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A framework assessing the footprints of food consumption. An application on water footprint in Europe

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ABSTRACT

Innovative sustainable food systems should be defined to meet the future food demand (both in terms of quality and quantity) and to overcome the threats that current food systems are posing to the natural capital. To achieve this ambitious goal, the transition to sustainable food habits should be supported by methodological frameworks and modelling tools promoting human and environmental health. The proposed framework provided a standardized system-based approach for the analysis of environmental impacts of food systems, assessed in terms of use of natural resources (water and ecological footprint) and GHG emissions (carbon footprint). The framework is applied to the assessment of water footprint of cradle-to-gate European food consumption, resulting in an average water footprint consumption of 3291 (±557) litre (per day per person). The case study showed the potentiality of our framework as a support tool for policy making in designing specific incentives for the reduction of environmental impacts related to the agri-food sector, as well as in the evaluation of agronomic strategies in the light of pursuing the environmental sustainability of food commodities production. The main novelty presented in the case study is to use food consumption data coming from surveys harmonized across European countries to assess the real food demand.

1. Introduction

Food production and consumption have direct and indirect effects on human health. As defined by the "One health" approach (FAO et al., 2008), direct effects are related to food safety and nutritional quality and indirect effects concern the impacts of food production and processing on the environment. Both definitions consider/include the use of natural resources and emissions (Mohammed et al., 2019; Ritchie and Roser, 2017; Rosa et al., 2020).

The expected increase of food demand due to world population increase (UN, 2019) and the transition of diets towards a greater intake of products of animal origin, mainly in developing countries (Drewnowski and Poulain, 2018; Schmidhuber and Shetty, 2005) generate a strong concern on the probable increase of environmental impact of food production. Among these threats, the biodiversity loss and the perturbation of the ecosystem services regeneration capacity play a pivotal role (FAO, 2019). Sustainable food systems, considered as the set of actors and processes involved starting from food production to food consumption and disposal (FAO and Nguyen, 2018), should be defined in order to meet the future food demand (both in terms of quality and quantity), under the constraints due to the limited availability of natural capital resources and the threats that current food systems are posing to natural capital. To achieve this ambitious goal, international institutions and the scientific community launched the challenge of developing methodological frameworks and modelling tools supporting the definition of diets that can promote human health by respecting the health of the environment (United Nations, 2015; WHO, 2019; Willett et al., 2019). These tools should comply with two challenging requirements: high flexibility, to represent peculiarities of the analysed food systems (IPES-Food, 2016), and a strong standardized assessment procedure, in order to guarantee the comparability and the integration of the results (Brouwer et al., 2020; EU Science Hub, 2015; European Commission and SCAR Food Systems., 2018).

Currently, the predominant approaches to the assessment of environmental impacts of food systems are focused only on one impact dimension at a time, disregarding the complexity and heterogeneity of the system (Meybeck and Gitz, 2017; Vanham et al., 2019). In particular, great attention has been given to the impact of food production on climate (Rose et al., 2019; Song et al., 2017; Wollenberg et al., 2016), neglecting other important aspects, for instance the impact on soil

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fertility (Barthel et al., 2019). Furthermore, the high heterogeneity in environmental impacts is not always adequately considered, disregarding the differences between production systems (e.g. intensive agriculture or organic farming) or food regime (highly influenced by area and income) (Balmford et al., 2018; Clark and Tilman, 2017; Poore and Nemecek, 2018).

A multi-indicator assessment approach has recently begun to develop, especially in the Life Cycle Assessment (LCA) community (Cucurachi et al., 2019), but standardized tools are needed to provide methodological support to these multi-impact assessments. Progress has, for example, already been made in the assessment of the Consumer Footprint (Sala and Castellani, 2019).

In this work, we propose an innovative assessment framework providing a standardized approach for the analysis of environmental impacts of food systems. Food consumption is considered as the main driver of food production. Therefore, the proposed framework is based on the assessment of environmental impacts derived from the production of food necessary to satisfy different patterns of food consumption. Understanding the link between consumption patterns and impacts is a key condition for the development of strategies supporting the transition of food systems towards sustainability.

The framework allows to develop impact assessment based on different scenarios. Such scenarios are defined by i) the type of subject, the analysis can be carried out at individual level or population level, ii) the type of food consumption, dietary pattern schemes (e.g. Mediterranean diet) or real consumption, and iii) the methodologies of food production and processing (e.g. organic or conventional agriculture). The framework, based on a multidimensional approach, considers several dimensions of environmental impacts in terms of use of natural resources (land and water) and flows (e.g. emissions into the air, flows into water).

The paper is structured as follows. Section 2 presents the conceptual model of the framework and the methodology used in the assessment modules of the framework. In Section 3, the framework is applied to the assessment of the water footprint demand of European food consumption. The impact of food production on water usage is very significant, for example it is estimated that agriculture could be responsible for up to 70% of global freshwater withdrawals (FAO and World Water Council, 2015). Despite this, the impact of food systems on water (both consumption and scarcity) has been addressed more recently by the scientific world and institutions (Hallström et al., 2015; Halpern et al., 2019) than other issues, such as GHG emissions. For this reason, the available scientific knowledge is still limited, and it is of interest to develop case studies, as has been done in this study.

2. Materials and methods

The framework structure of the environmental impact assessment of food consumption patterns is presented in Fig. 1. The assessment process can be divided into three phases: the quantification of food demand; the quantification of raw food necessary to satisfy the food demand; the estimation of the environmental impacts derived from food production and processing. Each phase is addressed with a specific assessment module (in purple in Fig. 1). The module ‘consumption pattern’ quantifies the food demand. The ‘food composition and processing’ module allows the conversion of processed foods and composite dishes into raw food. The ‘Environmental indicators’ module contains all the databases of indicators used to assess the environmental impacts of food production and processing.

Food demand represents the estimation of the quantity of food products consumed by an individual or a population, according to the level of analysis. The framework considers either a real-based or a scheme-based food demand. Real-based food demand refers to the estimation of the real consumption pattern of subjects in a specific area and in a specific period. Scheme-based food demand estimates the quantity of food consumed by subjects strictly adhering to a specific dietary pattern scheme (e.g. Mediterranean diet, the planetary health diets, or national nutritional guidelines). Details on the module

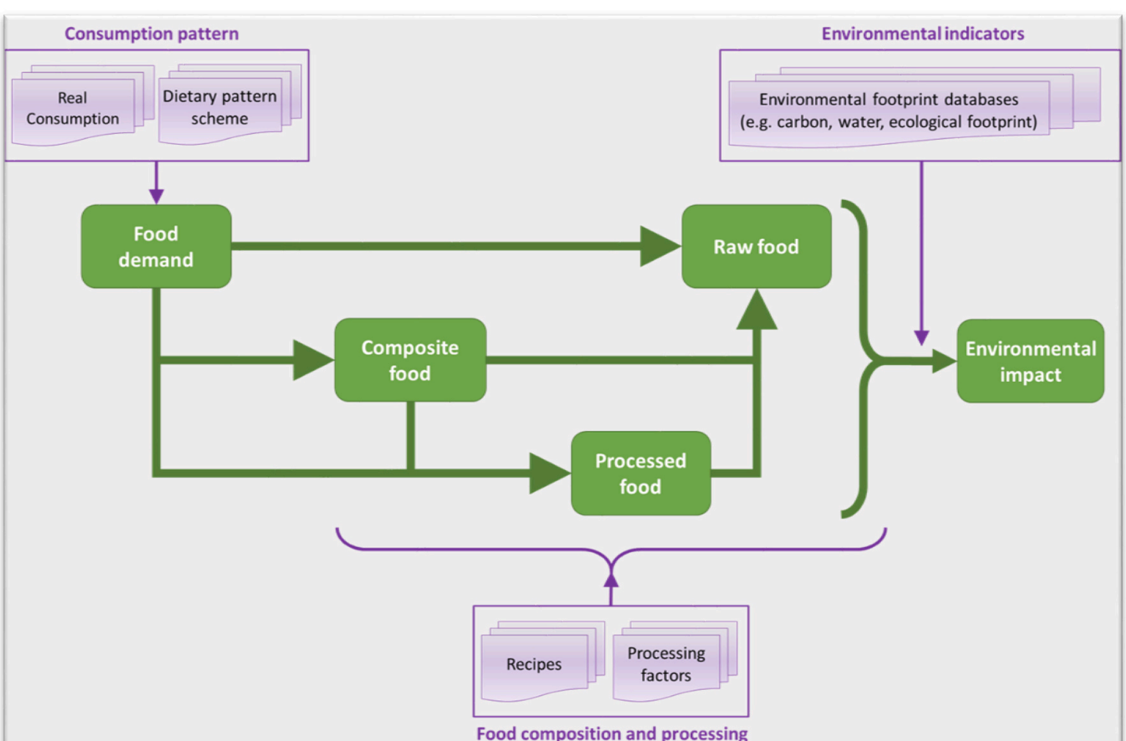

Fig. 1. Framework of the environmental impact assessment of food consumption patterns. Green blocks represent quantities assessed, purple boxes are the three modules of the framework. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

estimation of food demand are explained in Section 2.2.

Food demand is expressed in terms of raw food, processed food and composite dishes consumed. Raw food represents raw agricultural commodities derived from food production and that have not undergone any form of processing (e.g. apple, lettuce, raw milk). Processed food is obtained processing raw food, without adding any other ingredients, for example unsweetened orange juice, roast chicken, grated carrots. Composite dishes are multi-ingredient foods, including both industrial and home-cooked dishes (e.g. cheeseburgers, lasagne, goulash). To compute the quantity of raw food needed to satisfy the food demand, a double step analysis is implemented. Composite dishes are broken down into ingredients (that can be both processed food and composite dishes). Subsequently, all processed food is transformed into the quantities of raw food from which they are derived, applying a yield coefficient that considers weight losses of the products due to processing phase. More details are described in Section 2.3.

The total quantity of raw food necessary to satisfy the food demand constitute provides the input value for the quantification of the environmental impact derived from food production. The impact of primary production (both plant and animal) are assessed in terms of the natural resources required for production (ecological footprint and water footprint) and the emissions produced (carbon footprint). Methodological details on footprints are explained in Section 2.4.

Each module is supported by one or more databases, whose details are provided in the following subsections. The structure of each module is conceived to allow high flexibility of analysis in terms of resolution of available data (e.g. it is possible to manage consumption data at regional level and impact data at country level), easy maintenance, fast periodic data updating and the expansion of modules with new databases.

2.1. Food classification system

The framework is based on an international food classification system to standardize coding of food products. We adopted the 'exposure hierarchy' of the FoodEx2 classification, which is managed by the European Food Safety Authority (EFSA, 2011b, 2015). This classification system contains 4546 terms, structured in seven levels of aggregation. Level one includes 21 categories (e.g., fruit and vegetable juices and nectars, milk and dairy products, grain and grain-based products), while level seven is most detailed (e.g. it distinguishes between *Roho labeo* and *Labeo calbasu*, two species of carp). FoodeEx2 can easily be matched with other international food classifications, such as LanguaL™ (Møller and Ireland, 2018) and GEMS (WHO, 1995), allowing the comparison of studies and the integration of data collected in different contexts.

2.2. Consumption pattern

To assess the real-based food demand, a database with serving sizes and daily frequencies provided by a selection of diet schemes has been implemented in the consumption pattern module. The first schemes of diet regimes implemented are the Mediterranean diet and the Italian nutritional guidelines (Bach-Faig et al., 2011; CREA, 2019).

To assess the real consumption pattern, two databases were implemented: FAO food balance sheets, providing essential information on national food systems considering domestic food supply of the commodities (Jalava et al., 2016; Vanham et al., 2013), and EFSA's Comprehensive European Food Consumption Database, describing the consumption habits of citizens of the European Union (EFSA, 2011a).

For the analysis of the case study (presented in section 3), we referred to EFSA's Comprehensive European Food Consumption Database, henceforward called EFSA consumption database. The EFSA consumption database was started in 2010 and updated through the dietary surveys provided by Member States (Huybrechts et al., 2011; Merten et al., 2011). Data are available for chronic (regular) or acute (maximum) consumption, and are provided as a mean for the whole population, or broken down by age group (infants, toddlers, other children, adolescents, adults, elderly, very elderly).

2.3. Food composition and processing

This module contains databases allowing the conversion of processed food and composite dishes into raw food. Recipes databases allow to break down composite food into their ingredients. Ingredients could be raw food (e.g. a tomato and corn salad is transformed into quantities of lettuce, tomatoes, corn, salt and olive oil) or processed food (e.g. cheeseburger is broken down into quantities of flour, cheese, salt and minced meat). In line with Mertens et al. (2019), standardized recipes allowing comparison among countries have been defined by expert dieticians.

Processing factor databases allow to compute the required quantity of raw food necessary to obtain a processed food. For instance, in order to produce 1 kg of apple juice 1.54 kg of apples are required, therefore the processing factor is equal to 1.54. Two databases of containing processing factors have been implemented in the framework: the technical conversion factors developed by the FAO (2000) and the weight, measure and conversion factors for agricultural commodities and their products developed by the USDA (1992).

2.4. Environmental indicators

Currently, our framework includes the ecological footprint (EF), carbon footprint (CF) and water consumption footprint (WF). This is in line with several recent papers (Fang et al., 2014; Galli et al., 2012, 2013). The ecological footprint measures the total environmental pressure of the human population in terms of the biologically productive area of sea and land (including cropland, grazing land, forest land, fishing grounds, and built-up land) necessary to regenerate the resources consumed and to absorb the waste produced (Wackernagel et al., 1999). We implemented the National Footprint Accounts (NFA) database (Lin et al., 2018) which contains level impact assessments at country level.

The carbon footprint is defined as the total amount of greenhouse gas (GHG) caused by food production and processing (Wiedmann and Minx, 2008), measured in terms of emitted CO_2-equivalents (Moss et al., 2008). As suggested by several authors (Hjorth et al., 2020; Kause et al., 2019; Moberg et al., 2019), we implemented the data about greenhouse gas emissions collected by Clune et al. (2017) in our framework. This study referred to a Global warming potential (GWP) of more than 1700 assessed in kg CO2/kg of product estimated at country level.

Although the carbon and ecological footprint are similar, they present some differences (Mancini et al., 2016). The ecological footprint is built upon the idea of seeking alternatives to the appropriated carrying capacity defined as the maximum population size that can be supported, given set of resources (Dietz and Neumayer, 2007; Ehrlich, 1982). It intends to deal with the question of how much area of biologically productive space is required to produce consumed resources and to absorb generated waste. Within the Ecological Footprint methodology, the carbon Footprint component is only defined as the regenerative forest capacity required to sequester the anthropogenic carbon dioxide emissions that is not absorbed by oceans (Mancini et al., 2016).

However, the carbon footprint is linked with the indicators of GWP which represents the quantities of GHGs that contribute to global warming when considering a specific time horizon such as 100 years (Høgevold, 2011; Wiedmann, 2009). It is concerned with the question of how much CO_2-equivalent weight of the total GHG emissions is over the life cycle of products or activities.

Furthermore, there are other differences between the two indicators such as the components and unit used.

The ecological footprint account for six different components, detailed before, and it is expressed in the common unit of global hectares (gha) that is equal to the hectares of land normalized to world average productivity of all biologically productive space within a given year (Galli et al., 2011).

The components of the carbon footprint include a variety of GHGs such as CO_2, CH_4, and N_2O. The use of GHG characterization factors as determined weightings dependent on the 100-year GWP has a broad base of acceptance (Ridoutt and Pfister, 2013). The carbon footprint is measured on how much CO_2-equivalent weight of the total GHG emissions is over the life cycle of products or activities. The scientific community highlights the importance of using both indicators (Bello et al., 2018; Fang et al., 2016; Galli et al., 2012; M. Li et al., 2020; Z. Li and Hu, 2021; Solarin, 2019; Steen-Olsen et al., 2012; Yilanci et al., 2021).

For this specific work, we focused on indicators related to water consumption. The data used follows the Water Footprint Network (WFN) methodology (Hoekstra et al., 2011). The Water Footprint (WF) measures the total volume of fresh water used directly or indirectly to produce a food product (Hoekstra et al., 2011). We implemented data on WF extracted from Report 48 'Water Footprint Animal Products' Vol2 and Report 47 'Water Footprint Crops' Vol2 (M. Mekonnen and Hoekstra, 2010) considering all three types of impact defined by the authors (on green, blue and grey water), henceforward called water footprint database.

More recently the concept of water scarcity was proposed to assess the water impact (Pfister and Hellweg, 2009). This approach is regulated by ISO 14046 (ISO, 2014) (ISO 14046) and follows the LCA principles. In these years the approach of water scarcity and water footprint have created scientific discussions (Boulay et al., 2013; Hoekstra, 2016; Pfister et al., 2017; Pfister and Hellweg, 2009; Quinteiro et al., 2019; Ridoutt and Huang, 2012; Wang et al., 2021; Wang et al., 2021; Hoekstra, 2016; Pfister et al., 2017; Boulay et al., 2013; Ridoutt and Huang, 2012; Pfister and Hellweg, 2009). The water scarcity indicator has been introduced to give importance to blue water mainly. Combining blue water scarcity with green water scarcity can be an excellent instrument (Quinteiro et al., 2019) and provides a good basis for a future integrated water scarcity assessment.

Although the limitation of the WF approach, the assessment of the water footprint consumption is still quite relevant in the scientific community (Hogeboom, 2020; M. M. Mekonnen and Hoekstra, 2020; Yin et al., 2021), it could be valuable as a supporting tool in policy and for diverse stakeholders in achieving the Sustainable Development Goals (Berger et al., 2021). The WF approach can also support producers to design their products to reduce the indirect use of water along the all supply chains and promote sustainable agricultural practices for better use of water resources (specifically green water resources) (Nouri et al., 2020).

Furthermore, the framework allows to easily include new indicators and new widely approved methodologies.

All footprint information is collected at country level. If the country-specific data is missing, it is imputed as the average of all data available at continental level. Footprint data refers to the impact caused by the food production 'at the farm gate'. This definition is in line with several papers, and is based on the assumption that there is a scarcity of studies accurately estimating the footprints in the subsequent phases of the food system. Moreover, the processes downstream of food production (such as food processing, packaging, conservation, logistics and cooking) are characterized by a high heterogeneity which currently requires a resolution scale and is not adequate for a large-scale assessment which is the goal of this framework. This model assumption certainly has an influence on the estimation of the overall environmental impacts of food systems, but it is in line with the choice of other authors who estimated that almost 75%–90% of the impacts registered along the food system occur at the farm gate (Jefferies et al., 2012; Wheeler et al., 2013). Furthermore, the framework allows to integrate the knowledge about all the stages of the food system as soon as it will be made available in the literature at the appropriate level of resolution.

3. A case study. The water footprint of European food consumption

In this section, we apply our framework to assess the WF of food consumption in the European Union. We based the assessment on chronic food consumption data collected from the EFSA consumption database (EFSA, 2011c) which includes 58 surveys performed from 2001 to 2015 in 22 EU countries (Austria, Belgium, Bulgaria, Croatia, Czech Republic, Cyprus, Denmark, Estonia, Finland, France, Greece, Germany, Hungary, Ireland, Italy, Latvia, Netherlands, Portugal, Romania, Spain, Sweden, United Kingdom).[1] Details on the used data are reported in Table 1.

To compute country-specific WF, we assume that the food is produced in the same country of consumption, without considering import/export trade (Hoekstra et al., 2011). As for the processing factors an identity function was considered (i.e. 100 g of processed food correspond to 100 g of raw food commodities). The WF of fish and fish products is considered null due to the unavailability of reliable data for this food category, which is in accordance to other papers published on the topic (Gephart et al., 2014). Also, other food categories, such as Vitamin C, flavour agents and infant formulae, have null water footprint due to the lack of studies on these foods. The consumption of these food categories is marginal compared to the total amount of food consumed, so the impacts of these assumptions is minimal with respect to the overall estimates of WF, for example based on consumption data the total fish consumed in Europe term of mass (g) is around 1% of the total food consumed.

WF is assessed considering three scenarios based on a specific age category (adults' food consumption, Section 3.1.1), a food category (consumption of meat and meat products, Section 3.1.2), and a spatial resolution (Italian food consumption, Section 3.1.3). The analyses are performed with SAS 9.4, databases are managed and stored in Access® 2016, using Access Structured Query Language (SQL) language.

3.1. Results

3.1.1. European water footprint of adult food consumption

The category 'adults', with includes everyone with an age of 18 up to and including 64 years (EFSA, 2011c), is the age category whose data are available in the largest number of countries considered (as reported in Table 1). In order to guarantee data consistency, we considered only the data referring to 'adults', excluding the sub-categories of pregnant and lactating women, which have very specific nutritional needs. For this reason, in the following analyses we refer to survey data from 2003 to 2015 in 19 countries, excluding Cyprus, Bulgaria and Greece.

The mean daily WF of food consumed by an Europeans adult is 3291 (±557) litre (per day per person). This result is lower than the estimates obtained in studies based on FAOSTAT food balance sheets. For instance, Vanham et al. estimated an individual WF of EU28 food consumption equal to 4265 l/day (Vanham et al., 2013). This difference can be explained based on results of several studies demonstrating that in FAOSTAT food balance sheets the consumption of some food categories is overestimated, especially for the most impactful categories (e.g. meat, dairy products) (Del Gobbo et al., 2015; Grünberger, 2014; Russo et al., 2017).

In Fig. 2, the mean daily WF calculated for adult food consumption in each nation is shown. The estimated national WFs are characterized by a high variability, ranging from a minimum of 2442 litres per capita per day in the United Kingdom (first position in our ranking of the least impactful countries, see Table 2) to a maximum of 4514 litres per capita per day in Latvia (last position in our ranking). The Italian daily WF per capita is 3196 l, slightly below the European mean, placing Italy at the 8th place of the ranking. The high variability in national WF estimates is

[1] Data extracted from the European consumption database on May 3, 2019.

Table 1
Availability of food consumption data by country and age category.

Country	Age category						
	Infants	Toddlers	Other children	Adolescents	Adults	Elderly	Very elderly
Austria	NA	NA	2010	2010	2010	2010	2010
Belgium	NA	2002	2002	2004	2004	2004	2004
Bulgaria	2007	2007	2007	NA	NA	NA	NA
Croatia	NA	NA	NA	NA	2011	NA	NA
Czech Republic	NA	NA	2003	2003	2003	NA	NA
Cyprus	NA	NA	NA	2003	NA	NA	NA
Denmark	2005	2005	2006	2006	2006	2006	2006
Estonia	2013	2013	2013	2013	2013[a]	2013	2013
Finland	2007	2007	NA	2007	2012	2012	NA
France	2014	2014	2014	2014	2014	2014	2014
Greece	NA	NA	2004	NA	2005[b]	NA	NA
Germany	2001	2001	2006	2007	2007	2007	2007
Hungary	NA	NA	NA	NA	2003	2003	2003
Ireland	NA	NA	NA	NA	2008	2008	2008
Italy	2005	2005	2005	2005	2005	2005	2005
Latvia	2014	2014	2014	2014	2014	2014	2014
Netherlands	NA	2006	2006	2006	2007	2010	2010
Portugal	2015	2015	2015	2015	2015[c]	2015	2015
Romania	NA	NA	NA	NA	2012	2012	2012
Spain	2012	2012	NA	2012	2012	2012	NA
Sweden	NA	NA	2010	2010	2010	2010	2010
United Kingdom	2008	2008	2008	2008	2008	2008	2008

Note: The year refers to the most updated survey available. NA: No data available.
[a] Estonia carried out specific surveys on pregnant women. These data are not included in the specific analysis on the adult population.
[b] Greece reported data only related to lactating women. These data are not included in the specific analysis on the adult population.
[c] Portugal carried out specific surveys on lactating women and pregnant women. These data are not included in the specific analysis on the adult population.

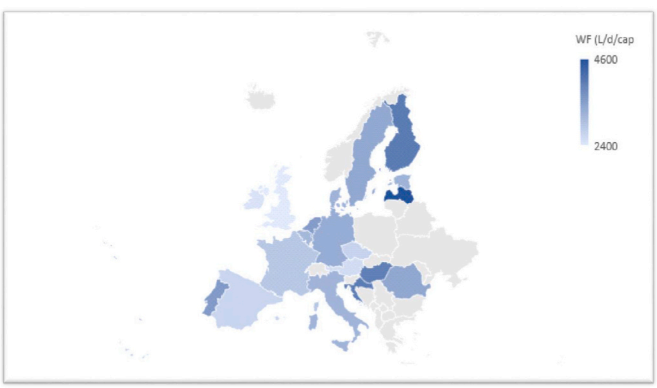

Fig. 2. Mean national daily water footprint (l/day (d)/per capita (cap)) of food consumed by adult population. European countries without available data are reported in grey.

mainly due to the great difference in dietary patterns across European countries, related to heterogeneous cultural habits, as well as climatic and environmental conditions. In Table 2 the daily national WF estimates for the 19 most consumed food categories are reported.

3.1.2. European water footprint of adult consumption of meat and meat products

The category 'meat and meat products' contributes most to the mean daily WF (Table 2). The high variability among countries in terms of daily water impact per capita due to the 'meat and meat products' category is directly related to the difference in national eating habits. Latvia, Croatia, Romania and Hungary registered the highest consumption of meat and meat products, which resulted in a WF of (2085.6, 1982.2, 1482.6, and 1654.5 l per day per capita, respectively). these results are in line with findings presented in another study (da Silva et al., 2018).

To assess the contribution of each country to the overall European WF of 'meat and meat products', the mean daily WF per capita should be weighted by the percentage of the adult population in the respective country compared to the total European adult population. By considering this correction, the currently presented WF ranking of countries will be different. For example, the total WF consumption of 'meat and meat products' by German adults accounts for 37.37 billions of litres, while consumption in Latvia accounts for a WF of 1.64 billion of litres. This, despite the fact that the individual WFs are 750 l/day for Germany and 2000 l/day for Latvia. The current framework allows to calculate the WF per capita or for the global population, based on the objective of the assessment study the most suitable approach can be chosen.

3.1.3. Consumption data of Italy

Focusing on the Italian national food consumption survey INRAN 2005–2006 (Leclercq et al., 2009), the mean daily WF (per capita) has been estimated including the chronic food consumption of:

- Infants: up to and including 11 months of age;
- Toddlers: from 12 up to and including 35 months of age;
- Other children: from 36 months up to and including 9 years of age;
- Adolescents: from 10 up to and including 17 years of age;
- Adults: from 18 up to and including 64 years of age;
- Elderly: from 65 up to and including 74 years of age;
- Very elderly: from 75 years of age or older.

Results are shown in Fig. 3. The highest means for the daily WF are recorded for the age categories; elderly, adults and adolescents (3282, 3188, 3179 l per day per capita, respectively). Despite important differences in age-related nutritional requirements between these three categories (McMurray et al., 2014; Roberts and Dallal, 2005), their WFs differ by a maximum of 3%. To check whether similar WFs could be related to substantially different food patterns, we estimated a WF for 19 food categories (Table 3). The distribution of the WF between these 19 food categories is highly different between age groups. For instance, the mean daily WF impact for 'meat and animal' is 35% higher for adolescents' than the WF of 'other children' for the same food category.

Focusing on the 'adults' category, we observed that around 60% of the mean daily WF is related to the consumption of animal products

Table 2
Mean national daily water footprint (l/day/per capita) of food consumed by adult population according to 19 food groups of first level of FoodEx2.

Food categories	Austria	Belgium	Croatia	Czech Republic	Denmark	Estonia	Finland	France	Germany	Hungary	Ireland	Italy	Latvia	Spain	Nether lands	Portugal	Romania	Sweden	United Kingdom	EU - 19 countries
Alcoholic beverages	24.6	40.2	32.1	83.5	59.2	37.2	18.8	39.0	47.8	19.6	50.2	35.3	22.2	27.4	41.0	68.9	24.25	36.8	69.6	39.9
Animal and vegetable fats and oils and primary derivatives thereof	54.5	210.2	169.5	165.4	357.4	120.1	520.0	250.0	236.7	339.2	250.5	753.2	110.0	370.6	406.1	323.9	272.98	112.1	41.8	259.0
Coffee, cocoa, tea and infusions	341.0	711.8	369.1	42.9	694.0	312.5	857.3	633.6	673.5	185.9	195.4	377.9	364.6	305.1	549.0	355.2	77.4	474.0	268.6	405.2
Composite dishes	610.5	154.9	6.2	68.4	14.7	0.3	12.9	0.2	232.9	15.2	12.5	18.6	82.3	0.2	333.8	10.4	355.6	613.3	360.4	170.8
Eggs and egg products	8.0	19.4	109.6	62.9	31.0	87.5	28.4	26.6	19.8	89.7	26.4	31.8	160.8	68.8	10.2	77.4	129.8	29.6	22.6	54.4
Food products for young population	0.0	0.5	0.4	0.3	0.0	0.2	0.1	0.5	0.0	0.4	0.0	0.2	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.1
Fruit and fruit products	112.7	98.9	159.8	90.5	168.8	473.4	214.7	98.0	116.0	142.7	63.9	104.7	192.7	98.7	87.7	159.8	117.7	125.2	80.3	140.1
Fruit and vegetable juices and nectars (including concentrates)	245.1	236.1	84.2	28.5	260.4	100.1	278.9	56.8	373.3	68.7	187.4	33.1	106.6	58.5	304.3	41.8	6.9	247.5	225.4	151.5
Grains and grain-based products	338.0	230.0	295.5	303.9	155.7	250.9	317.0	273.1	276.8	304.4	266.6	374.5	278.6	285.3	252.7	606.9	306.24	232.9	217.8	291.7
Legumes, nuts, oilseeds and spices	42.6	17.8	35.2	54.5	51.9	46.4	62.3	26.4	38.3	48.3	36.0	17.8	52.7	51.8	47.7	50.8	41.01	35.5	38.8	40.2
Major isolated ingredients, additives, flavours, baking and processing aids	0.0	0.0	1.9	0.3	0.1	0.7	1.1	0.0	0.0	0.2	0.0	0.0	0.2	0.0	0.0	0.5	0.0	0.0	0.0	0.3
Meat and meat products	393.6	838.1	1982.2	1346.3	735.7	969.6	866.3	931.9	750.4	1654.5	777.9	954.7	2085.6	899.2	712.5	1303.9	1482.6	882.5	494.8	1072.4
Milk and dairy products	190.7	315.9	430.8	336.6	543.6	604.5	625.4	369.3	278.9	924.6	370.0	363.5	588.9	610.8	489.5	443.5	376.14	438.8	286.6	445.0
Products for non-standard diets, food imitates and food supplements	3.9	4.8	0.4	0.4	0.1	0.3	14.9	5.9	0.7	0.0	2.7	0.0	2.5	8.9	2.2	4.6	0.1	4.0	2.9	3.0
Seasoning, sauces and condiments	27.6	40.2	8.0	19.1	11.8	20.3	72.7	18.3	72.2	8.7	68.2	1.4	160.1	7.0	91.9	5.4	1.8714	113.1	153.4	45.2
Starchy roots or tubers and products thereof, sugar plants	2.4	9.3	42.4	16.1	9.7	21.3	7.8	12.4	4.4	34.3	10.2	10.7	35.6	8.8	6.6	37.5	33.1	11.1	6.4	16.8
Sugar and similar, confectionery and water-based sweet desserts	173.7	179.5	100.9	62.1	174.9	111.2	120.2	98.9	168.9	77.9	152.0	36.6	174.6	39.5	199.5	54.9	61.0	126.1	148.4	118.2
Vegetables and vegetable products	13.4	14.8	90.8	38.3	35.0	47.9	18.5	58.4	19.2	44.6	19.4	81.1	95.2	28.0	18.7	24.3	106.2	11.9	24.3	43.1
Water and water-based beverages	0.4	0.7	0.1	0.6	0.2	0.2	0.1	0.5	1.0	0.2	0.2	0.6	0.2	0.3	0.1	0.4	0.2	0.1	0.0	0.3
Total daily WF	2582.7	3122.0	3919.2	2720.6	3304.3	3204.6	4037.5	2899.9	3310.7	3959.1	2489.4	3195.8	4513.5	2868.9	3553.7	3570.3	3393.4	3494.4	2442.2	3291.8

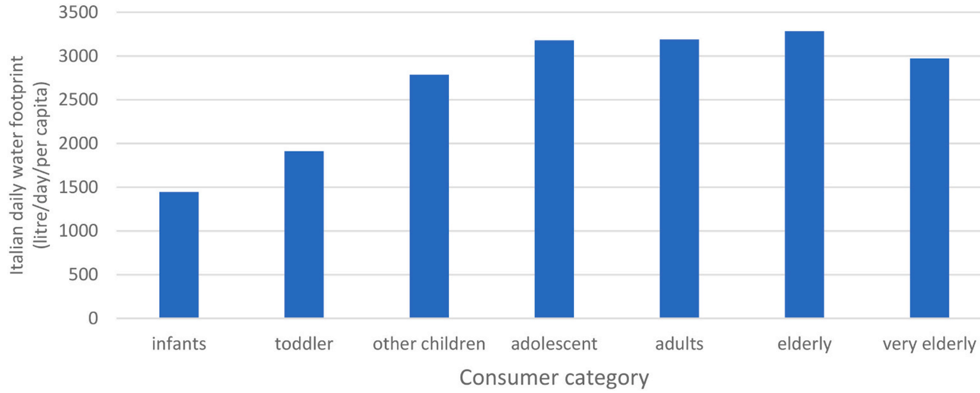

Fig. 3. Mean daily water footprint (per capita) due to chronic food consumption in Italy, by age category of consumers.

Table 3
Water footprint (WF) of the mean daily chronic food consumption in Italy per capita, according to age and food category (WF is expressed in litre per day per capita).

Food categories	Infants	Toddler	Other children	Adolescent	Adults	Elderly	Very elderly
Alcoholic beverages	0.00	0.00	0.20	0.78	35.29	45.77	33.93
Animal and vegetable fats and oils and primary derivatives thereof	113.49	301.56	595.40	713.97	753.24	776.92	653.53
Coffee, cocoa, tea and infusions	0.00	34.34	69.01	97.25	379.28	518.57	456.58
Composite dishes	5.50	7.97	14.60	25.62	18.63	15.19	13.31
Eggs and egg products	0.44	12.58	29.79	31.04	31.80	30.93	30.07
Food products for young population	572.03	235.91	15.02	1.73	0.22	0.00	2.59
Fruit and fruit products	14.30	51.44	72.86	78.91	104.72	144.76	139.45
Fruit and vegetable juices and nectars (including concentrates)	28.95	116.90	114.61	108.33	33.08	23.10	22.56
Grains and grain-based products	23.33	196.72	360.61	434.06	365.76	346.47	349.42
Legumes, nuts, oilseeds and spices	5.73	14.95	18.02	12.78	17.81	20.56	16.47
Major isolated ingredients, additives, flavours, baking and processing aids	0.00	0.02	0.00	0.01	0.03	0.02	0.00
Meat and meat products	43.80	345.41	773.99	1049.65	954.70	899.95	751.19
Milk and dairy products	620.12	527.88	448.67	434.07	363.48	344.20	404.43
Products for non-standard diets, food imitates and food supplements	0.00	0.00	0.00	0.00	0.04	0.00	0.10
Seasoning, sauces and condiments	0.00	0.27	0.79	1.80	1.37	0.67	0.48
Starchy roots or tubers and products thereof, sugar plants	1.15	4.74	9.87	12.67	10.74	12.10	11.60
Sugar and similar, confectionery and water-based sweet desserts	13.41	38.52	126.39	115.39	36.63	18.23	13.60
Vegetables and vegetable products	2.45	21.15	43.37	61.65	81.06	85.11	73.29
Water and water-based beverages	0.36	0.00	0.00	0.00	0.59	0.00	0.00
Overall WF	1444.7	1910.34	2785.92	3179.7	3187.81	3282.53	2833.05

(meat, milk and dairy products, eggs, and animal fats); while the consumption of grains, fruits and vegetables only accounts for 20% of the total impact.

4. Conclusion

In this paper we presented a new framework for the assessment of environmental impacts of food consumption patterns aimed to support large-scale assessment, which is mainly performed by policy makers, providing an application to evaluate the water footprint of food consumption in Europe.

The major innovation of the framework is that it includes a multi-dimensional system-based approach to the assessment of the environmental impact of food systems. The strengths of the framework are i) the possibility to assess environmental impacts based on the quantification of real-based or scheme-based food demand, ii) the great flexibility of analysis, that can be performed at individual or population level (considering different classifications, e.g. gender, age, health status, income), iii) the multi-impact approach (carbon footprint, water footprint and ecological footprint are considered), and iv) the possibility to differentiate the impacts based on the production area.

However, the current framework still suffers from some limitations, which are caused mainly due to the lack of available data, both in terms of dimension currently included in the footprint databases (such as biodiversity, phosphorus or nitrogen release, toxicity related impacts of food system) or phases of the food system (e.g. packaging, food logistic, cooking). The current framework is mainly focused on addressing the issue of having a good estimation of the food consumed in Europe, and to assess the demand of natural resources to produce the food consumed. In the case study, an estimation of the water consumed, according to the WFN methodology, was provided by the current framework. The assessment methodology proposed in the current study can be improved by adding new modules, for example by integrating the demand of resource with their availability (e.g. water scarcity). Therefore, by recognising the importance of including more information in the environmental impact assessment, the framework has been designed to incorporate and implement new data sources. And for this purpose, the chosen standard for food classification (FoodEx2) already foresees the possibility of collecting information, such as process, packaging, cooking. Additionally, one of the first developments in the framework will be to include the impact of food waste in the assessment of the environmental impacts of food consumption.

Another limitation of the study is the assumption that the food is produced where is it consumed. In further developments of the framework, we could overcome this limitation by including an import/export module which takes the differences between areas of production and consumption into account.

The application of the framework to the assessment of WF of European food consumption tested the modularity of the framework. In accordance with other studies (Mertens et al., 2019), the case study stressed the importance of having tools that allow managing the heterogeneity of the environmental impacts deriving from food production according to spatial aggregation (by continent or by nation), food categories and age of consumers.

The framework might represent a comprehensive tool, which might be useful for scenario analysis, allowing to deal with aspects of human health (diets) and environmental health (production and processing models linked to demand). Indeed, it can be effective in assessing the impact deriving from proposed changes to current diets, in order to support a transition towards more sustainable food systems. The conclude, the current framework could support policy making in designing specific incentives for the reduction of environmental impacts related to the agri-food sector and could play a role in the evaluation of agronomic strategies in the light of pursuing the environmental sustainability of food commodities production.

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Credit authorship contribution statement

D. Gibin: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Writing – review & editing. **A. Simonetto:** Methodology, Software, Formal analysis, Statistical analysis, Data curation, Writing – original draft, Writing – review & editing. **B. Zanini:** Validation, Writing – review & editing. **G. Gilioli:** Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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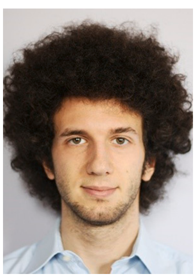

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