Journal of Cleaner Production 140 (2017) 753–765

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Environmental impacts of food consumption in Europe

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ARTICLE INFO

Article history:
Received 11 December 2015
Received in revised form
13 May 2016
Accepted 14 June 2016
Available online 16 June 2016

Keywords:
Food production
Food consumption
Food LCA
Food waste
Dietary habits
LCA

ABSTRACT

Food consumption is amongst the main drivers of environmental impacts. On one hand, there is the need to fulfil a fundamental human need for nutrition, and on the other hand this poses critical threats to the environment. In order to assess the environmental impact of food consumption, a lifecycle assessment (LCA)-based approach has been applied to a basket of products, selected as being representative of EU consumption. A basket of food products was identified as representative of the average food and beverage consumption in Europe, reflecting the relative importance of the products in terms of mass and economic value. The products in the basket are: pork, beef, poultry, milk, cheese, butter, bread, sugar, sunflower oil, olive oil, potatoes, oranges, apples, mineral water, roasted coffee, beer and pre-prepared meals. For each product in the basket, a highly disaggregated inventory model was developed based on a modular approach, and built using statistical data. The environmental impact of the average food consumption of European citizens was assessed using the International Reference Life Cycle Data System (ILCD) methodology. The overall results indicate that, for most of the impact categories, the consumed foods with the highest environmental burden are meat products (beef, pork and poultry) and dairy products (cheese, milk and butter). The agricultural phase is the lifecycle stage that has the highest impact of all the foods in the basket, due to the contribution of agronomic and zootechnical activities. Food processing and logistics are the next most important phases in terms of environmental impacts, due to their energy intensity and the related emissions to the atmosphere that occur through the production of heat, steam and electricity and during transport. Regarding the end-of-life phase, human excretion and wastewater treatments pose environmental burdens related to eutrophying substances whose environmental impacts are greater than those of the agriculture, transports and processing phases. Moreover, food losses which occur throughout the whole lifecycle, in terms of agricultural/industrial and domestic food waste, have also to be taken into consideration, since they can amount to up to 60% of the initial weight of the food products. The results of the study go beyond the mere assessment of the potential impacts associated with food consumption, as the overall approach may serve as a baseline for testing eco-innovation scenarios for impact reduction as well as for setting targets.

1. Introduction

Current patterns of food production and consumption are increasingly considered to be unsustainable. On the one hand, there is the need to fulfil a fundamental human need for nutrition, and on the other hand this poses critical threats to the environment. Ensuring food security requires a revised research agenda (Godfray et al., 2010) in which supply chains are systematically assessed and improved. In fact, food systems are related to global changes (e.g. in land use, water availability etc.), and there are several nexuses and feedbacks from food system outcomes to drivers of environmental and social change (Ericksen, 2008). Lifecycle thinking and assessment, and their analytical power in assessing supply chains, have been advocated as reference methodologies for assessing those impacts. An increasing number of studies in the literature address the environmental assessment of single products, but only a few adopt a consumption-oriented approach to assess the impact of the food supply chain in large geographical areas. However, studies at meso- and macro scales are fundamental in providing decision makers with information for making a transition to more

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http://dx.doi.org/10.1016/j.jclepro.2016.06.080

sustainable production and consumption patterns, by decoupling environmental impacts from responses to societal needs, while still ensuring economic growth.

At the macro scale, environmental impacts associated with consumption have traditionally relied on a ‘top down’ approach, such as using the sectorial economic information of input–output tables. The basic idea of those approaches is to calculate the physical material flows of economic sectors and then supplement this with environmental data in order to assess the sustainability of product groups (e.g. Huppes et al., 2008; Tukker et al., 2006; Weidema et al., 2005; Nijdam et al., 2005). According to those studies, food and drink, transport, and housing account for 70–80% of the entire lifecycle impact of products. Food consumption is responsible for 20–30% of the environmental burdens of total consumption, with meat products and dairy products sharing a major part of the total environmental impacts.

Several ‘bottom up’ product-oriented Life Cycle Assessments (LCAs) have been carried out (in accordance with ISO 14044:2006) to specifically assess the impacts of the most representative foods consumed in a specific region. For example, Foster et al. (2006) carried out an LCA study of food types that are representative of the foods on a list of 150 highest-selling items provided by a UK retailer. Muñoz et al. (2010) assessed Spanish food consumption by carrying out an LCA of the annual composition of Spanish food purchases by households, catering, restaurants and institutions. Similarly, Eberle and Fels (2014) assessed the environmental impacts of German food consumption and food losses by analysing statistical data on production, trade and consumption. Some authors have implemented hybrid approaches involving both ‘bottom up’ and ‘top down’ methods in order to overcome some of the possible problems arising from truncation errors of the former method and the non-specific nature of the data of the latter. For example, Pairotti et al. (2015) use a hybrid approach to explore the environmental burdens of the Mediterranean diet and compare these to those of an average Italian diet and those of two empirical scenarios of healthy and vegetarian food consumption patterns.

In order to comprehensively assess the impact of food consumption at EU level, in 2012, the European Commission's Joint Research Centre developed a lifecycle-based approach that focuses on specific representative products which are then up-scaled to overall EU consumption figures, named the Basket of Products (BoP) indicators (EC-JRC, 2012). The project focused on indicators that measure the environmental impact of the consumption of goods and services by the average European citizen, focusing on housing, food and transport, via the identification and environmental assessment of the most representative products of each category (basket of products). The present study improves upon and complements the previous pilot study by focusing on the environmental impacts of food and beverage consumption.

A detailed product-based LCA (from ‘cradle to grave’) has been conducted, in order to:

- identify the most representative food and beverage products consumed in the EU-27 via a statistical analysis of food consumption, using 2010 as the reference year,
- evaluate, via an LCA, the lifecycle environmental impact of the average food consumption of an EU-27 citizen in one year following the International Reference Life Cycle Data System (ILCD) recommendations for impact assessment (EC-JRC, 2010),
- develop a baseline scenario for the food BoP against which to test eco-innovation options for impact reduction and to help set targets, based on Sala et al. (2015).

The paper is organised as follows: firstly, we present the method for the selection of the products to be included in the BoP. We then detail the modelling framework, the assumptions regarding the lifecycle inventory and the characterisation of the impacts. The results and discussion section focuses on the key finding of this study, its limitations and its possible use as a baseline scenario for testing eco-innovation options. Conclusions are drawn in the final section of the paper.

2. Method

The development of the basket of products method responds to the needs to analyse and monitor European consumption patterns and their global influence, in order to shift to more resource-efficient consumption practices that have a lower impact on the environment. Specifically, the Basket of Products (BoP) indicators quantify the environmental impacts of EU-27 consumption practices using lifecycle data, data on expenditure and consumption statistics. The BoP regarding human nutrition is particularly significant, as food and beverage production and consumption is responsible for over one third of the overall environmental burden caused by private consumption (Tukker et al., 2006). The main steps for the calculation of the environmental impacts of the BoP are:

- selection of the most representative products, in terms of mass and economic value (section 2.1),
- definition of a modular approach with a disaggregated inventory model used to represent average EU basket products (section 2.2),
- definition of key assumptions according to the goal and scope of the study (section 2.3),
- collection and adaptation of inventory data (section 3),
- calculation of the environmental impacts, adopting the ILCD methodology (EC-JRC, 2011) (presented in section 4 as results).

2.1. Selection of the products for the food basket of products (BoP food)

A quantitative and qualitative analysis of the structure of EU-27 food consumption (during the years 2000–2010) was performed, including an analysis of international trade. This led to the selection of products that are representative of apparent food consumption for the year 2010. Specific data on apparent consumption (defined as Production − Exports + Imports) was sourced from Eurostat and FAO databases, as well as from specific nutrition and food consumption literature concerning current emerging consumption trends (e.g. EEA, 2012; EC, 2014). The final selection of products for the basket was based on the following:

- firstly, the consumption data was subdivided into main food categories, namely meat and seafood, dairy products, crop-based products, cereal-based products, vegetables, fruit, beverages, pre-prepared meals,
- amongst these categories, the food products with the largest apparent consumption in terms of mass and economic value were chosen for inclusion in the basket,
- it was verified that products which had already been identified as being responsible for large environmental burdens (e.g. meat and dairy products – Foster et al., 2006; Tukker et al., 2006; Gerber et al., 2013) were included in the BoP,
- the BoP also includes products that are representative of emerging food consumption trends and types of food and beverages whose consumption has been increasing during the past decade, independent of the magnitude of their environmental impact and the extent of their apparent consumption.

Table 1 illustrates the products selected for BoP food (reference year 2010, country coverage EU-27) and the respective data on their apparent consumption. The annual consumption of the BoP amounts to 540.9 kg per inhabitant per year. The BoP consumption is thus representative of 58% of the total apparent yearly consumption per inhabitant (933.2 kg/inhabitant) of all food and beverage products reported in the Eurostat-Prodcom database.

2.2. Structure of the applied inventory model

In order to carry out the LCAs of the representative products in the BoP, an appraisal framework was developed regarding the assumptions and models to be used for assessing each product. This was essential for achieving consistent and comparable LCA results.

The process-based lifecycle inventories were developed for each lifecycle stage of the selected representative products, updated to the year 2010, via the following approach:

i) A literature review was carried out concerning existing LCA studies of the single basket products.
ii) The approaches of such reviewed studies, for each lifecycle stage of each product, were assessed for appropriateness for the present study via the implementation of a pedigree matrix (see section 2.3).
iii) Once the approach was selected for the assessment of each basket product (see Table 2), the respective processes were tailored to account for the average EU situation (e.g. energy mix, production of pesticides and fertilisers – see following paragraphs)

2.3. Key assumptions for performing the Life Cycle Assessment

The reference system is the EU-27 per capita consumption in 2010 for the products listed in Table 1. The functional unit is defined as the average food consumption per person in the EU in terms of food categories (including the food losses at each stage).

System boundaries consider a cradle-to-grave approach (Fig. 1), divided into six lifecycle stages: agriculture/breeding, industrial processing, logistics, packaging, use and end of life.

At various stages of their lifecycle, all food systems include the production of scraps or other materials that may often be considered to be co-products. As a consequence, the problem of the allocation of environmental burdens is present in almost all food chains. This problem is further complicated by the fact that the mass of the co-products very often greatly exceeds the mass of useful food products obtained; for example, in the case of olive oil manufacturing, 2.1 kg of husks are produced for every kg of olive oil. Performing the allocation on the basis of mass would result in the displacement of a large part of the impact burden associated with the food chains to the co-products rather than to the product for which the supply chain was built (Notarnicola et al., 2012). Based on these considerations, the environmental impacts incurred during food production are allocated on an economic basis.

As regards the use of fertilisers in the agricultural stage of each product, emissions of N_2O from managed soils and CO_2 emissions from lime and urea application have been estimated according to the IPCC methodologies (IPCC, 2006a). Ammonia emissions to air and the nitrate leaching in the soil were also estimated by applying the calculation suggested by the IPCC guide. It is assumed that all nitrogen that volatises converts to ammonia, and that all nitrogen that leaches is emitted as nitrate. It is estimated that 5% of phosphorus applied through fertilisers is emitted to freshwater resources (Blonk Consultants, 2014).

Pesticides are among the most important inputs in the agricultural phase, and have a significant impact on ecological and human toxicity. The approach indicated by Sala et al. (2014) was followed in order to estimate the consumption of pesticides. This approach consists of a framework developed to assist the quantification of pesticide fractions, starting from different levels of publicly available data. The data used for the estimation of the quantities of pesticides used in various crops were obtained from the EC (2007). The emissions of pesticides during their use were assessed, assuming that 100% of the active pesticide ingredient is emitted to soil (de Beaufort-Langeveld et al., 2003).

The analysis of farming systems required data on animal growth,

Table 1
Basket of products and apparent consumption (year 2010, EU-27).

Product groups	Basket products	Total apparent EU-27 consumption of the food product (Mt/year)	Per-capita apparent consumption of the food product (as kg/inhabitant p.a. and as % of the overall basket)	Economic value of the total apparent EU-27 consumption of each food product (billion €/year)[a]
Meat	Pig meat	20.58	41.0 (7.6%)	33.66
	Beef	6.90	13.7 (2.5%)	26.36
	Poultry	11.49	22.9 (4.2%)	23.21
Dairy products	Milk and Cream	40.25	80.1 (14.8%)	22.90
	Cheese	7.52	15.0 (2.8%)	28.95
	Butter	1.83	3.6 (0.7%)	5.93
Cereal-based products	Bread	19.75	39.3 (7.3%)	26.90
Crop-based products	Sugar	14.97	29.8 (5.5%)	8.04
	Sunflower oil	2.73	5.4 (1.0%)	2.37
	Olive oil	2.68	5.3 (1.0%)	4.70
Vegetables	Potatoes	35.24	70.1 (13.0%)	10.17
Fruit	Oranges	8.72	17.4 (3.2%)	5.10[b]
	Apples	8.07	16.1 (3.0%)	4.73[b]
Bevereages	Mineral water	52.74 (G litres)	105 (litres) (19.4%)	8.92
	Roasted Coffee	1.75	3.5 (0.6%)	9.28
	Beer	35.07 (G litres)	69.8 (litres) (12.9%)	28.68
Pre-prepared meals	Meat-based dishes	1.44	2.9 (0.5%)	13.74
	Total (basket)	**271.73**	**540.9** (100.0%)	**263.64**
	Total Eurostat-Prodcom per capita apparent consumption (kg/inhabitant p.a.)		**933.2**	

[a] Estimated using a) the cost of goods at the seller's factory and b) the trade value associated with the goods as they cross the border.
[b] Estimated economic value of sold products only.

Table 2
Overview of LCI datasets relative to the agriculture/production phase.

Representative products	Activities	Data source and reference area
Coffee	Production of coffee cherries	Coltro et al. (2006) Brazil, Salomone (2003)
	Green coffee production (wet process)	
	Coffee roasting for the production of soluble coffee	Humbert et al. (2009)
	Coffee roasting for the production of ground coffee	
Beer	Barley cultivation	Blonk Consultants (2014), EU
	Malt production	Kløverpris et al. (2009)
	Beer production	Schaltegger et al. (2012)
Mineral water	Treatment of natural water	Vanderheyden and Aerts (2014), Belgium
	Bottling water	
Bread	Wheat cultivation	Blonk Consultants (2014), EU
	Production of wheat flour from dry milling	Renzulli et al. (2015)
	Bread production	Espinoza-Orias et al. (2011)
Beef	Beef cattle breeding	Blonk Consultants (2014), Ireland
	Slaughtering beef cattle for the production of beef meat	
	Beef meat processing	
Pork	Pigs breeding	Blonk Consultants (2014), Netherlands
	Slaughtering pigs for the production of pig meat	
	Pig meat processing	
Poultry	Broilers breeding	Blonk Consultants (2014), Netherlands
	Slaughtering broilers for the production of poultry meat	
	Poultry meat processing	
Milk	Dairy cattle breeding	Blonk Consultants (2014), Netherlands
	Processing of raw milk for the production of standardised full milk	Fantin et al., 2012
Butter	Processing of raw milk for the production of cream	Djekic et al. (2014), Europe
	Production of butter	
Cheese	Processing of raw milk for the production of standardised skimmed milk	Djekic et al. (2014), Europe
	Production of cheese	
Sugar	Sugar beet cultivation	Blonk Consultants (2014), Germany
	Production of sugar from sugar beet	
Sunflower oil	Production of sunflower seeds	Blonk Consultants (2014), Europe
	Crude sunflower oil production from crushing (solvent process)	
	Refining sunflower oil	
Olive oil	Olive cultivation	Notarnicola et al. (2013), Italy
	Extra virgin olive oil production from milling olives	
	Bottling extra virgin olive oil	
Potatoes	Potato cultivation	Blonk Consultants (2014), Germany
	Storage of fresh potatoes for fresh consumption	EPD (2012)
	Storage of fresh potatoes for the production of chips and frozen potatoes	
	Production of frozen potatoes	Ganesh (2013)
	Production of chips	
Apples	Apple cultivation	Milà i Canals et al. (2007), Europe
	Selection, conditioning and storage	Cerutti et al. (2014)
Oranges	Orange cultivation	Pergola et al. (2013), Italy
	Selection, conditioning and storage	
Pre-prepared meals based on meat	Cultivation of carrots, onions, tomatoes	Frischknecht et al. (2007)
	Production of processed ingredients (chicken meat, refined sunflower oil, tomato sauce)	EC (2006), EU
	Pre-processing the ingredients	Schmidt Rivera et al. (2014), EU
	Manufacturing of pre-prepared meals	

enteric emissions and feed production. The animal breeding models taken into account in this study for the various types of products (dairy products, and meat from beef, pork and poultry) are those reported by Blonk Consultants (2014). In particular, the animal enteric fermentation and the type of manure management used in the production of livestock products were accounted for. The feed production processes were also taken into account. The inventories regarding the impacts of livestock were calculated according to the approach indicated by the IPCC in Vol.4 chapter 10 (IPCC, 2006b).

Logistics consists of international trade, local distribution and retail. In the present study, trade from outside of the EU is called international trade and it was considered for all products in the basket (with the exception of pre-prepared meals, for which data on imports per country were not available). The countries of origin and amount of imports were considered in relation to domestic production. Transport from those countries, which represents the source of at least 90% of total EU imports of a specific product, was considered in the study. Distribution consists of transport by lorry from the manufacturer/farm to a regional distribution centre, and the further transport by lorry from the regional distribution centre to the retailer. The total distance travelled was assumed to be 500 km for all products. If refrigerated transport is needed, a 20% increase in fuel consumption was assumed (Lalonde et al., 2013). The energy consumption associated with the time during which the product is stored in a retail facility was considered using data from the Danish LCA Food database (Nielsen et al., 2003).

The use phase is assumed to consist of: i) consumer transport (a 4 km transport by passenger car from the consumer's home to the retailer and back) and ii) domestic consumption.

The end-of-life phase includes the treatment of food scraps and unconsumed foods, together with the environmental assessment of human metabolism products, modelled according to the method of Muñoz et al. (2007). Specifically, each basket product was considered in terms of its nutritional composition (e.g. fibre/carbohydrate/protein) in order to account for the impacts of human excretion (Ciraolo et al., 1998).

Different data quality requirements were implemented in order to choose the inventory data that were most appropriate for the

Table 3
Inventories of the agricultural phase of different products (per cultivated ha per year).

		Apple	Barley	Wheat	Coffee	Olives	Orange	Potato	Sugar beet	Sunfl. Seeds
Products	t	31.4	5.7	7.1	9.0	5.8	25.0	41.6	58.9	1.3
Coproducts (total weight)	t	–	4.0	4.0	–	–	–	–	–	–
Inputs										
Fertilisers										
N	kg	62	145	149	238	30	240	100	150	57
P_2O_5	kg	4	10	19	26	7	100	101	40	50
K_2O	kg	47	14	17	233	7	180	131	140	21
Lime fertiliser	kg	52	329	327	1057	0	0	365	291	400
Water	m^3	3000	0	0	0	654	4000	351	186	33
Pesticides (total weight)		Weight of active ingredient divided by the respective % content (reported in Table 4)								
Diesel	kg	231.7	131.2	138.5	161	78.7	250	243.9	164.5	92.6
Electricity	kWh	952	0	0	0	771	3200	1446	0	305
Outputs										
Emissions to air										
N_2O from N fertilisers (direct)	kg	0.9	3.3	3.3	3.4	0.4	3.4	2.6	3.3	0.5
N_2O from N fertilisers (indirect)	kg	0.1	1.2	1.2	0.3	0.0	0.3	0.9	1.2	0.4
NH_3 from N fertilisers	kg	7.5	32.7	33.3	28.9	3.6	29.1	27.2	33.3	9.1
CO_2 from fertilisers	kg	43.3	234.1	235.8	669.4	0.0	233.5	204.7	202.4	189.0
Emissions to water										
NO_3 from N fertilisers	kg	82.4	275.0	281.7	316.2	39.5	318.9	215.2	281.7	87.7
P from fertilisers	kg	0.1	1.3	1.3	0.6	0.2	2.2	3.5	2.2	1.2
Emissions to soil										
Pesticides		100% active ingredient (reported in Table 4)								

Table 4
Inventories of pesticides use in the agricultural phase of different products (per cultivated ha per year).

Pesticides (active ingredient)	% active ingredient in the pesticide		Apple	Barley	Wheat	Coffee	Olives	Orange	Potato	Sugar beet	Sunfl. Seeds
Azoxystrobin	25	kg		0.09	0.09						
Captan	50	kg				1.50					
Carbaryl	85	kg				1.20					
Carboxin	29.5	kg									0.47
Chloridazon	65	kg								0.50	
Chlorpyrifos	44.5	kg	0.80			1.20		1.20			0.10
Copper	50	kg				0.03	0.0				
Dimethoate	38	kg					0.53		0.15		
Diquat	17	kg							0.30		0.10
Epoxiconazole	12.5	kg								0.13	
Ethephon	21.7	kg		0.09	0.09						
Ethofumesate	20.8	kg								0.54	
Fluazinam	38.8	kg									0.43
Fosetyl-aluminium	80	kg						0.45			
Glyphosate	40	kg	0.70	0.27	0.27	2.00	0.24	4.00		0.45	
Mancozeb	75	kg	2.00					0.45	4.80		
Mcpa – sodium salt	25	kg		0.30	0.30						
Methomyl	25	kg							0.05		
Mineral oil	100	kg	1.60				0.16	1.20	0.30		
Pencycuron	22.9	kg		0.33	0.33						
Phenmedipham	16.2	kg								0.71	
Propiconazole	25.5	kg		0.11	0.11						
Prosulfocarb	78.4	kg							0.60		
Sulfur	80	kg	2.10							0.47	
Tebuconazole	25.8	kg									0.10
Trinexapac-ethyl	26.6	kg		0.05	0.05						

present study and approach. Data quality was assessed in a pedigree matrix focusing on the parameters of: time-related coverage, geographical coverage, technology coverage, completeness and consistency.

Specifically, the most representative datasets for each product in the basket were identified by applying the above mentioned data-quality requirements to the collected existing LCA literature concerning the basket products. LCI data sources of the agriculture and production stages of the BoP food are summarised in Table 2. All of the agricultural datasets, taken from the literature or from databases, have been modified in order to adapt them to the method and assumptions previously reported.

Foreground data were obtained from scientific literature and direct industrial sources. Background data were mainly taken from the Agrifootprint (Blonk Consultants, 2014) and Ecoinvent v.3 (Frischknecht et al., 2007; Weidema et al., 2013) databases. For the electricity profile the EU-27 ELCD dataset was used.

Country-specific import data for the BoP food were taken from the Eurostat international trade database for the year 2010 (Eurostat, 2015). Distances and modes of transport used in import countries were also accounted for.

The impact assessment method for the characterisation of the lifecycle inventories is the ILCD (version 1.04), which recommends a set of 14 midpoint impact categories (EC-JRC, 2011) (see Table 7).

Table 5
Inventories of the breeding phase of animal-derived products.

		Milk	Beef cattle for slaughter	Pigs for slaughter	Broilers for slaughter
Products	kg	1000	1000	1000	1000
Coproducts (total weight)	kg	25	–	–	–
Inputs					
Feed					
Grass	kg	1364	21,376	0	0
Grass silage	kg	0	7666	0	0
Maize silage	kg	717	0	0	0
Compound feed	kg	219	1563	0	1679
Mix of by-products	kg	105	0	0	0
Pig feed	kg	0	0	2057	0
Water	m^3	2	138	9	3
Heat from gas	MJ	57	0	99	1179
Diesel	kg	0	130	0	0
Electricity	kWh	58	304	13	48
Outputs					
Emissions to air					
Methane, biogenic (from enteric fermentation)	kg	15.94	194.84	14.47	0.00
Methane, biogenic (from manure management)	kg	6.32	54.92	4.04	0.60
N_2O (direct)	kg	0.04	0.36	0.27	0.00
N_2O (indirect)	kg	0.05	0.51	0.16	0.00
NH_3	kg	3.84	39.29	13.21	13.10
Solid waste	kg	35.00	–	–	–
Losses					

Table 6
Amounts of packaging per typology, per 1-kg or 1-L packaged product.

	Unit	Glass	Paper	Cardboard	Corrugated board box	Aluminium	LDPE	HDPE	PET	PP	PS
Mineral water[a]	g								23		
Beer	g	522		32		3					
Coffee – soluble	g	2600	4		54	14					
Coffee – ground	g				14	16					
Apples[b]	g										3
Oranges	g				84						
Potatoes – fresh	g							4			
Potatoes– frozen	g					4			8		
Potatoes – chips	g					20			20		
Bread	g									4	
Olive oil	g	786	7		47	6	8				
Sunflower oil	g				24				43		
Sugar	g		15								
Milk[a]	g								28		
Cheese	g				115						
Butter	g					15					
Beef	g						4				33
Pork	g						4				33
Poultry	g						4				33
Pre-prepared meal	g				42		28		69	8	

[a] Referred to as 1-L product.
[b] Only 20% of product is packed.

3. Life cycle inventory

Lifecycle inventory data are reported along with the main choices and assumptions made in this study regarding: i) the agricultural and breeding stage; ii) industrial processing and packaging; iii) other stages.

3.1. Agricultural/breeding stage

Tables 3 and 4 show the inventories of the agricultural phase of the different products that pertain to one ha of cultivated area per year. Mineral water is excluded because there is no agricultural phase in its lifecycle. Table 3 is an input–output table that reports data regarding products and co-products, fertilisers and pesticides used, consumption of diesel for agricultural operations, and electricity used to pump water for irrigation. The outputs are the emissions to air, water and soil that derive from the use of fertilisers and pesticides (see section 2.2). Table 4 gives a detailed inventory of pesticides applied to the different crops, in which the weights of the different active ingredients applied to one ha of crops are reported together with the percentage of active ingredient contained in commercial pesticides. The emissions from the combustion of diesel (taken from the Agri-footprint database, Blonk Consultants, 2014) in agricultural machinery have not been reported in this table, but are considered in the inventory. As regards water use, according to data in the inventories, no water input is applied in the cultivation of wheat, barley and coffee.

Table 5 shows the inventories of the breeding phase of animal-derived products. There are four inventories related to the rearing of dairy cows that produce milk, which is also the basis for the production of cheese and butter, and to the rearing of beef cattle, pigs and broiler chickens which will be sent to slaughter. The main

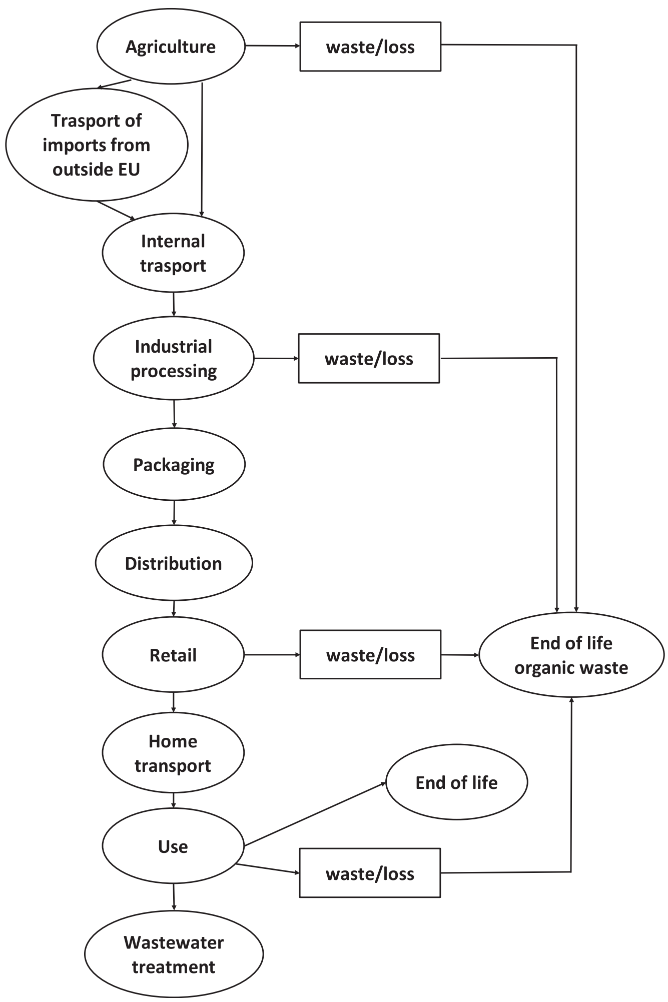

Fig. 1. System boundaries for the basket of products – food.

data are taken from the Agrifootprint database. The table reports the feed used, the water consumed and energy inputs, together with the emissions deriving from manure management and the enteric fermentation of ruminants and (in minor amounts) non-ruminant animals. Losses of milk in this stage have also been considered.

3.2. Industrial processing and packaging

The industrial phase is very different from product to product. The inventory was built for each activity included in the production phase of each product by collecting literature or database data. The main sources of data are reported in Table 2. Details on the types and quantities of packaging used for each basket product are illustrated in Table 6.

3.3. Other stages

As indicated in the section on the assumptions concerning the LCA method (section 2.3), logistics consists of international transportation from outside the EU, and distribution and retail transport.

For the inventory of the international transport of goods, the share of imported goods in the total (production + imports) was calculated. For each kg of imported goods, the inventory of transport for each mode was also calculated, considering the different exporting countries, means of transport and distances. Only green coffee is totally imported from abroad, while for all the other products in the basket the share of imports compared to the total available amount of product is quite low (or very low in some cases). The inventories of distribution and retail were obtained by applying the assumptions described in section 2.3.

The use phase consists of consumer home transport and domestic consumption. The purchased amount of the various products in each mode of travel was estimated to prepare the inventory of this phase. The assumption is that 30 products are bought in a single purchase, including food and non-food products; the impact of transport is therefore allocated between the purchased products considering that each product is one of thirty items purchased (3.33% of the transport burden) (Vanderheyden and Aerts, 2014).

As regards home preparation, the following operations are considered together with the specific energy consumption (Foster et al., 2006):

- Boiling: 2 MJ of natural gas/kg product (coffee, potatoes)
- Frying: 7.5 MJ of natural gas/kg product (potatoes, sunflower oil)
- Baking: 0.75 kWh electricity/kg product (potatoes)
- Roasting: 8.5 MJ of natural gas/kg product (meat products)

The end-of-life phase includes the solid waste treatment of food scraps and unconsumed foods, and the wastewater treatment of the waste excretion of human metabolism. Specifically, as mentioned in the previous section, the model by Muñoz et al. (2007) was used to assess the environmental impact of human excretion.

Data on food losses were obtained from the FAO (2011) which highlights the losses that occur along the entire food chain, and makes assessments of their magnitude.

Data on food scraps and unconsumed foods are input into a waste treatment scenario based on Eurostat data (Eurostat, 2014) concerning the disposal of waste in the EU-27. The statistics indicate the following disposal treatments: 8% of food waste is sent to landfill, 5% is incinerated, and 87% is sent for other recovery treatment. As it is assumed that such a recovery treatment is 80% composting and 20% anaerobic digestion for biogas production (Jungbluth et al., 2007), it is estimated that 69.6% of total waste is composted while 17.4% is anaerobically digested.

4. Results and discussion

Lifecycle inventories have been characterised in the lifecycle impact assessment step. The ILCD methodology (EC-JRC, 2011), characterisation factors (v1.04), and normalisation factors (Sala et al., 2015) have been applied. Long-term emissions have been excluded, and only generic non-site-specific characterisation factors were used.

The characterisation results of the apparent consumption by an EU citizen of the 17 different products within the BoP food during the 2010 reference year are reported in Table 7. The results indicate that, in the majority of the impact categories, the typologies of foods with the greatest burdens are meat products (beef, pork and poultry) and dairy products (cheese, milk and butter).

This result is the effect of two factors: the magnitude of the impact related to the specific food, and the quantity of its relative consumption at European level. Beef meat, for instance, is the meat-product food-type with the greatest environmental burden since, although its annual consumption is the lowest of all the meat products in the BoP (13.7 kg/citizen per year), it has the highest environmental impact per kg.

On the other hand, pork meat, whose impact in the BoP is as high as beef, presents a lower environmental burden compared to beef, but this is counterbalanced by higher per-capita consumption

Table 7
Characterisation results of the average apparent consumption of the seventeen representative food products in the food basket of products. Results are reported for an average consumption of one EU-27 citizen in one year (2010). The results regard the whole life cycle of each basket products from 'cradle to grave'.

Impact category	Unit	Mineral water	Beer	Coffee	Apples	Oranges	Potatoes	Bread	Olive oil	Sunflower oil	Sugar	Milk	Cheese	Butter	Meat – beef	Meat – pork	Meat – poultry	Pre-prepared meal	Total
Climate change	kg $CO_{2eq.}$	2.9E+01	8.0E+01	4.0E+01	8.3E+00	1.2E+01	4.6E+01	4.4E+01	1.3E+01	3.9E+01	3.1E+01	1.1E+02	1.9E+02	8.7E+01	3.1E+02	2.7E+02	1.4E+02	1.8E+01	**1.4E + 03**
Ozone depletion	kg CFC-$11_{eq.}$	3.9E-06	1.1E-05	5.4E-06	1.1E-06	1.2E-06	6.2E-06	6.2E-06	1.5E-06	1.3E-06	1.4E-06	4.6E-06	6.9E-06	9.9E-07	8.1E-07	3.9E-06	2.1E-06	1.6E-06	**6.0E−05**
Human toxicity	CTU_h	2.6E-06	6.8E-05	2.0E-06	4.8E-07	8.5E-07	5.7E-05	7.3E-05	2.1E-06	7.9E-05	7.5E-05	2.0E-04	3.5E-04	2.0E-04	3.4E-04	4.4E-04	1.6E-04	1.3E-05	**2.1E−03**
Particulate matter	kg $PM_{2.5}$ eq.	1.6E-02	7.0E-02	2.3E-02	3.8E-03	6.1E-03	2.1E-02	2.5E-02	1.2E-02	2.0E-02	2.7E-02	6.0E-02	9.5E−02	4.7E-02	1.8E-01	1.6E-01	7.4E-02	9.6E-03	**8.5E−01**
Ionising radiation HH	kBq U^{235} eq.	2.9E+00	6.1E+00	6.0E+00	1.0E+00	1.0E+00	4.9E+00	6.4E+00	1.2E+00	3.8E-01	5.4E-01	3.8E+00	5.8E+00	9.2E-01	6.0E-01	3.7E+00	2.0E+00	1.7E+00	**4.9E + 01**
Photochemical ozone formation	kg $NMVOC_{eq.}$	1.4E-01	3.2E-01	1.1E-01	3.2E-02	4.3E-02	1.3E-01	1.3E-01	6.2E-02	1.0E-01	8.2E-02	2.2E-01	2.8E-01	1.0E-01	4.1E-01	4.2E-01	2.0E-01	4.0E-02	**2.8E + 00**
Acidification	mol $H^+_{eq.}$	1.8E-01	8.8E-01	5.2E-01	7.0E-02	1.3E-01	4.8E-01	6.7E-01	1.5E-01	7.0E-01	1.0E+00	2.2E+00	3.7E+00	2.0E+00	7.5E+00	6.7E+00	2.7E+00	2.1E-01	**3.0E + 01**
Terrestrial eutrophication	mol N_{eq}	4.6E-01	2.6E+00	1.4E+00	1.9E-01	4.7E-01	1.6E+00	2.4E+00	4.6E-01	2.8E+00	4.4E+00	9.2E+00	1.6E+01	8.8E+00	3.3E+01	3.0E+01	1.2E+01	7.0E-01	**1.3E + 02**
Freshwater eutrophication	kg $P_{eq.}$	1.2E-03	2.8E-02	2.9E-03	2.4E-04	3.7E-03	2.7E-02	2.4E-02	1.7E-03	2.0E-02	6.8E-03	7.1E-02	7.2E-02	1.2E-02	5.6E-02	8.9E-02	1.8E-02	1.9E-03	**4.4E−01**
Marine eutrophication	kg $N_{eq.}$	4.8E-02	3.3E-01	2.4E-01	3.0E-02	8.1E-02	3.6E-01	5.7E-01	6.6E-02	3.9E-01	4.9E-01	9.5E-01	1.6E+00	6.3E-01	2.4E+00	2.6E+00	1.1E+00	8.0E-02	**1.2E + 01**
Freshwater ecotoxicity	CTUe	1.7E+01	4.4E+02	4.0E+02	4.9E+01	9.5E+01	8.2E+01	7.3E+01	2.6E+01	2.4E+02	7.4E+01	2.9E+02	4.9E+02	2.7E+02	5.5E+02	8.6E+02	3.8E+02	5.0E+01	**4.4E + 03**
Land use	kg C deficit	7.0E+01	4.0E+02	2.8E+02	6.5E+01	9.9E+01	2.2E+02	3.4E+02	4.8E+02	1.4E+03	3.0E+02	8.2E+02	1.4E+03	7.7E+02	2.9E+03	3.2E+03	1.7E+03	1.2E+02	**1.5E + 04**
Water resource depletion	m^3 water eq.	3.3E+00	1.3E+00	1.4E+00	1.8E+00	4.1E+00	3.1E+00	1.1E+00	1.4E+00	1.7E+00	2.5E+00	3.3E+00	8.7E+00	6.5E-01	5.5E+00	1.7E+00	1.1E+00	1.0E+00	**4.4E + 01**
Resource depletion	kg $Sb_{eq.}$	8.6E-04	3.5E-03	1.0E-03	1.6E-04	3.8E-04	2.0E-03	3.8E-04	7.0E-04	8.2E-04	3.9E-04	1.2E-03	9.7E-04	8.5E-04	8.1E-04	1.1E-03	6.1E-04	1.8E-04	**1.6E−02**

(41 kg/citizen per year). The same can be stated for dairy products, for instance milk, for which the relatively low environmental burden per unit is counterbalanced by its per-capita consumption of 80.1 kg/citizen per year. Fruit contributes the least to the overall result since its relatively low impact is coupled with light packaging, fresh consumption and the general lack of domestic processing or cooking.

All other foods fall between these two profiles, as each is the subject of either a specific process or material, such as for instance the packaging, or domestic operations (cooking, refrigeration, baking, frying, etc.), that leads to a relevant specific environmental impact.

Fig. 2 shows the contribution of the six lifecycle stages of the entire basket to every impact category. Concerning this analysis, the agricultural phase has the greatest environmental burden in many impact categories; it is characterised by the impacts of all the agronomic and zootechnical activities, which involve high energy consumption with associated emissions of greenhouse gases, particulate matter, ammonia, sulphur dioxide, nitrogen oxide and heavy metals.

The second most burdening stages are processing and logistics, which are characterised by the energy production responsible for emissions to the atmosphere, occurring during the production of heat, steam and electricity and during transport. The other lifecycle phases make only a minor contribution to the overall impact.

The results were found to be (almost always) in line with published results regarding LCAs of specific single types of food (e.g. Notarnicola et al., 2011, 2012; Corson & van der Werf, 2012).

The results are also consistent with other studies found in the literature that assess the most representative foods consumed in specific regions. For example, Foster et al. (2006) confirm and highlight the high impact of dairy and meat products and of the agricultural stage of all food products, particularly in terms of eutrophication. Similar results are also described in Muñoz et al. (2010); food production was found to be the most burdening lifecycle stage in the Spanish diet, whilst human excretion, as a lifecycle stage, was found to be important in terms of eutrophication due to the emissions of nutrients into sewage. In the Eberle and Fels (2014) study of German food consumption, animal products were found to cause the highest environmental burdens, and food loss was also found to have major environmental impacts. The results of the present study also indicate that food losses must be accounted for in food-related LCAs, since they can account for up to 60% of the initial weight of the foodstuffs. The results illustrated in this paper are in line with those of the JRC (2015) study of the energy use and greenhouse gas (GHG) emissions in the EU food sector, which highlighted the fact that the amount of energy necessary to cultivate, process, pack and bring food to European citizens' tables accounts for 17% of the EU's gross energy consumption, equivalent to approximately 26% of the EU's final energy consumption. The GHG emissions of Pairotti et al. (2015) study, concerning the comparison of the Mediterranean diet to other diets, has a carbon footprint value per person per year of these diets ranging between 1700 kg CO_2eq and 2000 kg CO_2eq. This is slightly higher than the global warming indicator of the present study which amounts to 1445 kg CO_2eq. This result is also in line with the one in the study of Eberle and Fels (2014) which reports carbon footprint of the German diet of 1800 kg CO_2eq/year.person (stating that this value might be overestimated due to allocation issues). Similarly, the carbon footprint of Muñoz's previous studies (Muñoz et al. 2009, 2010) concerning the Spanish diets ranges from 1560 to 2084 kg CO_2eq. person^{-1} year^{-1}.

To assess the robustness of the results, a sensitivity analysis was carried out by changing some key variables. Since the results showed that the greatest impact of basket is due to the

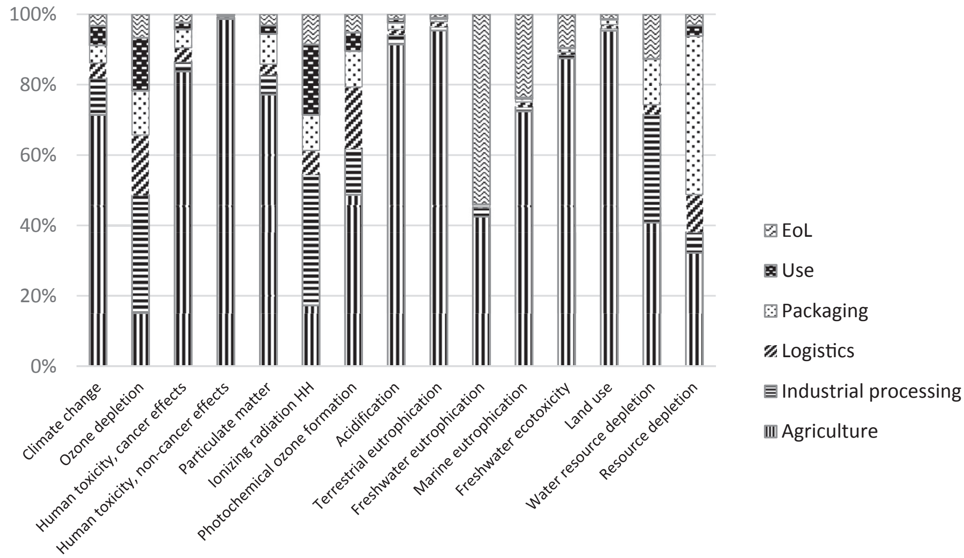

Fig. 2. Relative contribution of the six life cycle phases to the impact of the entire basket in each impact category.

consumption of meat and dairy products, a first change was made to the inventories of such products, in particular to the most critical and variable phase, which is animal breeding. The second change regarded the inventory of the agricultural phase of the other products, different from meat and dairy; specifically, some important hypotheses and assumptions were changed (consumption and emission modelling of fertilisers and pesticides). The third element that was modified is represented by the logistics. Table 8 shows all the variables that have been tested for sensitivity in the three considered cases. The limits of the range were obtained by comparing the values used in this study with those of the collected references. The table shows the factors which are to be multiplied by the data of this study which are intended as a baseline. As can be noted in many cases the ranges used are very broad, especially in the agricultural phase. The sensitivity analysis results are shown in Fig. 3. Despite the wide range of variability tested, results for the whole basket change, considering the three cases, from a minimum of −12% to a maximum of +30%.

The results of this impact assessment could be used to provide a baseline for monitoring and analysing options and targets for the implementation of possible improvements to the various supply chains. The results are not meant to be used as an absolute measure of the environmental impact per person. Castellani et al. (2016) tested several strategies to assess the robustness of the identification of hotspots of the most dominant types of environmental impact and the critical lifecycle stages. Based on the literature, technical reports and scientific papers (e.g. Garrone et al., 2014; Tukker et al., 2009; Weidema et al., 2008; WRAP, 2013; Notarnicola et al., 2015) and the hotspots shown in the present study, three main strategies for reducing the impacts of food supply chains were identified:

i) an environmentally sustainable increase in agricultural productivity coupled with measures that aim to reduce emissions to air, water and soil,
ii) dietary changes (e.g. reducing the consumption of meat and dairy products)
iii) greater efficiency in reducing food losses and managing food waste (e.g. through improved rates of food-waste recovery).

The adoption of these strategies requires the identification and setting of adequate targets. Many improvements and related

Table 8
Range of factors used for the sensitivity analysis in the three considered cases. The baseline inventory values of the main study are represented by a factor value of 1.

Meat and dairy products			Agricultural phase of other products			Logistics		
Variables	Factor		Variables	Factor		Variables	Factor	
	min	max		min	max		min	max
Feedstuffs	0.9	1.4	N fertilizer	0.3	2.5	International transport	0.5	1.5
CH_4 emissions from enteric fermentation and manure management	0.7	1.1	P_2O_5 fertilizer	0.4	3	Distribution	0.5	1.5
N_2O emissions (direct and indirect)	0.9	2	K_2O fertilizer	0.5	4	Home transport	0.5	4
NH_3 emissions	0.5	1.1	pesticides	0.5	2			

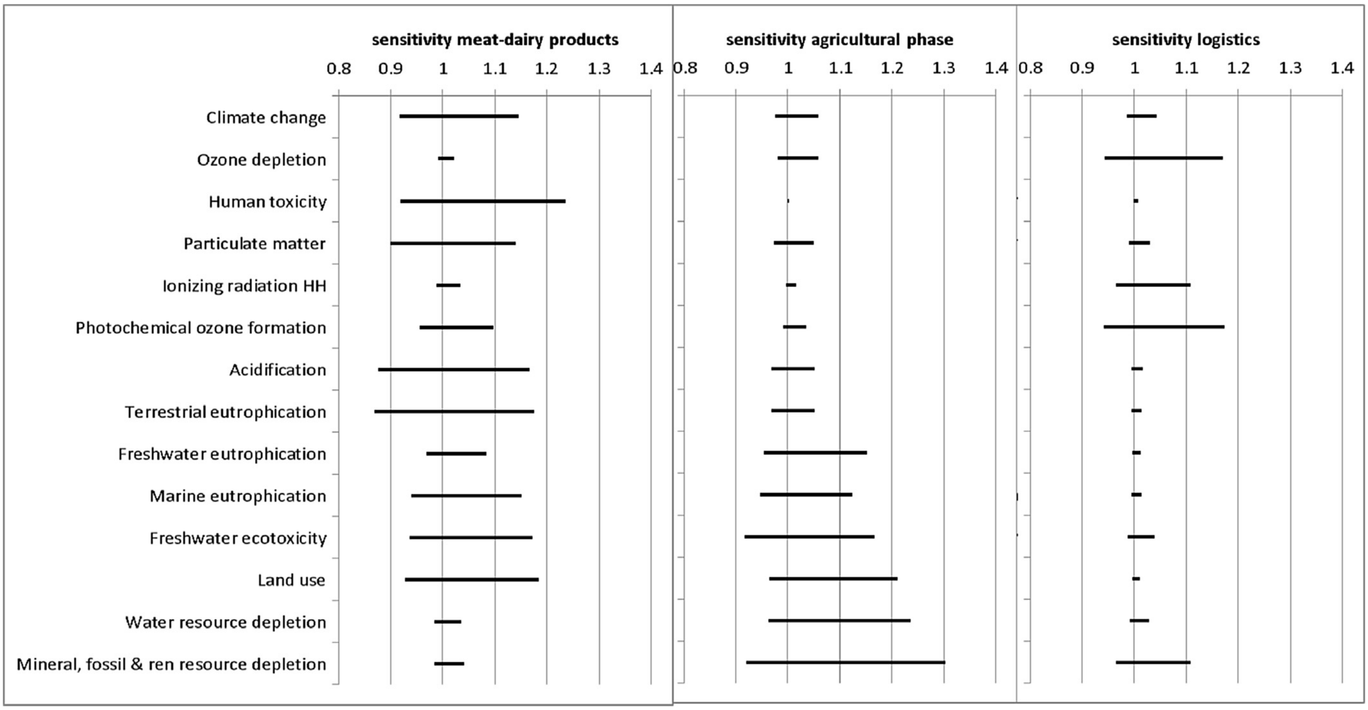

Fig. 3. Results of the sensitivity analysis of the three considered cases.

Table 9
Variation in food quantity used in dietary changes scenario 1 and 2: 25% or 50% reduction in the consumption of beef, dairy, pig meat, poultry and eggs, which is being compensated by a higher intake of cereals.

Product groups	Representative product	Baseline	Scenario 1: 25% reduction		Scenario 2: 50% reduction	
		Per-capita consumption (kg/pers.*yr^{-1})	Variation (%)	Per-capita consumption (kg/pers.*yr^{-1})	Variation (%)	Per-capita consumption (kg/pers.*yr^{-1})
Meat	Pig meat	41	−25%	31	−50%	21
	Beef	13.7	−25%	10	−50%	7
	Poultry	22.9	−25%	17	−50%	11
Dairy	Milk & cream	80.1	−25%	60	−50%	40
	Cheese	15	−25%	11	−50%	8
	Butter	3.6	−25%	3	−50%	2
Cereal-based	Bread	39.3	25%	49	50%	59
Sugar	Sugar	29.8	0%	30	0%	30
Oils	Sunflower oil	5.4	0%	5	0%	5
	Olive oil	5.3	0%	5	0%	5
Vegetables	Potatoes	70.1	0%	70	0%	70
Fruit	Oranges	17.4	0%	17	0%	17
	Apples	16.1	0%	16	0%	16
Beverages	Mineral water	105	0%	105	0%	105
	Roasted coffee	3.5	0%	4	0%	4
	Beer	69.8	0%	70	0%	70
Pre-Prepared meals	Meat based dishes	2.9	0%	3	0%	3

targets (e.g. halving food losses by 2050) are proposed in the literature and policy contexts, focusing on one specific issue at a time. A lifecycle-based approach shifting to a more comprehensive and systematic approach to setting targets has been developed by Sala et al. (2015) and may be applied by using the food basket of products approach and results. This can be done through the development of scenarios for improvement based on the baseline calculation made for the identification of hotspots, i.e. analysing the effect of changing some parameters related to possible improvements (such as the composition of the basket due to dietary shifts, cooking habits, efficiency improvements in the agricultural and processing phase, etc.) on the final results of the basket of food products.

To provide an example of how this can be done, two preliminary scenarios on dietary changes were tested and compared with the baseline. The scenarios are built according to the dietary changes to healthier diets as described in Westhoek et al. (2014). These diets consist of a 25% or 50% reduction in the consumption of beef, dairy, pig meat, poultry and eggs, which is being compensated by a higher intake of cereals. Details on how this shifts affect the amount of products in the BoP nutrition are provided in Table 9. Results (presented in Fig. 4) show that the partial substitution of meat and dairy products with cereal based ones can reduce the impact generated in all impact categories. Even if this is a quite simple

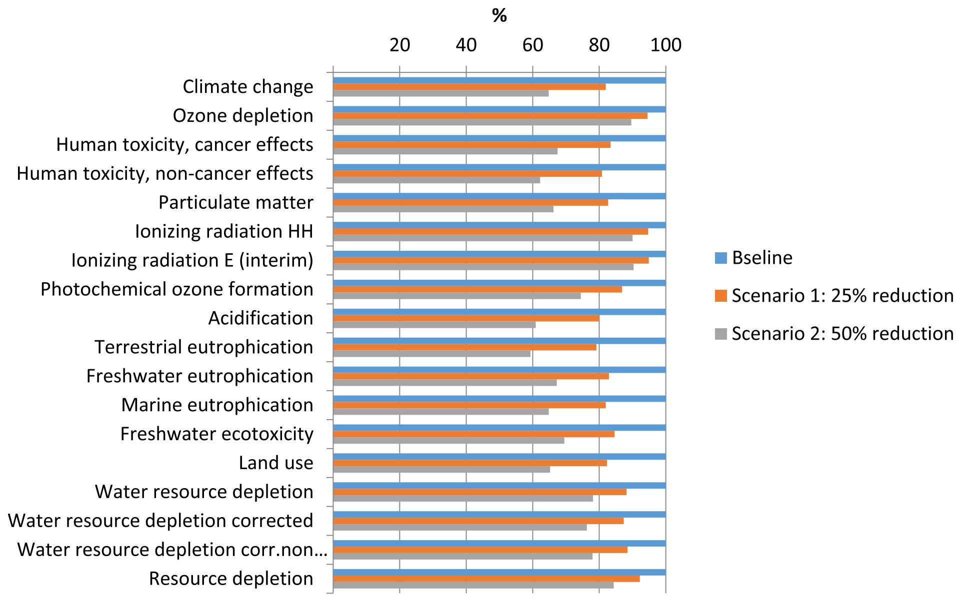

Fig. 4. Comparison of results between the baseline situation and the two scenarios on dietary change (25% or 50% reduction in the consumption of beef, dairy, pig meat, poultry and eggs, which is compensated by a higher intake of cereals). Results are refers to the entire BoP nutrition. The highest result for each impact category is represented as 100% and the others are scaled accordingly.

example of scenarios for the food sector, it helps to describe how the BoP model can be used to calculate and to compare the effects of possible improvement options discussed in the policy context.

The present study represents an attempt to assess the impacts associated with food consumption in the EU, systematically identifying representative products and building an inventory based on assumptions of average situations in the EU. However, some limitation of the studies should be noted in order to correctly interpret the results. For example, in the case of water consumption due to crop irrigation, some countries may have different irrigation needs which may affect the results. Moreover, for certain products (such as pesticides for example) there is no information on the active ingredients used in different countries, and this may change the relative contribution of pesticides to ecotoxicity impacts. In addition, it is assumed that 100% of all pesticides are emitted to soil, which may overestimate the role of this emission compartment and overlook the actual fate of the pesticide after application (see, for example, the ongoing effort by Rosenbaum et al., 2015). At the level of impact assessment, we used characterisation factors that are not spatially resolved, which may result in specific local impacts associated with a combination of pressures and vulnerabilities of the systems being overlooked. For example, a single result for water depletion impacts may not capture the differences between the environmental impacts in countries with or without water scarcity issues. Moreover, several impacts attributed to agricultural systems are not yet part of the LCA modelling system (e.g. terrestrial ecotoxicity, possible impacts of OGM crops, impacts on biodiversity, reduction in soil quality, etc.). This may imply a possible underestimation of the relative importance of some lifecycle stages and elementary flows.

5. Conclusions

The results of the environmental LCA carried out on the average consumption of the most representative food types in the EU-27 in 2010 indicate that, in the majority of the impact categories, the most burdening foods are meat products (beef, pork and poultry) and dairy products (cheese, milk and butter). These results are confirmed by other studies found in the literature.

In general, it was found that the end-of-life stage must be taken into consideration, especially human excretion and wastewater treatments, since their burden is often higher than that of the transport and operations occurring in the industrial food manufacturing plants.

The losses that occur during the whole lifecycle in terms of food scraps and wasted food in both the agricultural/industrial and domestic phases must also be taken into consideration, since they can account for up to 60% of the initial weight of the food products.

From a methodological point of view, this study has had several important results. A framework was developed that is fully replicable and fully coherent with the structure of the main LCA databases, as well as highly disaggregated process inventories based on a modular approach. Moreover, we identified datasets for the basket of food products based on comprehensive bibliographic research, and we compiled a basket of food products that represents about 60% of European food consumption habits.

Future developments of this study could entail the expansion of the basket of products to cover a greater range of food products that would represent almost 100% of European food consumption habits (e.g. considering a larger share of the Eurostat-Prodcom apparent yearly consumption patterns) and implementing new datasets.

Acknowledgements

The project for developing the “basket of products – food” was financially supported by the Directorate-General for the Environment (DG ENV) of the European Commission in the context of two Administrative Arrangements: “Scientific support for the screening and development of potential resource efficiency and product-group indicators as well as targets for the reduction of the overall environmental impact of EU consumption” (No. 07.307/2013/666404/SER/A.1) and “Indicators and assessment of the environmental impact of EU consumption” (No. 070201/2015/SI2.705230/SER/ENV.A1). The authors would like to thank Malgorzata Goralczyk for her contribution in managing the project.

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