 (17.35)	7.28 (24.56)	35.11 (25.47)
Fish/Seafood	26.34 (34.69)	20.49 (27.2)	29.10 (34.11)	26.46 (32.11)	38.72 (53.85)	23.67 (33.08)	32.03 (37.93)
Eggs	7.92 (16.2)	5.11 (11.44)	7.31 (15.11)	9.30 (16.33)	11.67 (24.92)	7.75 (15.86)	7.36 (14.64)
Dairy products	**217.2 (215.6)**	**149.4 (137.3)**	**251.0 (178.0)**	**167.3 (151.9)**	**532.8 (339.2)**	**188.1 (183.2)**	**244.3 (279.5)**
Milk and fresh dairy products	181.43 (211.3)	121.8 (135.0)	212.91 (178.4)	131.71 (149.4)	480.58 (338.3)	152.05 (181.2)	205.75 (275.4)
Cheese	32.47 (38.61)	24.98 (27.26)	28.74 (30.85)	33.56 (35.21)	49.70 (66.78)	35.36 (40.23)	38.58 (50.2)
Milk product imitates	3.33 (27.39)	2.62 (20.64)	9.35 (50.41)	1.99 (17.82)	2.50 (26.03)	0.75 (8.00)	0.00 (0)
Composite dishes	**271.7 (184.3)**	**256.94 (185.5)**	**253.87 (171.9)**	**275.39 (182.2)**	**317.24 (191.3)**	**278.71 (191.4)**	**293.2 (190.9)**
Plant-based dishes	208.84 (174.6)	207.55 (182.8)	205.39 (168.2)	207.10 (169.4)	229.27 (181.4)	203.08 (174.6)	244.23 (177.1)
Animal-based dishes	62.88 (73.2)	49.40 (58.59)	48.48 (59.84)	68.29 (70.52)	87.97 (95.01)	75.64 (90.99)	48.96 (55.99)
Drinks	**1385 (721.0)**	**1299 (692.9)**	**1518 (689.2)**	**1260 (681.1)**	**1652 (744.1)**	**1465 (783.9)**	**1534 (866.7)**
Fruit & vegetable juices	65.13 (131.1)	74.45 (138.7)	99.26 (161.4)	37.16 (77.37)	79.91 (160.3)	61.11 (139.7)	59.38 (115.3)
Tea/Coffee/Cocoa	434.20 (377.34)	364.06 (343.7)	497.84 (379.7)	382.75 (347.8)	656.87 (422.7)	435.54 (391.9)	515.31 (373.8)
Soft drinks	95.30 (205.5)	167.89 (274.9)	76.99 (199.1)	68.95 (151.4)	43.24 (115.0)	93.32 (204.5)	64.20 (147.7)
Alcoholic beverages	147.61 (295.0)	167.81 (357.4)	118.62 (248.8)	128.48 (213.4)	94.53 (196.8)	230.18 (411.2)	188.88 (314.1)
Drinking water	642.93 (544.9)	525.03 (471.3)	724.89 (546.7)	642.78 (550.7)	777.37 (614.2)	644.95 (546.9)	706.35 (670.3)
Miscellaneous	**72.37 (58.54)**	**79.58 (63.25)**	**69.57 (56.55)**	**68.27 (54.96)**	**77.35 (59.7)**	**70.37 (59.16)**	**61.10 (48.72)**
Sugar/Confectionaries	18.06 (22.79)	26.73 (29.78)	16.63 (20.94)	14.85 (17.89)	13.70 (20.89)	15.42 (18.75)	17.92 (17.38)
Animal fats	3.80 (8.6)	3.38 (7.36)	1.91 (5.38)	4.85 (9.81)	2.89 (9.52)	5.13 (9.71)	3.38 (6.22)
Vegetable fats	11.60 (13.93)	9.28 (10.89)	13.16 (13.57)	11.04 (13.52)	20.10 (21.14)	8.89 (10.72)	13.50 (15.57)
Herbs/Spices/Condiments	19.23 (28.45)	17.09 (25.44)	19.79 (28.67)	19.39 (29.0)	21.47 (29.68)	20.58 (30.98)	14.64 (21.89)

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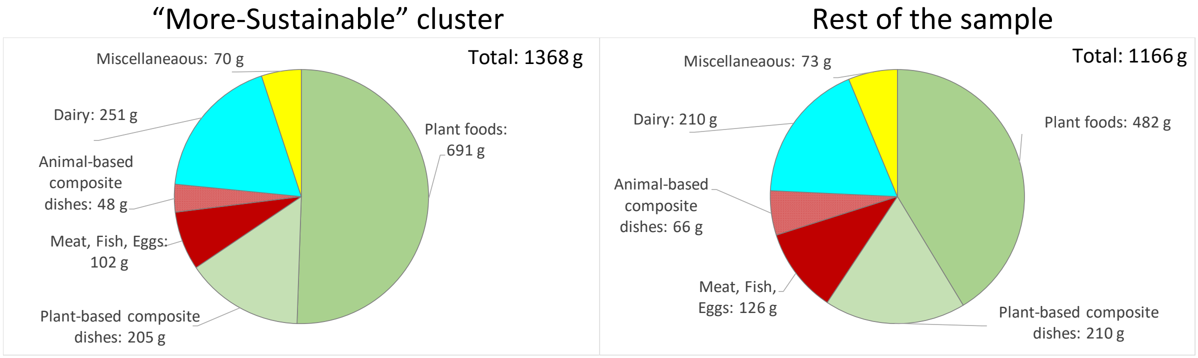
Snacks/Desserts/Others	19.69 (35.75)	23.10 (36.69)	18.08 (36.06)	18.14 (30.55)	19.19 (40.18)	20.35 (41.64)	11.67 (24.42)

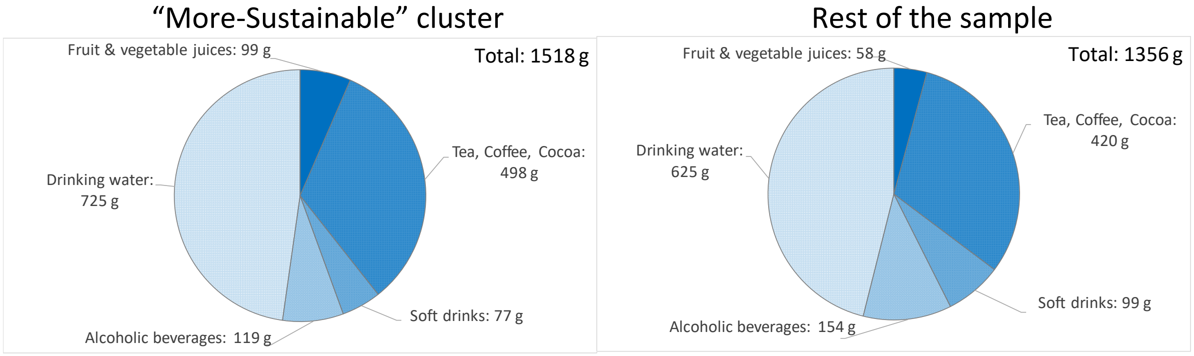
[1] Results are presented as means (standard deviation); statistical tests of differences in means between the clusters, based on ANOVA and chi-square, were all significant (<0.01), with and without adjustment for individual energy intakes, age and gender.

Figure 2. Mean food intakes (g/d) in the “More-Sustainable” cluster and in the rest of the sample: A. All foods except drinks; B. Drinks.

A. All foods except drinks



B. Drinks



In the classification approach, 1125 diets were identified as “More-Sustainable”, 576 of which were also identified with the clustering approach. The “More-Sustainable” class contained a higher percentage of women (69.1 % vs 61.9 %) and displayed lower dietary GHGE (3485 vs 3834 g CO_2eq/d) than the “More-Sustainable” cluster (data not shown).

Table 3 shows the average food composition (% of diet weight) of the individual diets in the “More-Sustainable” cluster and in the rest of the sample as well as p-values indicating statistically significant differences between the two. Corresponding statistics are shown with respect to the “More-Sustainable” class. Compared to the rest of the sample, the “More-Sustainable” cluster was characterized by considerably higher intake of plant foods, slightly higher intake of dairy, lower intake of meats, and lower intake of sugar/confectionaries, soft drinks and alcoholic beverages. Similar results were, with the exception of composite dishes, obtained with the classification approach. The only food sub-group for which the two approaches result in a difference in the internal comparison (i.e. between “More-Sustainable” class/cluster vs rest of sample) is plant-based composite dishes. In the clustering approach, both animal- and plant-based composite dishes were lower in the “More-Sustainable” cluster resulting in a statically significant lower share of total composite dishes in this cluster than in the rest of the sample. In the classification approach, however, the “More-Sustainable” class had a larger share of plant-based and a smaller share of animal-based composite dishes compared to the rest of the sample. As a result the share of total composite dishes was not statistically different between the class and the rest of the sample.

Table 3. Contribution (%) of food groups and sub-groups to total diet weight in the “More-sustainable” cluster[1] and in the “More-sustainable” class[2] compared with the corresponding overall rest of the sample

	Clustering approach			Classification approach		
Food group % total diet weight (sd)	**« More-Sustainable » cluster[1]**	**Rest of the sample**	*P-value[3]*	**« More-Sustainable » class[2]**	**Rest of the sample**	*P-value[4]*
N	1498	6804		1125	7177	
Plant foods	**24.79% (8.65)**	**19.86% (7.94)**	***0.0000***	**25.16% (8.12)**	**20.06% (8.1)**	***0.0000***
Grains	8.15% (4.23)	8.50% (4.54)	*0.2431*	8.81% (4.16)	8.38% (4.53)	*0.0001*
Vegetables	5.28% (4.18)	3.82% (3.34)	*0.0000*	5.17% (3.85)	3.92% (3.48)	*0.0000*
Starchy roots	2.01% (2.54)	1.98% (2.45)	*0.1692*	1.84% (2.5)	2.01% (2.46)	*0.4332*
Legumes/Nuts/ Oilseeds	0.74% (1.24)	0.63% (1.16)	*0.0017*	0.67% (1.15)	0.65% (1.19)	*0.4923*
Fruits	8.60% (6.47)	4.91% (4.67)	*0.0000*	8.68% (6)	5.09% (4.93)	*0.0000*
Meat/Fish/Eggs	**3.71% (2.26)**	**5.31% (3.27)**	***0.0000***	**3.92% (2.5)**	**5.19% (3.23)**	***0.0000***
Livestock meat	0.72% (0.96)	1.60% (1.93)	*0.0000*	0.54% (0.85)	1.58% (1.9)	*0.0000*
Poultry	0.72% (1.11)	0.91% (1.42)	*0.0000*	0.81% (1.25)	0.89% (1.39)	*0.4355*
Processed meat	0.85% (1.02)	1.21% (1.35)	*0.0000*	0.83% (0.92)	1.20% (1.35)	*0.0000*
Meat imitates	0.04% (0.3)	0.01% (0.18)	*0.0000*	0.03% (0.24)	0.01% (0.2)	*0.0016*
Offals/Other meat	0.05% (0.28)	0.14% (0.57)	*0.0000*	0.05% (0.26)	0.13% (0.56)	*0.0000*
Fish/Seafood	1.08% (1.32)	1.10% (1.52)	*0.1465*	1.35% (1.54)	1.05% (1.47)	*0.0000*
Eggs	0.26% (0.55)	0.33% (0.71)	*0.0000*	0.31% (0.74)	0.32% (0.68)	*0.2586*
Dairy products	**8.96% (6.45)**	**8.12% (7.55)**	***0.0000***	**8.97% (7.09)**	**8.16% (7.41)**	***0.0016***
Milk and fresh dairy products	7.62% (6.49)	6.67% (7.49)	*0.0000*	7.44% (7.13)	6.75% (7.36)	*0.0030*
Cheese	1.03% (1.13)	1.36% (1.56)	*0.0000*	1.18% (1.21)	1.32% (1.54)	*0.0000*
Milk product imitates	0.30% (1.56)	0.08% (0.78)	*0.0000*	0.35% (1.71)	0.09% (0.79)	*0.0000*
Composite dishes	**9.35% (6.75)**	**12.09% (9.18)**	***0.0000***	**11.74% (8.46)**	**11.58% (8.91)**	***0.0516***
Plant-based	7.61% (6.62)	9.28% (8.53)	*0.0000*	9.77% (7.89)	8.86% (8.3)	*0.0001*
Animal-based	1.74% (2.23)	2.81% (3.36)	*0.0000*	1.97% (2.44)	2.72% (3.31)	*0.0000*
Drinks	**50.77% (12.39)**	**51.67% (13.5)**	***0.0067***	**47.97% (12.13)**	**52.06% (13.41)**	***0.0000***
Fruit & vegetable juices	3.45% (5.45)	2.21% (4.27)	*0.0000*	2.08% (3.42)	2.49% (4.68)	0.0609
Tea/Coffee/Cocoa	16.96% (11.82)	16.14% (12.52)	*0.3159*	15.42% (10.56)	16.42% (12.66)	0.0000
Soft drinks	2.52% (5.79)	4.12% (8.27)	*0.0001*	1.52% (3.7)	4.19% (8.31)	0.0000
Alcoholic beverages	3.78% (6.67)	5.59% (8.98)	*0.0000*	3.70% (5.44)	5.51% (9.01)	0.0000
Drinking water	24.06% (14.65)	23.62% (15.45)	*0.5163*	25.25% (13.49)	23.45% (15.56)	0.0030

Miscellaneous	**2.43% (1.93)**	**2.95% (2.3)**	***0.0000***	**2.24% (1.6)**	**2.95% (2.32)**	***0.0000***
Sugar/ Confectionaries	0.58% (0.7)	0.76% (0.92)	*0.0000*	0.55% (0.58)	0.76% (0.92)	*0.0000*
Animal fats	0.06% (0.17)	0.17% (0.36)	*0.0000*	0.06% (0.17)	0.16% (0.36)	*0.0000*
Vegetable fats	0.46% (0.47)	0.44% (0.51)	*0.5782*	0.51% (0.5)	0.44% (0.5)	*0.0026*
Herbs/Spices/ Condiments	0.68% (0.98)	0.76% (1.16)	*0.1004*	0.59% (0.89)	0.77% (1.16)	*0.0000*
Snacks/Desserts /Others	0.64% (1.29)	0.81% (1.42)	*0.0011*	0.52% (0.95)	0.82% (1.45)	*0.0000*

[1] The “More-Sustainable” cluster was obtained by applying agglomerative hierarchical clustering on principal components of energy-adjusted multiple factor analysis with individual nutrient intakes and dietary GHGE as active variables.

[2] The “More-Sustainable” class consists of individual diets having simultaneously a Mean Adequacy Ratio above the median, a Mean Excess Ratio below the median and dietary greenhouse gas emissions below the median.

[3] Energy adjusted p-value of difference in means between the “More-Sustainable” cluster and the rest of the sample.

[4] Energy adjusted p-value of difference in means between the “More-Sustainable” class and the rest of the sample.

4. Discussion

The new clustering method used to identify the relatively more sustainable diets avoids several shortcomings of previous studies, such as working with theoretical diets, adopting preconceived views on the sustainability of specific food choices or adopting one-dimensional approaches to embrace a fundamentally multi-dimensional concept. Examining diets of adults from national food consumption surveys in five European countries (Finland, France, Italy, Sweden, the UK), this study found a cluster of 18 % of diets that were relatively more sustainable because they combined low dietary GHGE (21 % reduction vs average of all observed diets) and high nutritional quality. All categories of foods were represented in these diets, but compared to the rest of the sample they contained significantly larger quantities of plant-based products and smaller quantities of meat, soft drinks and alcoholic beverages.

Dietary GHGE was found to be strongly and positively associated with livestock meat consumption but negatively associated with the intake of free sugars. That consumption of livestock meat drives the level of GHGE in the diet is well known (Garnett, 2009; Gerber et al., 2013). It is less known that high consumption of free sugars is related to low environmental impact, although evidence of this relation can be found in the literature (Payne et al., 2016). For instance, a study assessing the environmental impact of several dietary scenarios in the UK found that the diet with the lowest dietary GHGE was a vegan diet with a large share of confectionaries and soft drinks (Berners-Lee et al., 2012). Furthermore, the results in this study suggest that dietary GHGE is practically unrelated to the intake of beneficial nutrients such as vitamins, minerals and fiber, thereby confirming results found in previous studies (Vieux et al., 2013a).

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Due to the complicated relationships between different dimensions of sustainability, unidirectional approaches (e.g. splitting one metric, either nutritional or environmental, into quantiles) are not suitable for studying diets. Such approaches explain why most epidemiological studies on the environmental impact of self-selected diets have found a weak correlation, or even a divergence between the nutritional and environmental dimensions (Perignon et al., 2017). For instance, diets from the lowest GHGE quintile in the French Nutrinet cohort of healthy volunteers were neither the diets with the least amount of non-beneficiary nutrients nor the diets closest to French dietary guidelines (Seconda et al., 2018). In fact, adherence to dietary guidelines is not necessarily associated with a lower environmental impact. The recommended DASH dietary pattern has for example been found to be associated with lower GHGE in the UK (Monsivais et al., 2015) but higher GHGE in the Netherlands (Biesbroek et al., 2017).

Six clusters were identified based on the nutritional and environmental characteristics of the diets. The relatively more sustainable of these clusters was characterized by large amounts of plant-based products and small amounts of animal-based products. Livestock meat and processed meat represented around 300 grams per week in this cluster which is less than the maximum of 500 grams recommended by international bodies (World Cancer Research/American Institute for Cancer Research, 2007). The presence of non-negligible amounts of animal-based foods in the relatively more sustainable diets implies that excluding entire categories of foods is not necessary in order to move towards more sustainable diets. The same conclusion can be drawn from results obtained with the classification approach. The results is also supported by a previous study which found that the diets of omnivores are not always those with the largest environmental impacts, and that some vegetarians and vegans can have diets with even higher impacts (Rosi et al., 2017). Our results suggest that policies intended to improve the sustainability of European diets should promote flexitarian diets, e.g. by reformulating dietary recommendations. The 21% GHGE reductions in the more sustainable cluster provides a useful reference for the development of sustainable food systems which requires that both demand- and supply-side aspects are considered.

In identifying sustainable food choices, multicriteria methods are preferable to unidirectional approaches. An important contribution of the present study was the original method used to identify more sustainable self-selected diets. Whereas MFA has been widely used in epidemiological studies to derive dietary patterns (Bertin et al., 2015; Gazan et al., 2016),

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considering consequences of food consumption (nutrient intakes and GHGE) as input data, rather than food consumptions themselves, is novel. It is worth noting that this approach avoids the use of food categorization, which may differ between countries, in identifying clusters. As some databases include multidimensional information (e.g. nutritional content, contaminants, price, environmental impacts) (Gazan et al., 2018a), the use of MFA, a method designed to study data composed of variables structured in groups, seems adequate. Using nutrient intakes and dietary GHGE as input data, as opposed to intakes of food items or food groups, avoids ex ante assumptions regarding the sustainability of specific foods or diets. The fact that the relatively more sustainable cluster had the largest content of plant-based foods was in accordance with current national food-based dietary guidelines (FAO Departments and Offices, 2017) and most studies on sustainable diets (EUPHA, 2017). On the other hand, it may be surprising that diets in the cluster with lowest dietary GHGE had the lowest nutritional quality (highest SED, 2nd highest MER, and lowest MAR). The reason is that these diets have the largest quantity of energy dense and nutrient poor foods (i.e., Sugar/Confectionaries, Soft drinks, Snacks/Desserts/Others) which have relatively low environmental impacts (Drewnowski et al., 2015; Masset et al., 2015).

This study has some limitations. Using large, representative and multi-cultural samples was valuable but aggregating different dietary surveys into one sample introduced a potential bias due to methodological differences in the data collection (e.g. dietary records based on varying number of days) (European Food Safety Authority, 2011). In order to minimize this potential bias, all variables included in the MFA were centered, scaled and adjusted for total energy intake. In the future it would be interesting to apply country-specific clustering to see if the results would differ from the results obtained in this study. Another limitation was that the cost of diets was not considered. However, previous studies have found that increasing sustainability does not necessarily increase the cost as it implies a lower consumption of meat which is a costly part of the diet (Fischer and Garnett, 2016). That European average GHGE coefficients were used is another limitation of this study. Using coefficients reflecting country averages would be preferable but are unfortunately available only for some food items in some countries. Furthermore, using only one environmental indicator, dietary GHGE, and only one average value per food item, is a simplification as environmental performance is represented by a diversity of highly variable and possibly uncorrelated metrics (Poore and Nemecek, 2018; Ridoutt et al., 2017).

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5. Conclusion

As data on the multiple metrics needed to address the sustainability of diet is becoming increasingly available (Gazan et al., 2018a; Johnston et al., 2014), multicriteria analyses such as the multiple factor analysis developed in the present study or more complex mathematical optimization models (Gazan et al., 2018b; van Dooren, 2018) are becoming ever more relevant. In particular, we think that the novel clustering method suggested in this paper would benefit from being generalized and that the results can be used to promote more sustainable dietary patterns adapted to specific populations. Recommendations originating from the actual preferences and choices of consumers have a greater potential to be adopted by consumers than is currently the case. The diets identified with this method can inform policy makers when specifying more sustainable dietary recommendations.

Using a multidimensional approach to identify self-selected diets with the best compromise between environmental and nutritional objectives, the present study suggests that diets with moderate amounts of animal-based products in the short-run is the most realistic path towards more sustainable diets, as it is already adopted by nearly one in five adults in Europe.

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