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Dietary choices and environmental impact in four European countries

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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-h recall or a diet record, from Denmark (DK, n = 1710), Czech Republic (CZ, n = 1666), Italy (IT, n = 2184), and France (FR, n = 2246). 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 = 7806) 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 2000 kcal, mean GHGE ranged from 4.4 (CZ) to 6.3 kgCO_2eq/2000 kcal (FR), and LU ranged from 5.7 (CZ) to 8.0 m^2*year/2000 kcal (FR). Dietary choices explained most of the variation between countries. A 5 energy percent (50 g/2000 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.

1. 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 (Mottet et al., 2017; Poore and Nemecek, 2018) with

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Nonstandard abbreviations

AIC	Akaike Information Criteria
β	Regression Coefficient
BIC	Bayesian Information Criterion
BMI	Body Mass Index
CI	Confidence Intervals
CV	Coefficient of variation, ratio of the standard deviation to the mean
CZ	Czech Republic
DK	Denmark
EFSA	European Food Safety Authority
en%	energy percent
FR	France
GHGE	Greenhouse gas emissions
IT	Italy
kcal	kilocalories
$kgCO_2eq$	kilogram carbon dioxide (CO_2) equivalents
LCA	Life Cycle Assessment
LU	Land use
NCI	National Cancer Institute
NRD	Nutrient Rich Diet,
SD	Standard Deviation
SHARP	environmentally Sustainable, Healthy, Affordable, Reliable and Preferred diets
SHARP-ID	SHARP Indicators Database

animal-sourced foods being the major contributors (Steinfeld et al., 2007). In line with the framework of the Lancet EAT Commission (Willett et al., 2019), studies on food patterns compared theoretically-constructed diets with national average diets (Gonzalez-Garcia et al., 2018; Hallström et al., 2015a; Springmann et al., 2018) 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 (Springmann et al., 2018); and more recently actual food intake data at the refined level of individual daily consumption have been used (Auestad and Fulgoni, 2015; Heller et al., 2013). 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 ~1000 food items for individual-based survey data using 24-h recalls or diet records (Mertens et al., 2016). 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 (Capone et al., 2013; Germani et al., 2014; Meier and Christen, 2013; Saxe et al., 2013; Temme et al., 2015; Vieux et al., 2012). 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 (Bingham et al., 1994) and systematic differences in life cycle assessment (LCA) databases (Garnett, 2008; Notarnicola et al., 2017a). 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.

2. Materials and methods

2.1. 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 1739 adult men and women (Pedersen et al., 2009). The national SISP04 (2003–2004) in CZ was based on two replicates of 24-h recall spaced over three-to-five months and included 1666 adult men and women (Leclercq C et al., 2009). The national INRAN-SCAI (2005–2006) in IT was based on a three-day diet record on consecutive days and included 2313 adult men and women (Ruprich J et al., 2006). The national INCA-2 Study (2006–2007) in FR was based on a seven-day diet record on consecutive days and included 2276 adult men and women (Agence Française de Sécurité Sanitaire des Aliments (AFSSA), 2009). 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) (EFSA (European Food Safety Authority), 2011; European Food Safety Authority, 2015). Intake data coded by FoodEx2 were disaggregated in 287 FoodEx2-codes in DK, 338 in CZ, 423 in IT, and 662 in FR.

2.2. 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 et al. (2009), i.e. biodiversity loss, nitrogen cycle disruption, carbon cycle disruption, and land use change, as discussed by Aiking (2014).

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 (Ekvall et al., 2016). 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) (BlonkConsultants, 2015a, 2015b), Ecoinvent (Global, Swiss Confederation) (Weidema et al., 2013), and primary production reports (Marinussen et al., 2012a; 2012b, 2012c, 2012d; Van Zeist et al., 2012a; 2012b, 2012c, 2012d), 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 (Bauman, 2004; Guinée et al., 2002), 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 (Foster et al., 2007). 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 (Weiss and Leip, 2012). 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 (FAO, 1996), and those of processed foods by their ingredient composition using recipes from the Dutch food composition table (NEVO Stichting, 2016). 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 (Bognar, 2002; Hoge Gezondheidsraad, 2005).

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 $kgCO_2$equivalents 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 (IPCC, 2007). 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.

2.3. 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 abovementioned 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 (Willett et al., 1997). Densities of food group intake, and of GHGE and LU were expressed per 2000 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.

2.4. 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 7806 adults for analysis.

2.5. 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 (Freedman et al., 2010; Tooze et al., 2006) (Tables 1–3, Figs. 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 (Fig. 3) and to explain densities by diet composition (Tables 4 and 5, Fig. 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 (Fig. 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 (Fig. 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 2000 kcal diet (densities) (see Fig. 1), and were fitted according to two levels of variance: individuals (level 1, $n = 7806$), 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 $\geq$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 2000 kcal; calculated by dividing the average amount of grams/2000 kcal by the

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 = 1739)			(n = 1666)			(n = 2313)			(n = 2276)		
	Mean	Med	(P25; P75)	Mean	Med	(P25; P75)	Mean	Med	(P25; P75)	Mean	Med	(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,/2,000 kcal [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,/2,000 kcal [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%)	1068		(46.2%)	936		(41.1%)
Educational level									[d]			[e]
- Low	248		(14.2%)	345		(20.7%)	692		(31.7%)	1039		(45.8%)
- Intermediate	943		(54.1%)	1194		(71.7%)	985		(45.1%)	495		(21.8%)
- High	548		(31.5%)	127		(7.6%)	507		(23.2%)	737		(32.4%)
Overweight,BMI≥25 kg/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 2184 subjects (129 missing).
[e] Data were available for 2271 subjects (5 missing).
[f] Data were available for 1710 subjects (29 missing).
[g] Data were available for 2312 subjects (1 missing).
[h] Data were available for 2250 subjects (26 missing).

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, per 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, per 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 200 kcal 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.

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 2000 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.

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.).

3. Results

3.1. 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 $kgCO_2eq$/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 $kgCO_2eq$/2000 kcal (FR), and of LU the density ranged from 5.7 (CZ) to 8.0 m^{2}*year/2000 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.

Regarding the demographic factors, age and gender

Table 3
Association of usual diet-related GHGE and LU densities (per 2000 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_2eq/2,000 kcal for GHGE density and 6.66 (SD 1.41) m^2*year/2,000 kcal 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.

Table 4
Contribution of the different food groups in daily diet weight per 2000 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				Between country variation [a]			
	Weight[b]	%en	%GHGE	%LU	Weight[b]	%en	%GHGE	%LU	Weight[b]	%en	%GHGE	%LU	Weight[b]	%en	%GHGE	%LU	Weight[b]	%en	GHGE per 2,000kcal	LU per 2,000kcal
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%*	*14.2%*	*13.3%*	*11.8%*	*7.9%*
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%	4.8%	6.2%	4.5%	4.9%
Ruminants (including beef, goat, sheep, deer, etc.)	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%	9.6%	9.2%	9.6%	9.6%
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%	5.8%	9.7%	6.9%	6.7%
Pork, horse, 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%	8.5%	8.5%	9.4%	9.4%
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%	2.0%	2.2%	2.0%	2.0%
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%	5.5%	2.9%	4.8%	2.2%
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%	0.5%	0.3%	0.7%	0.6%
Dairy products	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%	15.4%	12.8%	11.3%	11.2%
Milk products (excluding cheese/ butter)	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%	15.9%	11.3%	16.2%	16.2%
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%	9.7%	10.1%	9.0%	9.2%
Animal fat (including butter and lard)	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%	23.8%	23.7%	20.9%	21.0%
Plant-sourced foods, excluding beverages	*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%*	*15.9%*	*16.8%*	*6.3%*	*4.2%*
Plant fat (including vegetable oils and margarines)	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%	21.6%	29.0%	14.5%	21.0%
Grains and 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%	20.3%	14.9%	5.6%	2.9%
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%	11.1%	6.0%	2.4%	5.6%
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%	3.5%	5.4%	2.0%	3.9%
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%	4.3%	6.9%	4.4%	2.8%
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%	2.6%	1.5%	2.8%	1.6%
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%	0.8%	1.2%	0.6%	0.9%
Sugar & 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%	9.3%	11.9%	14.4%	15.5%
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%	2.2%	4.4%	1.9%	2.3%
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%	2.1%.	6.0%	7.8%	7.9%
Beverages, excluding 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%*	*19.9%*	*9.8%*	*14.9%*	*20.0%*
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%	18.2%	3.5%	14.0%	12.6%
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%	7.9%	4.3%	2.4%	8.0%
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%	8.3%	7.9%	6.7%	7.1%
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%	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 2000 kcal), energy (per 100 kcal, i.e. percentage of energy contributed by the food group) and diet-related GHGE and LU both per 2000 kcal, as outcome variable.
[b] gram per 2,000kcal.

Table 5
Association of diet-related GHGE and LU density (per 2000 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	200 kcal	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)								
proportion 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)
Proportion 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)
Proportion 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	200 kcal	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)
Proportion 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)
proportion 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)
proportion 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/2,000 kcal for GHGE density and 6.84 (SD 2.75) m^2*year/2,000 kcal 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.

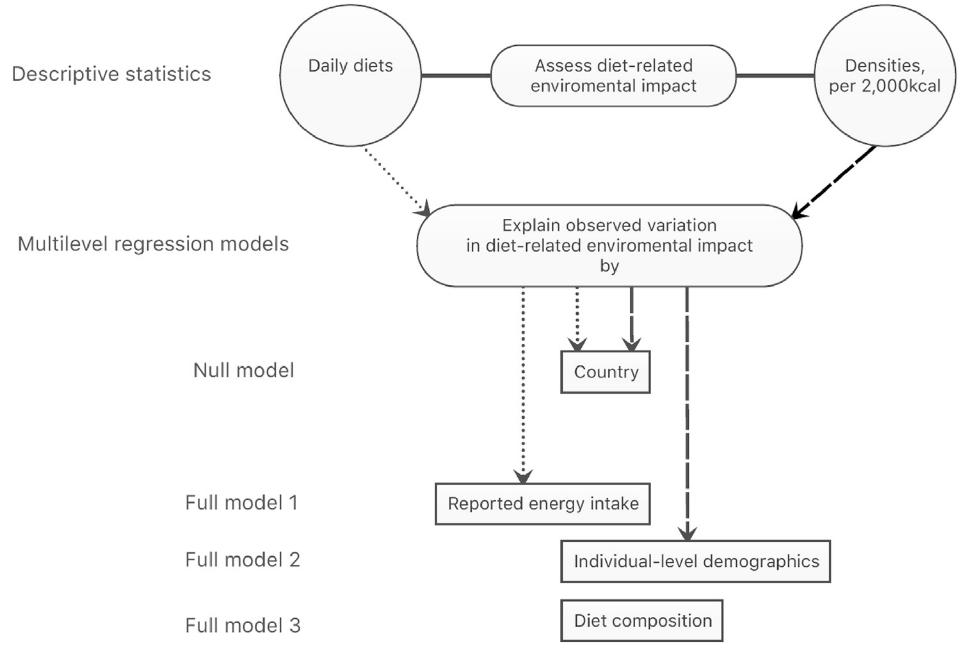

Fig. 1. Flowchart of the multilevel regression models to explain variations in diet-related environmental impact.
Dotted lines refer to multilevel regression models using environmental impact of daily diets as the dependent variable, and the dashed lines refer to multilevel regression models using densities of environmental impact, i.e. environmental impact expressed per 2000 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.

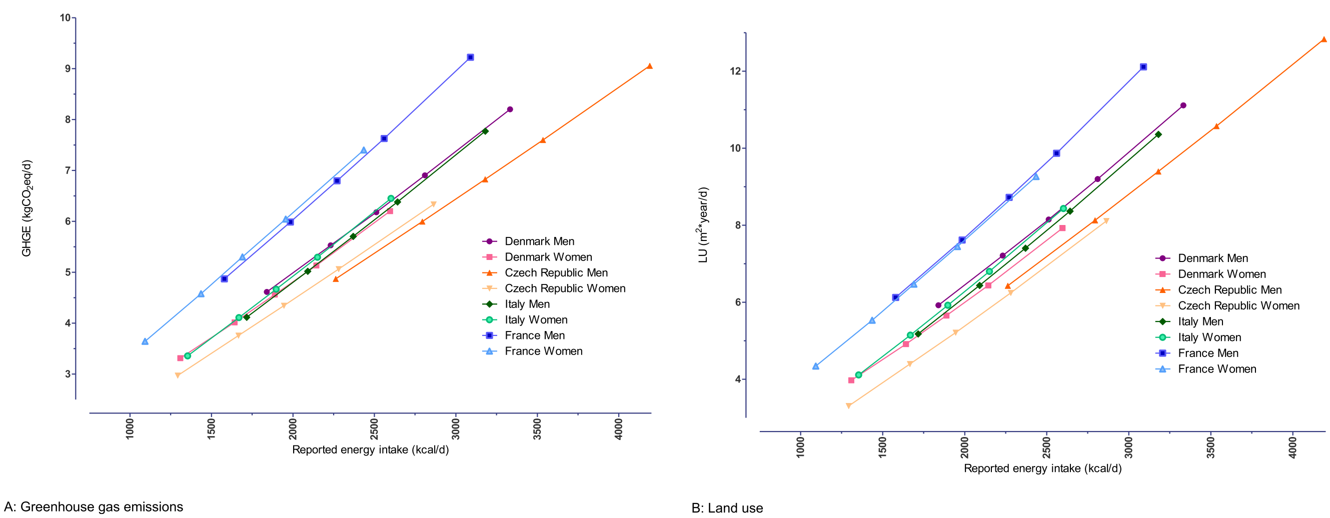

Fig. 2. Mean usual daily greenhouse gas emissions (GHGE, in $kgCO_2eq/d$) (1A) and land use (LU, in m^{2}*year/d) (1B) of men and women in four European countries according to usual reported energy intake of their diets. Dots are the mean observed values of the usual GHGE and LU of a daily diet, for the mean of quintiles for mean usual reported energy intake.

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%).

3.2. Daily reported energy intake in relation to daily GHGE and LU

Fig. 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

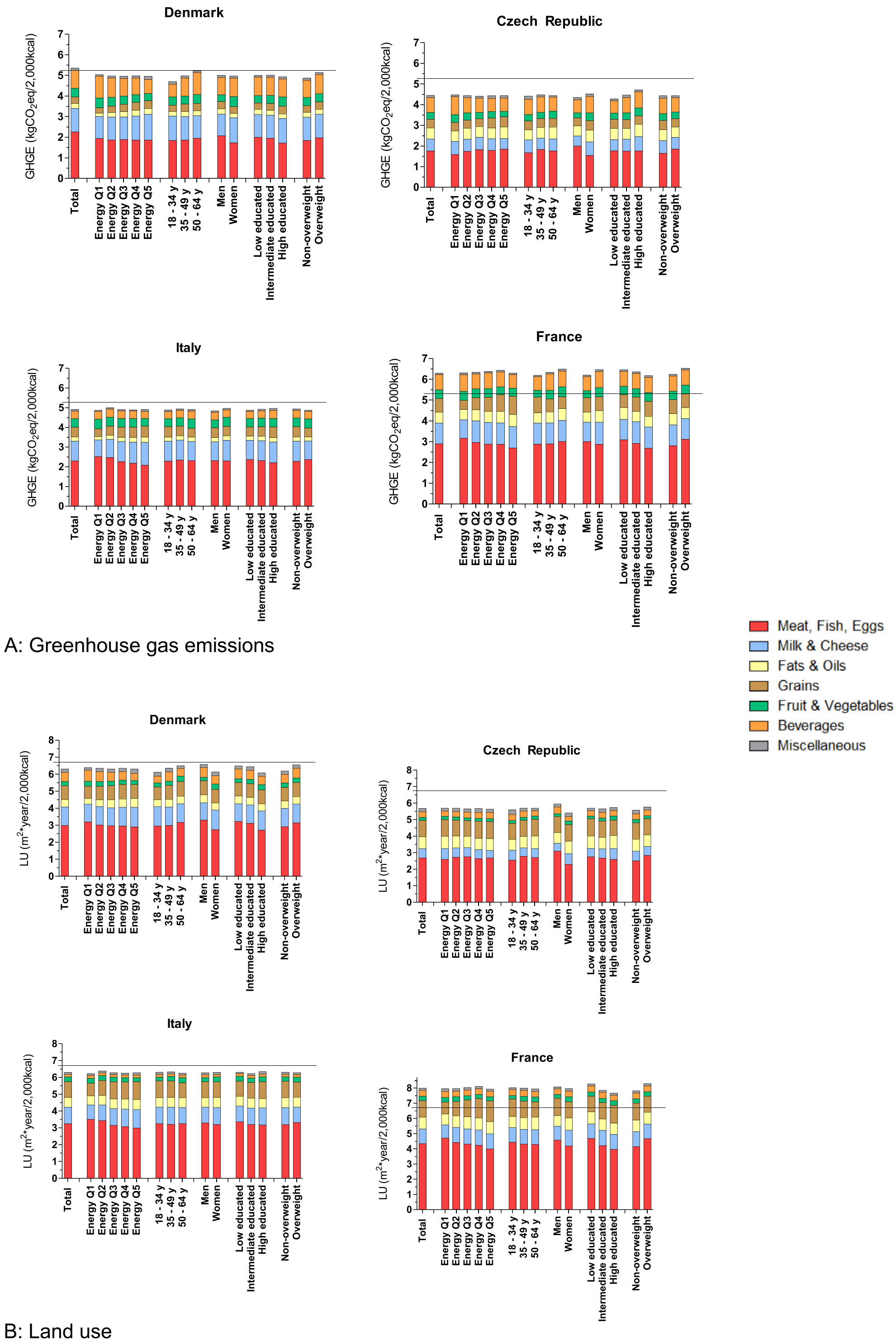

Fig. 3. Density of usual greenhouse gas emissions (GHGE, in $kgCO_2eq$/2,000 kcal) (2A) and of usual land use (LU, in m^{2*}year/2,000 kcal) (2B). Depicted is total density for each of the four countries, and stratified by energy intake (in gender-specific quintiles), and by demographic variables (age, 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(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 Fig. 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 Fig. 3 and Appendix A.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.

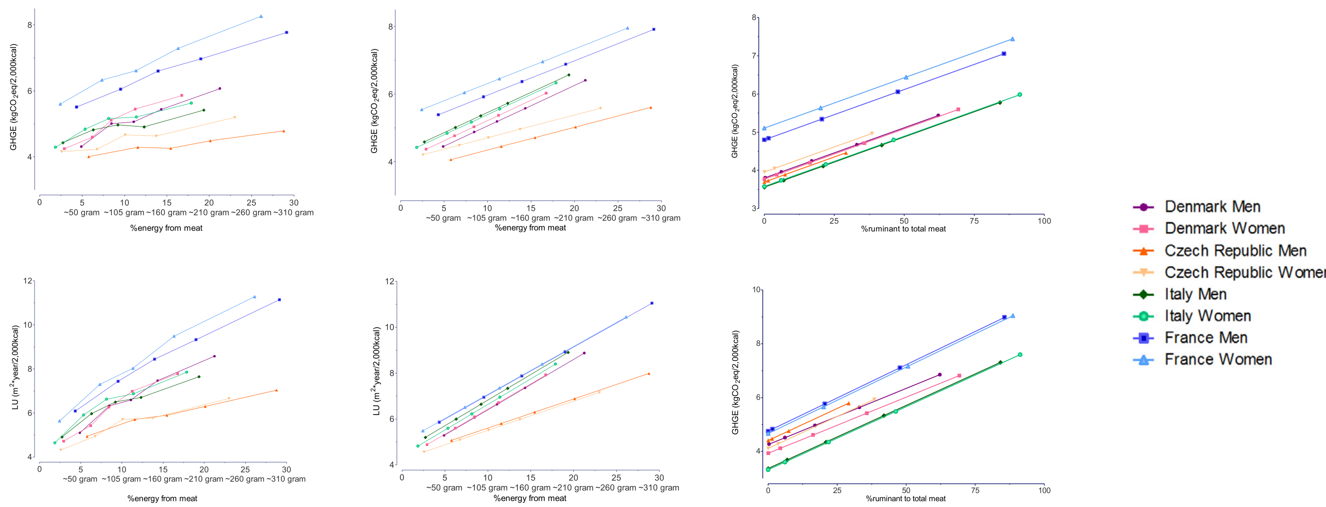

Fig. 4. Greenhouse gas emissions (GHGE density, in $kgCO_2eq$/2,000 kcal) and land use per 2000 kcal (LU density, in m^2*year/2,000 kcal) associated with the diets of men and women in four European countries according to percentage of energy from meat and percentage ruminant to total meat. Left figure 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.

3.3. Individual-level demographics in relation to GHGE and LU densities

Apart from quintiles for energy, Fig. 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).

3.4. Contribution of food groups in GHGE and LU density

Table 4 shows intakes of food groups (as densities, i.e. g/2000 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 and 69% (CZ, IT), of plant-sourced foods between 19 and 23% (DK, IT), and of beverages between 8 and 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 and 72% (CZ, FR), of plant-sourced foods between 23 and 28% (FR, CZ), and of beverages between 2 and 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.

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%).

3.5. Diet composition in relation to GHGE and LU density

Per 2000 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 $kgCO_2eq$/2000 kcal; 95%CI: 1.36; 2.80) and by 57% for LU density (3.92 m^{2*}year/2000 kcal; 95%CI: 2.63; 5.20) for a 20 energy percent difference in meat intake (about 200 g/2000 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 (Fig. 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.

Fig. 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 $kgCO_2eq$/2000 kcal; 95%CI: 1.73; 1.96) and by 48% for LU density (3.25 m^{2*}year/2000 kcal; 95%CI: 2.84; 3.65), with less between-country random effects, as also seen in Fig. 4. This heterogeneity of the country-specific estimates for ruminant meat was however related to the translation of energy percentage into grams per 2000 kcal that differed between the countries, i.e. grams of ruminant meat per energy percent was the lowest in FR (45 g/2000 kcal for 4.5 energy percent) and the highest in IT (46 g/2000 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 $kgCO_2eq$/2000 kcal; 95%CI: 0.14; 0.58), but non-significantly by 2% for LU density (−0.14 m^{2*}year/2000 kcal; 95%CI: 0.28; 0.00) for each 4 energy percent difference (about 60 g/2000 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.

For dairy products, a 20 energy percent difference (about 375 g/2000 kcal) was associated with a significant 16% difference in GHGE density (0.84 $kgCO_2eq$/2000 kcal; 95%CI: 0.59; 1.09), and a significant 10% difference in LU density (0.69 m^{2*}year/2000 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 $kgCO_2eq$/2000 kcal; 95%CI: 0.34; 0.03) and a non-significant 2% difference in LU density (−0.17 m^{2*}year/2000 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 35 g/2000 kcal) was associated with a non-significant 3% difference in GHGE density (0.14 $kgCO_2eq$/2000 kcal; 95%CI: 0.11; 0.38) and a significant 6% difference in LU density (0.44 m^{2*}year/2000 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 $kgCO_2eq$/2000 kcal; 95%CI: 0.24; 0.57) and a smaller but significant 4% difference in LU density (0.30 m^{2*}year/2000 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 210 g/2000 kcal) difference was associated with a significant 5% difference in GHGE density (−0.26 $kgCO_2eq$/2000 kcal; 95%CI: 0.47; −0.05) and a non-significant 1% difference in LU density (0.09 m^{2*}year/2000 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 1000 ml difference significantly differed by 12% for GHGE density (0.65; $kgCO_2eq$/2000 kcal; 95%CI: 0.56; 0.74) and by 4% for LU density (0.30 m^{2*}year/2000 kcal; 95%CI: 0.06; 0.54). Random country effects were not present for GHGE density, and trivial for LU density.

4. 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 fat 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 2000 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 2000 kcal diet using densities as attempts for dietary data harmonisation in this study (Mertens et al., 2018). 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 (Tables 1–3) 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 (Banna et al., 2017; Kipnis et al., 2003) and known differences between dietary assessment methods (De Keyzer et al., 2011). Relative estimates of calculated nutrient intakes are however known to perform better (Willett et al., 1997). Therefore, we expressed the diet-related GHGE and LU as densities (standardised to a 2000 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 $kgCO_2eq/d$) (Werner et al., 2014), 53% higher for IT (3.4 $kgCO_2eq/d$) (Germani et al., 2014), and 46% higher for FR (4.1 $kgCO_2eq/d$) (Vieux et al., 2012). 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. (Garnett, 2008). 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 (Notarnicola et al., 2017a). 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 (Notarnicola et al., 2017b). Conventional management practices were only captured in the present study, however they do not necessarily underperform organic practices (Castellini et al., 2012; Forleo et al., 2016; Lacour et al., 2018). Accounting for eating seasonal, for example, is expected to lower footprints of plant production, but reduction potentials are only minor on an absolute scale (Röös and Karlsson, 2013). 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 (Germani et al., 2014; Temme et al., 2015; Vieux et al., 2012; Werner et al., 2014), 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 (Notarnicola et al., 2017a) 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 (Perignon et al., 2017). 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 (Fig. 2), and no clear relationship with the densities (per 2000 kcal, Fig. 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 (Marteau et al., 2015).

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 (Gazan et al., 2018). In line with literature (Hallström et al., 2015b), 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 (Hallström et al., 2015a; Mertens et al., 2016). 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 (Guinée et al., 2002). 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 (Keating et al., 2014). 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 (Van Zanten et al., 2018). 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 (World Health Organisation (WHO), 2003), 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 (Appendix A.2). Moreover, simulating more rigorous changes in diet composition, e.g. by using the healthy reference diet proposed by the EAT-Lancet Commission (Willett et al., 2019), 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 (Mertens et al., 2018), we observed that the contributions of food groups to GHGE and LU did vary across population subgroups (Fig. 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 (Stok et al., 2017). 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 (Bouwman et al., 2016). 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.

5. 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.

Author contributions

P. van 't Veer and J.M. Geleijnse designed the research; M. Dofkova, L. Mistura, L. D'Addezio, A. Turrini, C. Dubuisson, S. Havard, E. Trolle were responsible for dietary data collection, G. Kaptijn developed the SHARP Indicators Database (SHARP-ID) necessary to estimate environmental impact of European diets in which H. van Zanten had an advisory role; E. Mertens, P. van 't Veer analysed data; E. Mertens, P. van 't Veer, J.M. Geleijnse and A. Kuijsten were responsible for data interpretation; E. Mertens wrote the paper which was reviewed by all authors for intellectual content. All authors read and approved the final manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.117827.

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