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Reducing Greenhouse Gas Emissions in the European Union through Sustainable and Healthy Diets

(s.s.d. AGR/15)

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Contents

ABSTRACT

Research activities performed over the course of the PhD relate to the implementation of the Su-Eatable Life (SEL) Project (LIFE16 GIC/IT/000038), a three-year project, financed by the EU LIFE program, aimed at reducing greenhouse gases emissions (GHG-e) and water consumption associated with food choices by engaging EU residents in the adoption of a healthier and more sustainable diet. First, in order to retrieve Carbon Footprint (CF) and Water Footprint (WF) values for food commodities, a systematic review (PRISMA protocol) of life cycle assessment (LCA) studies was conducted. Next, as part of a joint effort, a comprehensive database of CF (kg CO_2-eq/kg) and WF (L eq/kg) values for 323 food items, harmonized to a unique systems boundary (i.e., regional distribution centre, RDC), was compiled. Here, the reliability of CF and WF estimates was assessed by means of an innovative methodology combining the analysis of sample size, outliers (Tukey-test) and adherence to a normal distribution (Shapiro-Wilk normality-test). The database and accompanying research methodology framework were published in May 2021. In order to identify hot spots and mitigation potentials of food choices, an overview of the GWP variability across food groups resulting from the aforementioned database was then provided. Such analysis highlights the central role of protein source in determining diet sustainability; in this regard, the use of alternative functional units (FU) for CF, such as protein-based (kg CO_2eq-kg protein^{-1}) or serving size (kg CO_2eq-serving^{-1}), was explored. A review of the latest definitions of sustainable and healthy diets as well as of the best practices aimed at engaging citizens in sustainable behaviours was then performed, leading to the development of the Su-Eatable Life (SEL) healthy and sustainable dietary guidelines. Thereafter, the SEL engagement protocol was implemented during 8 and 6 month-long pilot experiments at 2 Italian company canteens (respectively), with the mentioned database providing the basis for calculating the experimental dietary GHG emissions and water footprint reductions. By combining CF and WF assessments of 1400 dishes served in the experimental locations with the associated canteen sales data (namely, sales per dish and influx of customers), the experimentally-induced variation in the impact of customer food choices was estimated as the difference between baseline values and functions of follow-up experimental values. The application of the SEL protocol resulted in an average reduction of 17-36% in GHG-e and 10-33% in WF of food consumption.

Keywords: carbon footprint, water footprint, mitigation potential, plant-based diets, food-service.

INTRODUCTION

I. Background

While global food systems have the potential to contribute to human and planet health, at present they're threatening both (Willet *et al*., 2019). Food production is a major driver of climate change, depletion of natural resources and environmental degradation (IPCC, 2019; MEA, 2005). Globally, the Food System is responsible for up to one third of anthropogenic greenhouse gas emissions (GHG-e), as well as 70% of water withdrawals; it also occupies 40% of the Earth's ice and desert free-land on top of playing a key role in land use change, mineral depletion, desertification, deforestation, eutrophication, acidification, biodiversity loss and genetic erosion (Poore and Nemecek, 2018; Crippa *et al.,* 2021; IPCC, 2019; MEA, 2005; Rosenzweig *et al*., 2020; FAO, 2017). According to the latest Special Report on Climate Change and Land by the Intergovernmental Panel on Climate Change (IPCC, 2019), the food system accounts for an estimated 10.8-19.1 billion tonnes of CO_2-equivalent emissions per year, contributing between 21% and 37% of total global emissions. Similarly, Crippa *et al.* (2021) estimate a value for food-system emissions of 18 Gt CO_2-equivalent per year globally, amounting to 34% of total GHG emissions. When considering the breakdown of emissions by stages, agricultural production is the major contributor (39%), followed by land use and land use change (LULUC) (32%), supply chain– i.e., industrial processing, transport, packaging, retail - (18%), and post-retail – i.e., cooking and waste disposal – (11%). Agriculture, Forestry, and other Land Use (AFOLU) sectors together account for more than 2/3 of total food system emissions. Currently, the livestock sector alone is estimated to contribute to 18% of total world GHG emissions from all sectors (Steinfeld *et al*., 2006), with 90% of that coming from ruminants (Gerber *et al*., 2013; Henderson *et al*., 2017). Moreover, the livestock sector accounts for 80% of anthropogenic land use (Stehfest *et al*., 2009) while displacing about 35% of agricultural crops (Foley *et al*., 2011), thus competing with crop production for human consumption. Agriculture is one of the sectors expected to be most impacted by climate change (Porter *et al*., 2014), hence to ensure food security for a growing population, while relying on finite resources and on a warming planet, will require a Great Food Transformation globally (Willet *et al*., 2019).

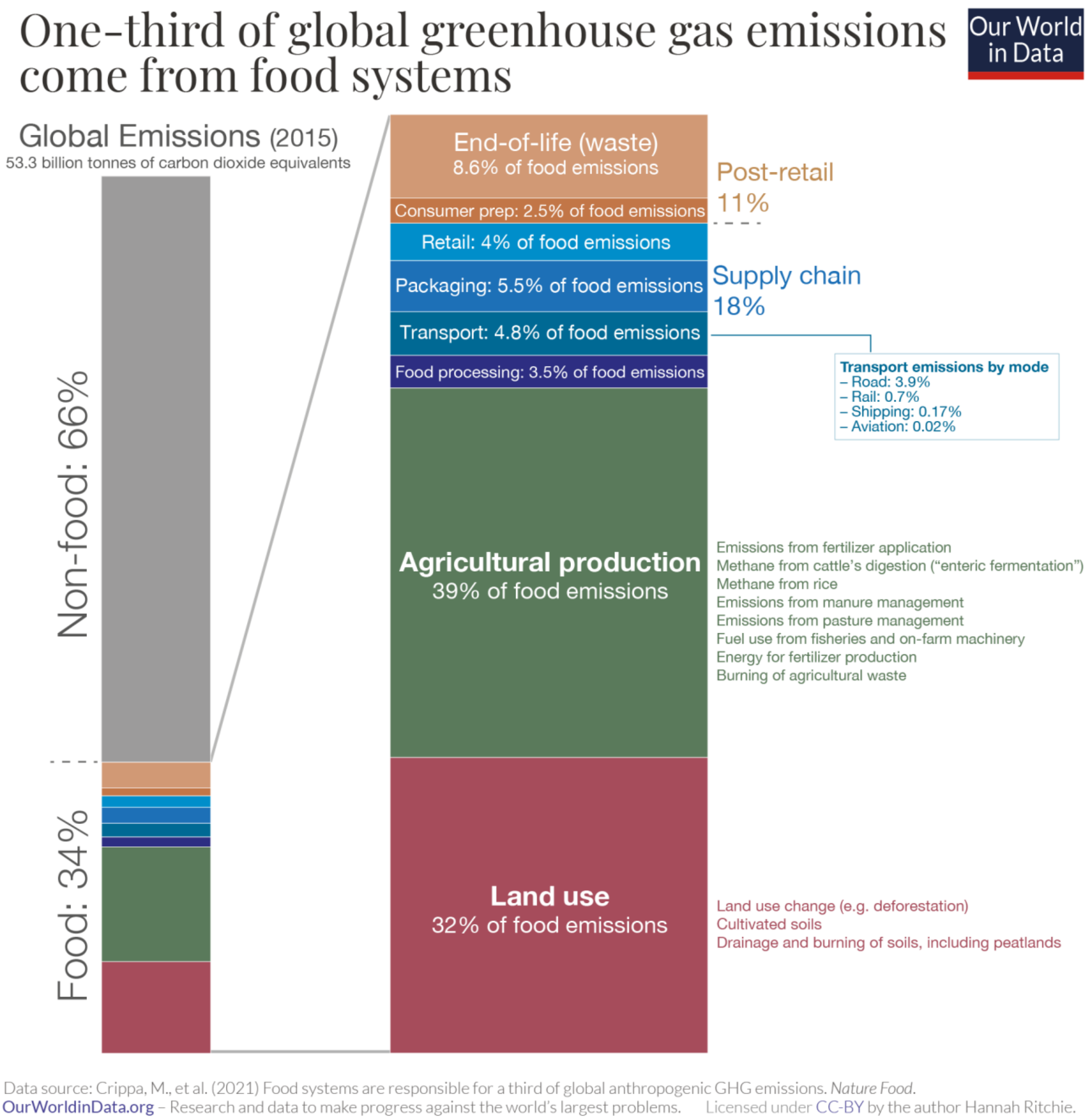

Figure 1. Food system contribution to global GHG emissions and breakdown by stages according to Crippa *et al* 2021.

Currently, the food system raises not only environmental but also health and social concerns. Despite producing enough food for all humanity (Diaz *et al*., 2019), the food system has failed the goal of actually feeding the world's population (Hawkes and Voegele, 2018; FAO, 2021). Paradoxically, while an estimated 720-811 million people in the world faced hunger in 2020, 1.4 billion people worldwide were overweight or obese (FAO, 2021). This coexistence of undernutrition with overweight/obesity accompanied by diet-related non communicable diseases

(NCDs) is referred to as the "double burden of malnutrition" (WHO, 2017). From a health perspective, due to saturated fat and cholesterol content, consumption of meat and animal-derived products above dietary recommendations appears to be related to a higher risk of NCDs compared to plant-based diets; to the contrary, plant-based foods are worldwide recognized as protective agents (Pan *et al*., 2012). Moreover, in 2015, on the basis of over 800 epidemiological studies, the International Agency for Research on Cancer classified consumption of processed meat as "carcinogenic to humans" and consumption of red meat as "probably carcinogenic to humans" (IARC, 2015). Despite the controversy raised among health-care scientists on the topic, the relationship between high intake of red meat/processed red meat and cancer (as well as cardiovascular diseases and other NCDs) has been further investigated and confirmed by several authors (Domingo and Nadal, 2017; Turesky, 2018; Ekmekcioglu *et al*., 2018).

In light of the above critical aspects of food systems, which determine simultaneous social, health and environmental challenges, the concept of sustainable diets has recently gained traction as a possible strategy to simultaneously address public health, environmental and food security issues. Several analyses have highlighted, for instance, that adherence to plant-based diets with low meat consumption, such as the Mediterranean Diet (or similar dietary patterns), could represent in developed countries a win-win bottom-up strategy to mitigate climate change and promote public health at the same time (Willet *et al*., 2019; Burlingame and Dernini, 2012; Poore and Nemecek, 2018).

Whether and to what extent specific dietary changes/interventions may address the wide-ranging negative externalities of food consumption is an active area of research, one to which the present study aims to contribute. Clearly, despite theoretical evidence of health and environmental benefits, a planetary shift towards sustainable diets is an ambitious challenge that requires a multi-dimensional intervention framework in order to overcome socio-cultural barriers and spur motivation. Additionally, though there are analytical instruments - such as LCA (ISO 14044), CF (ISO 14067) and WF (ISO 14046) studies - that employ standardized methodologies to estimate the environmental impact of foods, such instruments come with a series of limitations: for one thing, comprehensive databases providing CF, WF or GHG-e estimates for food products, while available as professional tools, are subject to license and subscription payments; and for another, publications at the pinnacle of scientific hierarchy - i.e., systematic reviews and meta-analyses – currently either do not report summary statistics for both WF and CF of food commodities or fail to include all food groups.

II. Scope of the study

This PhD research was carried out within the broader framework of the Su-Eatable Life (SEL) project, a three-year initiative, financed by the EU-LIFE alliance of research institutes in the life sciences, aimed at ascertaining the potential of reducing CO_2 eq. emissions and water use related to food consumption in Europe through the adoption of healthier and more sustainable diets. The scope of the author's research was to support SEL throughout all stages involving environmental analysis. Specifically, the aim of this study was to: i) develop a comprehensive and reliable database of CF and WF estimated of food commodities; ii) identify the environmental impact across different foods and mitigation options; iii) define sustainable diets as a demand-side mitigation strategy to reduce human global environmental impact; iv) evaluate the GHG-e and WF reductions related to food choices during the SEL social experiments.

Correspondingly, Chapter 2 of this thesis describes the methodological framework used to develop the CF and WF database; Chapter 3 analyses and compares the global warming potential of food commodities, highlighting the hot-spots and mitigation strategies; Chapter 4 explores the use of protein-bases and serving-size functional units to compare GWP of common protein sources in diets; Chapter 5 presents the SEL field experiments conducted in Italian company canteens.

Although the SEL project adopts a systemic bio-economic approach - encompassing environmental, social and economic aspects of sustainability - the analysis of socio-economic determinants falls beyond the scope of the present study. Moreover, the environmental complexity addressed by this study is limited to climate change and water withdrawals.

CHAPTER 1: STATE OF THE ART

1.1 The Anthropocene

During the past 11,700-years Planet Earth has dwelled in a geological epoch characterized by relatively stable conditions that have allowed the thriving of life in all forms: the Holocene (Steffen *et al*., 2004). Over the last 70 years, the grade of anthropogenic environmental pressure has altered Earth's functioning and processes to such an extent/rate that the stable living conditions characterizing the Holocene Epoch might be irreversibly altered (Rockström *et al*., 2009). The complex set of human-driven global social, technological, and environmental changes intensifying dramatically since 1950 has been identified as the "Great Acceleration" (Steffen *et al*., 2004). As shown in Figure 2, global warming, ocean acidification, ozone depletion, habitat destruction, species extinction, widescale natural resource depletion, eutrophication of rivers and lakes and desertification have all exponentially increased in parallel with analogous trends in socio-economic development indicators such as population, income, transportation and energy use (Steffen *et al*., 2004).

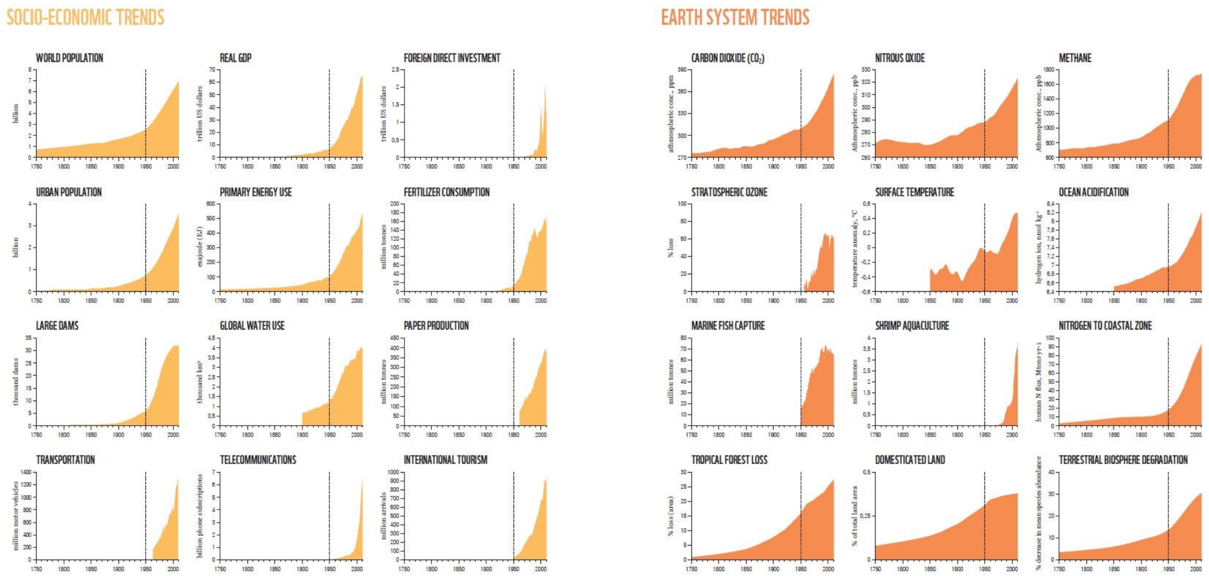

Figure 2. "The Great Acceleration graphs" showing the correlation between negative earth system trends and socio-economic trends (Source: WWF Living Planet Report 2018, citing Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O. & Ludwig, C. The trajectory of the Anthropocene: The Great Acceleration. The Anthropocene Review 2: 81-98, doi:10.1177/2053019614564785 (2015).

Some authors suggest that our planet has entered a new geological epoch, the 'Anthropocene', where Homo sapiens - one of the 8.7 billion species of the Biosphere – has become the overbearing driver of catastrophic alterations to Earth's complex System (Rockström *et al*., 2009; Crutzen, 2002; Steffen *et al*., 2007). In this regard, the latest concepts of planetary boundaries and safe operating space for humanity introduced by Rockström *et al*. (2009) have recently gained attention. The Planetary Boundaries framework offers, for the first time, an attempt to identify all the critical, interacting processes on Earth that contribute to the stability and resilience of the Earth system as a whole. Planetary boundaries identify a safe operating space for different bio-geochemical Earth functions and processes that, if trespassed, could provoke unacceptable environmental change with the potential to endanger humans (Campbell *et al*., 2017). These processes and functions are: climate change, ocean acidification, stratospheric ozone; biogeochemical nitrogen (N) cycle, and phosphorus (P) cycle; global freshwater use, land system change, Planet integrity (comprising loss of biodiversity and ecosystems), chemical pollution and atmospheric aerosol loading. At present, humanity has already transgressed planetary boundaries for climate change, biosphere integrity, changes in biogeochemical cycles (Rockström *et al*., 2009 a, b) and land system change (Steffen *et al*., 2015). There is also extensive discussion as to whether or not freshwater use has been exceeded (Gerten *et al*., 2015). Considering the interdependence of Earth's sub-systems, processes and functions, their transgressions are likely to push other PBs out

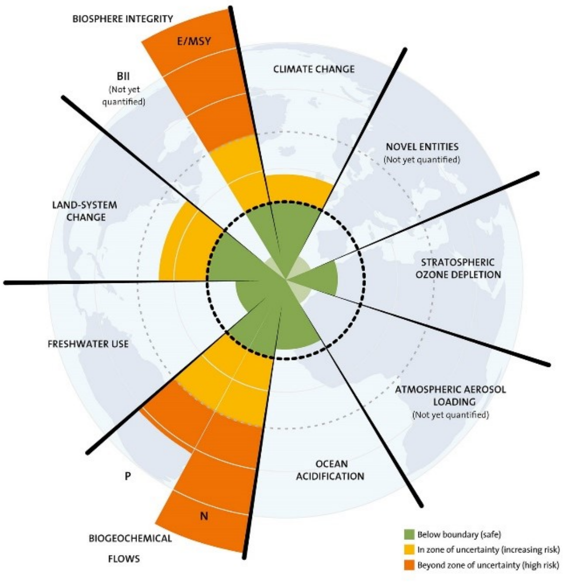

Figure 3. Actual state of planetary boundaries according to Steffen *et al* (2015). Green highlights a safe operating space, yellow an increasing risk and orange a high risk for 9 Earth processes and functions. Image source: F. Pharand-Deschênes /Globaïa accessed through www.stockholmresilience.org

of humanity's safe operating space (Rockström *et al*., 2009; Steffen *et al*., 2015).

Among all the above Earth functions/processes, Climate Change is considered the greatest threat that humanity has experienced in the last 10,000 years. The Climate crisis characterizing our Era is caused by the high rate of anthropogenic pressure and disturbance exerted upon the Earth's System atmosphere (Rockström *et al*., 2009). During the past 800,000 years, natural fluctuations in Earth's atmospheric CO_2 concentration have occurred, though never exceeding 300ppm. Since the advent of the Industrial Revolution in the 18th century, anthropogenic GHG emissions have consistently increased reaching over the past few years unexplored historical levels with an atmospheric CO_2 concentration above 400 ppm (IPCC, 2019 a; Richie and Roser, 2020). Humans are estimated to have caused an observed global warming of approximately 1.0°C by 2017 relative to pre-industrial levels (Allen *et al*., 2019). Human activities release every year approximately 50 Giga tonnes of CO_2-eq greenhouse gases into the atmosphere mainly as a consequence of the exploitation and combustion of Earth's System fossil energies (i.e., Planetary carbon stocks built over thousands of years), as well as land use change, agriculture and deforestation (IPCC, 2007). According to Richie and Roser (2020), energy use by industrial activities accounts for 24.2% of global emissions, followed by agriculture, forestry and other land use (AFOLU) (18.4%), energy use in buildings (17.5 %), transport (16.2 %), chemicals and cement industry (5.2%), and waste management (3.2%). Global warming is a reality. Extreme weather events - floods, draughts, heavy precipitations - have been on the rise both in intensity and frequency over the past decades (IPCC, 2019 b), and in turn negatively affect agricultural productions and food security. Accordingly, achieving food security for a growing population on a warming planet calls for a multitude of actions aimed at adaptation and mitigation in food systems, such as integrating climate change measures into national policies as well as improving education, awareness and individual/institutional capacity on climate change mitigation (Desa and UN, 2016).

1.2 Sustainable and healthy diets

Scientists across the health and environmental disciplines agree that a majority of the human population, most notably in affluent countries, have dietary habits that are both unhealthy and environmentally unsustainable (Willet *et al*., 2019). While this is sadly the case, it also leaves plenty of room for a significant change in dietary habits in the direction of choices that would benefit human health as well as contribute to keeping most of the critical environmental targets by 2050 within the planet boundaries (Eat Lancet Commission Summary report: Healthy Diets From Sustainable Food Systems, 2019). The global food system is the main catalyser of current environmental degradation (IPCC, 2019 a). Given that the food and the energy sectors are the largest contributors to GHG emissions (Crippa *et al.,* 2021; Richie and Roser, 2020), there is wide consensus that the best mitigation options for reversing global warming and ensuring a safe operating space for humanity are to change food systems and decarbonize the energy sector (Desa and UN, 2016; Willet *et al*., 2019). Willet *et al* (2019) and Springmann *et al* (2018) have estimated that an 80% reduction in food systems emissions can be achieved by 2050 via the adoption of plant-based diets, the latter thus representing the best mitigation option for the food sector. The concept of sustainable and healthy diets has recently gained traction as a possible strategy to address public health issues, decrease global warming and ensure food security for the world's growing population.

The Food and Agriculture Organization (FAO) of the United Nations has defined sustainable and healthy diets as: "dietary patterns that promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable". Sustainable healthy diets aim to "achieve optimal growth and development of all individuals and support functioning and physical, mental, and social wellbeing at all life stages for present and future generations; contribute to preventing all forms of malnutrition (i.e., undernutrition, micronutrient deficiency, overweight and obesity); reduce the risk of diet-related NCDs; and support the preservation of biodiversity and planetary health' (FAO and WHO, 2019). Indeed, several analyses have highlighted that adherence to plant-based diets with low meat consumption could represent a win-win bottom-up strategy in developed countries to reduce climate change and promote public health (Willet *et al*., 2019; Burlingame and Dernini, 2012; Poore and Nemecek, 2018; Garnett, 2014; Macdiarmid *et al*., 2011; Springmann *et al*., 2016). A meta-analysis from Tilman and Clark (2014) found a reduction of mortality of up to 18% by the adoption of vegetarian, pescatarian, and Mediterranean diets. Similar results are reported by Le and Sabaté (2014) and Orlich (2013) prospective cohort studies for vegan and vegetarian diets. All studies agree in considering as most impactful diets those that feature an excess consumption of meat (red meat in particular) and dairy products. The most recent and comprehensive work on the matter, linking the issue of healthy diets in the Anthropocene epoch with the safe operating space defined by planetary boundaries, is the one put forth by the EAT Lancet Commission (Willet *et al*., 2019). The 'planetary health plate' proposed by the Commission is a universal reference diet, applicable to all cultures, that allows food systems to remain within a safe operating space while providing food security for the estimated 10 billion global population by 2050 (Willet *et al*.,2019). The planetary health plate consists (by volume) of approximately half a plate of vegetables and fruits, while the remainder (considered in calories) consists primarily of whole grains, plant protein sources, unsaturated plant oils, and (optionally) modest amounts of animal sources of protein.

Most recently, fuelled by the dramatic surge in evidence regarding important environmental crises (such as global warming and climate change, the unprecedented dimension of ocean plastic pollution, water scarcity, soil loss and degradation). the commitment/engagement of governments and citizens on global environmental issues has reached a new peak.

Table 1 – Most relevant examples of sustainable diets proposed by scientific literature and/or related projects.

Authors	**Dietary principles**	**Targeted environmental issue**
Willet *et al*. 2019	Diversity of plant-based food; low amounts of animal source foods; use unsaturated rather than saturated fats; use limited amounts of refined grains, highly processed foods and added sugars; reduce food loss.	GHG, land use, water use, N&P use, biodiversity
Poore and Nemecek 2018	Cut meat consumption by half, especially beef, lamb, farmed crustaceans; reduce cheese; reduce consumption of oils, sugar, alcohol, and stimulants; use traced food with land sustainability evidence.	GHG, eutrophication, acidification, water scarcity, land use
Garnett 2014	Food diversity; energy balance; whole grain; field grown vegetables; small quantity of meat; moderate use of dairy; very limited high fat food; limited sugar and salt; oils and fats with balanced Omega 3:6 ratio; tap water.	GHG, land use
Livewell, WWF-UK	More vegetables; increase food variety; reduce food waste; moderate meat consumption; increase vegetable proteins; buy certified food; avoid food high in fat, salt, sugar; avoid soft drinks.	GHG, water use, land use

Against this backdrop, a global call for sustainable diets is not only timely but also responds to several of the 17 Sustainable Development Goals (SDG) that the United Nations have set as key development targets to be reached by 2030 for a sustainable and equitable world (THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT). Sustainable diets might also contribute to meeting the strict requirements of the Paris Agreement aimed at keeping global warming well below 2°C and reaching carbon emissions neutrality by 2050.

1.3 The role of Life Cycle studies in measuring food-related environmental impacts

LCA is a standardized method (ISO 14040 and ISO 14044) aimed at measuring the potential impact of a human activity or product on different environmental indicators through its entire life cycle or, as it is often referred to, from 'cradle to grave' (Finnveden *et al*., 2009). When approached comprehensively, health and social impact indicators may be included. Very similar approaches, though limited to the assessment of single environmental indicators, are the Carbon Footprint assessment (ISO 14067) and the Water footprint assessment (ISO 14046). The latter are standardized methods aimed at quantifying and reporting direct and indirect GHG emissions and water withdrawals related to products (respectively) in a way consistent with International Standards on LCA (NEN, 2018). The Carbon Footprint (CF) method was developed by the Carbon Trust (2006; 2007), i.e., a private company set up by the UK government "to accelerate the transition to a low carbon economy", and by the UK Department for the Environment, Food and Rural Affairs (DEFRA) (2006; 2007). The Water Footprint (WF) assessment method was established by the Water Footprint Network (WFN). The main difference between CF and the GWP indicator used in LCA is the exclusion of emission sources that account for less than 1% of the total GWP (BSI, 2011). Additionally, CFs are more commonly used in private companies and NGOs, while the LCA approach is predominant in academia. Despite these differences, CF and GWP are considered equivalent when expressed in the same functional unit and when accounting for the same 'system boundary' (Clune *et al*., 2017), i.e., unit processes included in the GHGe accounting/inventory.

LCA, CF and WF approaches are widely applied to the food sector and food products in order to identify production/consumption hotspots and improvement opportunities, as well as to compare the relative performance of different production systems and techniques (Garnett, 2014) and ultimately gauge the environmental impact of different food choices (Clune *et al*., 2017) while defining sustainable dietary patterns (Ruini *et al*., 2015). Different authors have attempted to build comprehensive food databases on available LCA studies, the most comprehensive of which - to our knowledge - are Clune's *et al* on GWP of fresh foods (2017), and the database on CF, WF and Ecological footprint accompanying Ruini *et al.* (2015) work on the double pyramid model developed by Barilla Center for Food and Nutrition (BCFN). With regard to WF studies, notwithstanding the absence of a database, the authors of the Water Footprint Network have provided over recent years quite an exhaustive series of reports and scientific articles covering WF calculations for a wide range of food commodities (Mekonnen and Hoekstra, 2010, 2011,2012; Pahlow *et al.,* 2015). In light of the increasing need to address sustainable diets through sustainable food production, numerous studies have compiled LCA data to compare different foods (Audsley *et al*., 2009; Berners-Lee *et al*., 2012; Bradbear and Friel, 2011; de Vries and de Boer, 2010; Foster *et al*., 2006; Nijdam *et al*., 2012; Sonesson *et al*., 2010; Roy *et al*., 2009).

1.4 Carbon footprint and Water footprint of current EU dietary patterns

During the second half of the twentieth century, there has been a significant shift in European dietary patterns towards unhealthy and unsustainable foods (WHO, 2002). Meat production and consumption in Europe has doubled since 1960, together with increased consumption of ultra-processed foods, unsaturated fats, salt and sugar (EUROSTAT, 2021; FAOSTAT, 2021). Despite the abundance in Europe of traditional healthy diets, such as the Mediterranean Diet, the Atlantic Diet (Vaz Velho *et al*., 2016) and the Scandinavian Nordic Diet (Adamsson *et al*., 2012), current European consumption - influenced by the effect of globalization - is much different from traditional sustainable patterns.

According to Castaldi *et al.* (2022) contemporary dietary patterns in Mediterranean EU countries are associated with average emissions of 4.46 kg CO_2eq d^{-1}. This figure does not differ much from that for the rest of Europe (21 other EU countries), where dietary impact is estimated at 4.03 kg CO_2eq per capita d^{-1}. Ferrari *et al* (2020) simulated a 50% reduction in food-related emissions for a sustainable Italian diet ensuring an adequate nutritional intake. According to Castaldi *et al* (2022) the traditional Mediterranean Diet is associated with GHGE of 2.31 ± 0.14 kg CO_2eq per capita d^{-1}, and its adoption throughout the EU would result in a 42-48% reduction in food-related emissions. This value is comparable to the GHGE associated with the planetary health diet scheme proposed by the EAT Lancet Commission, which is estimated at 2.49 kg CO_2eq per capita d^{-1} based on CFs applied to data from Castaldi *et al*., (2022). In developed countries, cutting back on animal-sourced foods in healthy dietary patterns, alongside reducing GHGE, has been shown to reduce also the WF of food supply chains (Vanham *et al*., 2013, Vanham *et al*., 2018; Mekonnen and Gerbens-Leenes, 2020; Ruini *et al*., 2015; Ercin and Hoekstra, 2016). Harris *et al.* (2020) conducted a systematic review and meta-analysis of the WF of global dietary patterns, and found the highest value for European diets with a median value of 3227 L per capita d^{-1}, the main contributor to the latter being animal sourced foods. Vanham *et al.* (2016) found higher WFs in Mediterranean countries, ranging from 3277 to 5789 L per capita d^{-1}. On the contrary, sustainable and healthy dietary patterns, such as the traditional Mediterranean Diet, is calculated to have a lower WF amounting to 2640 L per capita d^{-1} (Capone *et al*., 2013). Urgent action from all stakeholders is required to reverse currently unsustainable and unhealthy European consumption trends and achieve the Sustainable Development Goals (SDGs) and GHG-e targets set by the Paris Climate Agreement.

1.5. Behavioural interventions for dietary shift

In light of the increasing concern about the key role of food choices in mitigating anthropogenic environmental impact, initiatives have been implemented in recent years to incentivize the adoption of more sustainable dietary patterns.

A widely implemented intervention used to promote sustainable food consumption has been the use of environmental sustainability labels (Thøgersen *et al*., 2010; Shuai *et al*., 2014; Vlaeminck *et al*., 2014; Akaichi *et al*., 2016; Zanoli *et al*., 2015). Slapø and Karevold (2019) conducted a brief experiment with follow-up at a Norwegian University cafeteria in order to test the ability of 3 different labelling systems, combined with explanatory posters, to spur customers towards the most environmentally friendly food options: with the exception of traffic-light labels in relation to meat courses during the initial phase of the experiment, none of the labelling systems were found to significantly alter customer choices. A systematic review on the effects of ecolabels on food selection, purchase and consumption in field experiments or hypothetical environments (e.g., online supermarket platforms) analysed 76 interventions involving more than 40,000 participants: ecolabeling was found to be associated with higher sustainable food consumption in 79% of interventions (Potter *et al*., 2021). Labels consisted of visual logos, short-text messages or the combination of both for a wide range of sustainable claims including certification schemes (e.g., organic, GHG emissions, environmentally friendly, land/water sparing, pesticide-free).

Several recent field studies aimed at reducing the environmental impact of food consumption within the catering sector have focused on narrowly-defined aspects, such as food waste (Pirani and Arafat, 2016), tableware (Blanca-Alcubilla *et al*., 2020) and cooking methods (Fusi *et al*., 2016).

Tukker *et al*. (2010) used LCA data to gauge the impacts of household food consumption while highlighting the potential for mitigating those impacts through behavioural interventions.

An 8-week-long field experiment conducted in a UK-based chain of cafés tested the role of alternative language/descriptions in prompting customer selection of plant-based menus; the study found that changing the original dish name with a more appealing one, for instance by emphasizing taste or origin, was related to higher vegetarian menu sales (Bacon *et al*., 2018).

In a year-long large-scale series of observational and experimental field studies conducted in 3 cafeterias at an English Univeristy, Garnet *et al.* (2019) examined the impact of attempting to nudge meal selection by increasing the proportion of vegetarian meals offered: doubling the offer of vegetarian meals resulted in increased vegetarian sales by between 41% and 79%, with the strongest effect observed among diners with the lowest prior levels of vegetarian meal selection.

Ramsing *et al*. (2021) surveyed US households participating in a community-based, 12-week-long 'Meatless Monday' challenge, and found that the intervention was effective in initiating and maintaining positive change in food consumption patterns and attitudes; limitations of the study include participant sampling bias and respondent self-selection bias.

Colombo *et al*. (2020) used linear programming to optimise GHG-e of lunch menus at 3 primary schools in Sweden under the constraints of nutritional adequacy and minimum deviation from baseline food supply. The optimised menu, resulting in 40% fewer GHGE and 11% fewer costs, was served over a four-week period without notable changes in meal satisfaction, consumption or waste.

One of the most recent and comprehensive initiatives aimed at promoting sustainable and healthy diets in the catering sector is the *Livewell for LIFE UK* project jointly developed by WWF, Sodexo and the Food Ethics Council. In order to quantify the environmental impact of the sustainable and healthy plates offered - i.e., 'Livewell Plates'- LCA was performed on 79 food products by the use of existing LCA models (De Valk *et al*., 2016) and databases (i.e., AgriBalyse, AgriFootprint and FAOSTAT), while proxies were used for other 46 foods and beverages (Kramer *et al*., 2017). The project tackled GHG emissions, water and land use, and demonstrated that changing food offering can lower greenhouse gas emissions from the EU food supply chain by above 25%. Nevertheless, the interventions were focused on modifying food offering *in toto* rather than testing consumers choices (Barling *et al*., 2016).

In sum, recent interventions that take aim at the environmental impact of food choices either do not incorporate impact measurements or involve a complete menu makeover barring choice between alternatives with varying impact.

CHAPTER 2: A MULTILEVEL CARBON AND WATER FOOTPRINT DATASET ON FOOD COMMODITIES

This chapter describes the methodology adopted for the database development on CF and WF of food commodities and represents a marginally improved version of Petersson *et al*. (2021a):

‘*A multilevel carbon and water footprint dataset on food commodities*’ Scientific Data (2021) 8:127 | https://doi.org/10.1038/s41597-021-00909-8

The full database is uploaded as a supplementary material and can be accessed here: Petersson, T. et al. (2021b) SUEATABLE_LIFE: *a comprehensive database of carbon and water footprints of food commodities*. Figshare https://doi.org/10.6084/m9.figshare.13271111

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Abstract

Informing and engaging citizens to adopt sustainable diets is a key strategy for reducing global environmental impacts of the agricultural and food sectors. In this respect, the first requisite to support citizens and actors of the food sector is to provide them a publicly available, reliable and ready to use synthesis of environmental pressures associated to food commodities. Here we introduce the Su-EATABLE LIFE (SEL) database, a harmonised compilation of carbon (CF) and water (WF) footprint reference values for food commodities, based on a standardized methodology to extract information and assign reliable footprint values and uncertainties to food items, starting from peer-reviewed articles and grey literature. The SEL database and its innovative methodological framework for uncertainty treatment and data quality assurance provides a solid basis for evaluating the impact of dietary shifts on global environmental policies, including climate mitigation through greenhouse gases emission reductions. The database ensures repeatability and further expansion, providing a reliable science-based tool for managers and researcher in the food sector.

2.1 Background and Summary

Food is essential for human physical and psychological wellbeing; it is a driver of economy and a key element of cultural identity and human heritage. Food also plays a relevant role in present and future world sustainable development strategies, as the food chain accounts up to 37% of the global greenhouse emissions (IPCC, 2019 a), 70% of water withdrawals (WWAP, 2014) and strongly contributes to deforestation, mineral depletion, desertification, eutrophication, acidification, biodiversity loss and genetic erosion (Willet *et al.,* 2019; FAO, 2019). Each food product brings its share of generated environmental pressures during food production, processing, distribution and end-life (ISO, 2006). The degree of such environmental burden varies significantly with food type and with food production characteristics (Poore and Nemecek, 2018). However, only few indicators of food pressure have standardized procedures, the two most well-known being the carbon footprint (ISO, 2018) (CF) and the water footprint (ISO, 2014) (WF). The CF of a food product represents the total greenhouse gases emitted during all the phases of its production and distribution quantified using a life cycle approach. It is a straightforward indicator of the share of global GHG emissions that can be attributed to food producers or consumers and can be easily linked to climate policies. The WF of a food product is the amount of water that is consumed and polluted in all processing stages of its production. It is a consolidated indicator, frequently used to compare the relative impacts of different food types and dietary habits (Harris *et al*., 2020).

A global transition towards sustainable food production and consumption is among the most beneficial global strategies proposed to mitigate human impact on planet resources (Willet *et al*., 2019; IPCC, 2019 a) and is a fundamental asset of the new EU strategy "Farm to Fork" as part of the Green Deal. A clear link has been demonstrated between healthy and sustainable dietary choices[3] providing a win-win opportunity for all the stakeholders of the food sector, from consumers to food providers. The first step to support societal engagement on sustainable diets is to provide knowledge and tools that can allow turning ideas into action.

Several studies and analytical reviews of food CF and WF footprints have provided information on different dietary impacts (Rosi *et al*., 2017; Poore and Nemecek, 2018) and methodological issues (Poore and Nemecek, 2018; Clune *et al*., 2017; Hoekstra and Mekonnen, 2012), policy recommendation (Poore and Nemecek, 2018; Hoekstra and Mekonnen, 2012). A further step is to offer an open access database aimed at different kinds of stakeholders, from scientific experts to business company, citizens and policymakers, to be used for calculations, management and reporting. To meet this goal, we have created the SU-EATABLE LIFE (SEL) database, a ready to use data repository of CF and WF of food items, based on a standardized methodology to assign scientifically meaningful values of footprint to food commodities, starting from publications reported in literature. Structure and methodological approach, used to create the database, easily allow for further expansion or reorganization of specific food items and types depending on the specific user needs. As such it provides a flexible science-based tool for operators, managers and researcher in the food sector.

SEL database, developed in the framework of the EU SU-Eatable LIFE project, builds on the double pyramid database (Ruini *et al*., 2015) of the Barilla Centre for Food and Nutrition.

SEL database is organized in different levels of information (Fig. 4) suitable for different users and purposes. Level 1 reports CF and WF data of food commodities extracted from published studies and harmonized to refer to the same system boundaries and functional units. Each data is conceptually associated to a food item name, to a food type, sub-type and to a food group (Table 2).

Level of aggregation	**Description of the aggregated food commodity**
Group	Wide category of food commodity. The database includes 4 groups. 1) *Agricultural processed* covering manly plant based industrial processed food. 2) *Animal husbandry* covering products of terrestrial animal origin. 3) *Crops* covering fresh or minimally processed plant-based products like dried, canned, frozen vegetables and fruit. 4) *Fishing* which includes products from fresh and salted waters.
Type	Aggregated level of food commodity as generally known in the food system. It represents a group of items having similar characteristics. For example, the type "legumes" includes peas, lentils, beans, soybeans etc.
Sub-type	They refer to just three types (vegetables, fruit, shellfish) which include a large variability of items (i.e., the type "shellfish" includes the sub-types crustacean, bivalves and cephalopods).
Item	It is the most detailed level for aggregated data. Generally, the item name corresponds to common market definitions (ex. tomato, mussels, milk). The level of detail proposed depends on the available data source.

Table 2. Hierarchical classification applied to CF and WF data in the database.

This hierarchical assignment allows shifting easily among different levels of aggregation of food data information. At level 2, data from single studies of level 1 are aggregated to represent food "items" value and associated uncertainty, which support the user in determining how robust are the available data for technical and scientific purposes. Level 3 is a further level of data aggregation, where item values from level 2 are aggregated based on their "type" identifier. Level 4 is another possibility to represent a food commodity using the value of sub-types, which are created when a food type is quite broad. Step 3 distils all the information contained in the level 2, 3 and 4 into an easy-to-use sheet (SEL CF or WF DATA FOR USERS) to rapidly assign the correct value to a food item.

2.2 Methods

With the aim of obtaining a useful tool for stakeholders to explore, assess and use the information related to CF and WF of food commodities, we implemented a multi-step methodological framework to create an easy-to-use data repository of values of CF and WF of food items, which can be expanded or modified for tailored requirements using a science-based approach for each step of its creation (Fig. 4).

The overall methodological procedure is made of 3 steps. Step 1 is related to CF and WF data collection from literature, check for eligibility and harmonization to create the base level of the SU-Eatable database, "level 1". Step 2 is about the creation of other three informative layers with higher level of data aggregation. These might be the data of direct interests for stakeholders of the food systems. During this step a rigorous statistical approach is proposed to evaluate the quality of data analysed and criteria for the correct use of data, based on statistical evidence, are set and applied to the data. In Step 3 the complex set of statistical evaluations, done for each informative level, are summarized into an easy-to-use dataset reporting values of CF and WF of food items. Thanks to its multilevel approach the database provides a flexible tool for different purposes and levels of expertise. Each step is based on transparent procedures that make easy to replicate or implement or to modify each level of the database by users.

Each step of is described in details in the following paragraphs.

Step 1 - CF and WF data collection, harmonization and compilation of level 1 of SEL database

The first step to create the SEL database was to review the published data of CF and WF of food commodities. We revised literature data published till January 2020 including peer-reviewed papers, conference proceedings, public reports or studies where methods of data collection and handling were described, and Environmental Product Declarations (EPDs).

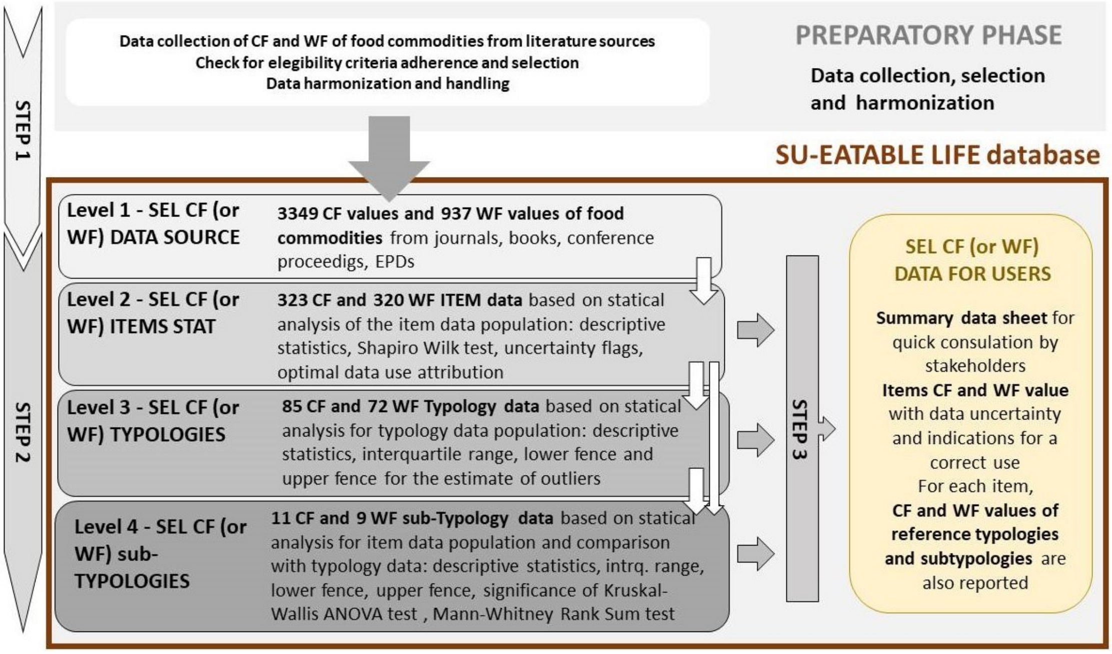

Figure 4 General outline of the different construction steps of Su-Eatable LIFE (SEL) database. ***Step 1*** *includes the preparatory phase where studies were collected from literature and public repositories, selected on the basis of eligibility criteria, CF and WF values of food commodities extracted and harmonized, and then reported into the level 1 information of the SEL database. In* ***Step 2*** *the other layers of information are created which represent different levels of aggregation of data reported in level 1. CF and WF values statistical analysis are reported for food items (level 2), types (level 3) and sub-types (level 4). In* ***Step 3*** *the complex set of data reported in Level, 1, 2 and 3 are summarized into an easy-to-use dataset suitable for quick consultation by technical and not technical users*.

For the collection of CF data a significant input came from the systematic review of Clune *et al*. (2017), who reviewed 369 published studies, covering the period 2000-2015, proving 168 varieties of fresh food products based on 1718 data entries. An additional source of studies reporting both CF and WF was the Double Pyramid database 2016 (BCFN 2016 https://www.barillacfn.com/en/publications/double-pyramid-2016/) built on the previous version of Ruini *et al*. (2015), which reports 1202 CF values from 468 sources covering 240 food items and 309 WF values from 136 data sources covering 152 food items (reference period 1998-2016). Part of CF data of this latter dataset, up to year 2014, were already revised and included in the Clune *et al.* (2017) study. To avoid double counting from these two sources, data from both sources were checked for authorship, plus the CF reported data were compared and if in disagreement the original data were checked in the paper. Data of Double Pyramid database 2016 not reported in Clune *et al*. (2017), mostly referring to processed food, were checked for eligibility applying the exclusion criteria reported in Table 3 an included in the present database.

A new literature search was done to integrate data not covered by the previous reviews using three online bibliographic sources SCOPUS (https://www.scopus.com/home.uri), Google Scholar (https://scholar.google.com/) and the Google search engine (https://www.google.com/), which was concluded in January 2020. To search the bibliographic sources, we used the combinations of two sets of words: The first referring to "impacts", which included the following words, *carbon footprint, water footprint, virtual water, greenhouse gases, environmental impact, life cycle, LCA, LCI, EPD*, the second referring to the "products" which included the words *food, beverages, fish, shellfish, crops, vegetables, fruit, meat*, *eggs, dairy*.

Exclusion criteria list
• Studies present in the Double Pyramid 2016 database not reported in public databases.
• Internal not published calculations in Double Pyramid 2016 database.
• Studies which do not properly specify objectives, methods, and results (Prisma protocol).
• CF studies not based on life cycle methodological approach.
• Studies which calculate the WF as 'consumed water', 'water use' or simple 'blue water' and are not based on the methodology to estimate the water footprint as reported by Hoekstra and Mekonnen (2012).
• CF studies where the functional unit is not expressed as kg CO_2equ/kg or litre of product neither it is possible to derive the functional unit from reported data.
• WF studies where the functional unit is not expressed as litres of water/kg or litre of product neither it is possible to derive the functional unit from reported data.
• CF studies with system boundary beyond the distribution centre of the final product, which do not report the contribution of the different life cycle stages to the CF.

Table 3. Exclusion criteria to be applied to CF and WF data collected from literature in order to be eligible for inclusion in the SU-Eatable database level 1.

Most recent EPDs were searched on the International EPD's System database (www.environdec.com). All the new added studies were evaluated for exclusion criteria (Table 3). Overall, the final list of data from single studies reported in the SEL database was distributed as follow: 3349 CF data, including 1397 data of fresh food commodities already reported in Clune *et al*. (2017), 803 CF data originally reported in Double Pyramid 2016 database, which were checked for eligibility and harmonized where needed, and 701 CF data added with this study; 938 WF data, including 288 WF data originally reported in double pyramid 2016 and 650 WF data added with this study. All the CF and WF values extracted from the collected studies were assigned a group, a type, a sub-type when existing, and an item name (Table 2) and were recorded on an excel sheet including the following additional information: type of bibliographic source, full reference, publication year, system boundary at distribution, country of production, region of production, relevant notes, presence of the same value in other data collections (i.e., Clune *et al*., 2017 or Double Pyramid 2016).

After this phase of data collection, CF data where further analysed and handled for the harmonization of the system boundary following the approach as reported in Clune *et al*. (2017). The system boundary considered in the SEL database is the distribution centre to consumers located in the country of origin. It hence excludes post market phase like for example cooking. The system boundaries at distribution have a wide range of specifications in the published papers. We accepted regional distribution centre (RDC), international distribution centre (IDC), European distribution centre (EDC), country ports of final destination, warehouses, wholesalers, city markets, up to retailers. For the specific case of international transport, which includes also the emissions for shipping to regional distribution centres of the hosting country, rather than excluding the studies we have created a dedicated type "imported", which however includes very few studies. The imported commodity is indicated in the database by a capital letter "I".

If CF values collected from literature referred to the system boundary "farm gate" or "slaughterhouse", additional post farm gate GHG emissions were added as proposed by Clune *et al*. (2017). These additional emissions also included packaging if not reported in the publication. We adopted the median value for distribution to RDC (0.09 kg CO_2/kg or kg CO_2/L) and packaging (0.05 kg CO_2/kg or kg CO_2/L) used by Clune *et al*. (2017). Data referring to slaughterhouse emissions were also taken from the same publication.

To address the share of WF for packaging and transportation to the market we analysed 256 EPD's. No significant increase of WF in downstream stages associated to packaging and distribution was found according to ANOVA test results (data not shown). Thus, we included in the analysis all system boundaries with the exception of 'cooking', human excretion and waste disposal.

To transform CF values from carcass or live weight to bone free meat, ratios reported in in Clune *et al*. (2017) were used, while the ration carcass weight to bone free meat for buffalo meat (1:0.684) was estimated from the studies of Gerber *et al*. (2013), Gurunathan *et al*. (2009), Li *et al*. (2018).

The final version of CF and WF data, after data handling was recorded in a sheet where in addition to the information mentioned above for each study, we also reported when additional post farm gate emissions (transport T, slaughtering S, packaging P) or meat conversion factors (cf) were applied. This complete dataset represents the *level 1* information sheet of the SEL database (Fig. 4).

Step 2 - Creation of derived CF and WF datasets with higher aggregation level (2, 3 and 4)

This step aims to represent the footprint of food commodities with a higher level of aggregation corresponding to food items, types and sub-types (Table 2), which might be of particular interest for different kinds of stakeholders. The item represents the higher detail of aggregated data to represent the footprint of a food commodity and it is often the most desirable information for food impact analysis and dietary evaluations. We propose here a methodological framework to evaluate the uncertainty associated to data used to represent food items. The methodological framework will support the users in their choice of the value to represent the food item on the basis of the available data present in the database. It also would easily allow for expansion and implementation of food item values.

Level 2 , SEL CF ITEM & SEL WF ITEM

These two datasets (CF and WF) report a comprehensive set of descriptive statistics for the list of food items present in the database. The sample data used to attribute a value and uncertainty to a food item is made of all the CF or WF values classified with that "item entry name" in the dataset of *level 1* of SEL database.

The item data .sample data is described in *level 2* by the following set of information.

Size: number of studies used for the analysis of item .sample data (n).

Location and central-tendency measures: in terms of mean, median, first quartile (Q1) and third quartile (Q3), including also the minimum (Min) and maximum (Max) observed values.

Variability measures: Standard Deviation (SD) Coefficient of Variation (CV) as absolute and relative dispersion indexes, the Interquartile Range (IQR) and the Median Absolute Deviation (MAD) as more robust indexes of variability.

Shape measures: Skewness (SK), kurtosis (KU) indexes and further assessed through the Shapiro-Wilk normality test (SW test).

The **median** of the item data .sample data was chosen to assign a value of central tendency which represents the item. The median offers the advantage of not being influenced by the presence of outliers which misrepresent the value of the mean making it a less meaningful measure. As such, the median represents the location estimator with the highest breakdown point (equal to 0.5) and with "the maximum proportion of observations that can be contaminated (i.e., set to infinity) without forcing the estimator to result in a “false” and not-representative value (Donoho, 1983; Leys, 2013). With these properties, the median also represents the most appropriate measure of central tendency to describe both positively and negatively skewed distributions (Privitera, 2012).

To describe the uncertainty associated to the position value (median) we used the descriptive static data relative to dispersion and shape of item data distribution. In particular we used skewness and kurtosis indexes which gave us information on the existence of a symmetric or skewed distributions as well as on their ‘peakedness’ measured as relative to the weights of the tails (Jones *et al*., 2011), thus enabling us to evaluate (for each distribution) the importance of extreme values over the entire set of data and the related level of dispersion (platykurtic versus leptokurtic distributions). We completed the shape analysis by carrying out the Shapiro-Wilk test whose formulation is based on Shapiro and Wilk (1965) with a new approximation accurate for $4 \leq n \leq 2000$ (Royston 1992).

To assess the uncertainty of the item value we propose a method based on three quality flags that can be combined into a quality attribution with a recommendation for data use (Figure 5).

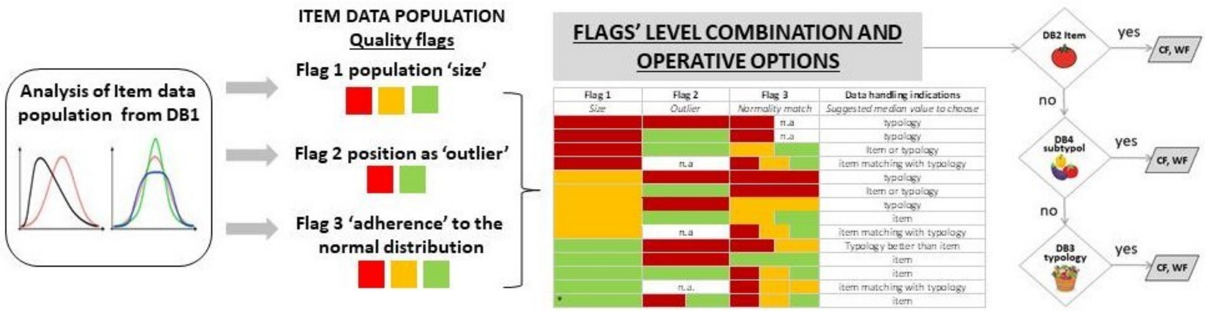

Figure 5. Method for attribution of CF (or WF) value to a food item based on data quality flags. The scheme shows the procedure applied to evaluate the level of uncertainty associated to CF or WF value of a food item and how this information is used to decide the best value that should be used to represent the item. Three quality flags related to a statistical aspect of the data sample to attribute the level of uncertainty. Each flag has different level of quality, red being the worst, green the best. Flags are then combined and expert judgement is used to associate a suggestion for data use to each flag combination. If the item median value is characterized by high uncertainty it poorly represents the item and caution is needed to use this data to represent the food commodity, the users is therefore redirected to a higher level of aggregation such as the sub-type or the type which includes the analysed item.

Flag 1: evaluation of the 'size' (n) of the "item sample data"

- ***Red:*** **n<4**, as three is the minimum number of observations needed for distinguishing the median from the mean and for evaluating the approximation of the empirical distributions to known parametric distributions, in accordance with the minimum requirements specified by Royston (1992).
- ***Yellow:*** **4<n≤8**, minimum level of observations needed for jointly evaluating kurtosis and skewness of a distribution (D'Agostino *et al*., 1990).
- ***Green:*** **n>8** number of observations required to identify cases in which location (as well as variability and shapes) measures can be properly computed and evaluated.
- ***Green with asterisk (*):*** applies to WF values which are global or regional or national average estimates. In this case green is assigned independently by "n". In this case the flags 2 and 3 do not apply for the evaluation of the WF item value.

Flag 2: evaluation of outlier position of items characterized by RED or YELLOW Flag 1. This flag is used to test if items with .sample data size n≤8, are outliers for their respective type .sample data. If they are outliers, they cannot be alternatively represented by the type value, as they will be particularly higher or lower than item data .sample data representing the reference type. An example of this in the SEL database is the CF value of the item "lobster" which has a yellow flag 1 (n=5). The item lobster is an outlier for the type "shellfish". In this case even if there is a certain level of uncertainty in the "lobster" item value, it is not advisable to substitute this value with the type value "shellfish".

To attribute flag 2 output the Tukey's rule was used (Hoaglin *et al*., 1986). The outlier identification is based on the quartiles of data distribution, where the first quartile Q1 is the value ≥ 1/4 of the data, the second quartile Q2 or the median is the value ≥ 1/2 of the data, and the third quartile Q3 is the value ≥ 3/4 of the data. The interquartile range, IQR, is Q3 − Q1. The data used to estimate quartile values are the medians of the items composing the type .sample data.

- **Red**: The median value of the analysed item (x), is an outlier, i.e., following the Tukey's rule it is more than 1.5 times the interquartile range from the quartiles, either $x<Q1 - 1.5\ IQR$, or $x> Q3 + 1.5\ IQR$.
- **Green flag**: The median value of the uncertain item analysed (x), is not an outlier, i.e., it is within 1.5 times the interquartile range from the quartiles, $Q1 - 1.5\ IQR < x < Q3 + 1.5\ IQR$.

- **NA, no flag**: the Tukey rule was not applied because the items coincide with the type, i.e., the type is only made by this sole item for the time being.

Flag 3: adherence to the normal distribution. It evaluates the level of dispersion and clustering of the observed data points to the centre. To test the adherence of the item data .sample data distribution to the normal distribution, the Shapiro-Wilk test was carried out. The three following colours were assigned:

- **Red:** characterizing those items: i) whose size was lower than 4 thus preventing the evaluation of normal distribution approximation, as detailed above; ii) items for which we rejected the null hypothesis of bell-shaped distribution at the 1% level of significance (p-value<0.01), therefore highlighting substantial asymmetric distribution and/or a heavy-tail distributions characterized by a level of clustering (low or high) not adequate to describe the findings with a synthetic measure, computed at the same item level.
- **Yellow:** for those items whose empirical distribution, even if departing from the Normal distribution, lead us to reject the null hypothesis with a greater level of errors (0.01≤p-value<0.05).
- **Green**: for those items whose empirical distribution led us to not reject the null hypothesis, therefore confirming the validity of central tendency measures (at the item level) to be used for summary description.
- **NA no flag:** the Shapiro-Wilk test could not be run due to an insufficient amount of data in the .sample data (n<3).

The outputs of the three flags were considered together to evaluate the uncertainty related to the median CF or WF value of food items, and based on the level of uncertainty indications for an optimal data use were provided (Table 4).

Flag 1	Flag 2	Flag 3	Data handling indications
Size	*Outlier*	*Normality match*	*Suggested median value to represent the food commodity*
[red]	[red]	[red] n.a	type
[red]	[green]	[red] n.a	type
[red]	[green]	[yellow] [green]	Item or type
[red]	n.a	[red] [yellow] [green]	item matching with type
[yellow]	[red]	[red]	type
[yellow]	[green]	[red]	Item or type
[yellow]	[red]	[yellow]	type
[yellow]	[red]	[green]	item
[yellow]	[green]	[yellow] [green]	item
[yellow]	n.a	[red] [yellow] [green]	item matching with type
[green]	[red]	[red] [yellow]	Type better than item
[green]	[red]	[green]	item
[green]	[green]	[red] [yellow] [green]	item
[green]	n.a.	[red] [yellow] [yellow]	item matching with type
[green] *	[red] [green]	[red] [yellow] [green]	item

Table 4. Flag output table. Combination of flag colours, attributed to the item data sample into recommendations for the optimal use of the footprint values. Multiple colours in one cell indicate multiple outputs for this cell that can be associated with colours of the other two cells in the same raw; n.a. indicates that the test could not be run (see methods for details), the asterisk * indicates that the WF value of the item is a global or regional or national mean.

A brief rational of the data handling indication is as follow:

1. *item:* the item statistics are sufficiently robust. The user can use the item median value to represent that food commodity.
2. *item or type:* although the sample data used to derive the median of the item is reduced in size and its distribution does not optimally fit a normal distribution, the median of the item is not an outlier for the type sample data, i.e., the value of the item in not exceptionally high or low compared with other items present in the type of reference. The user can use either the item median value or the type median value to assign a footprint value to the chosen item.
3. *item matching with type:* the type coincides with one single item, the two objects item and type, represent hence the same food commodity. The user will find the same median value in the Item and Type tables, the choice is hence univocal. In this case the level of uncertainty can be estimated from flag 1 and flag 3 because flag 2 cannot be calculated (n.a.).
4. *type better than item:* different statistical combinations can lead to this option. The uncertainty associated to the item value is sufficiently high to prefer the type value to represent the food commodity although the item value is not to be discarded.
5. *type (or sub-type):* the high uncertainty suggests precaution in using the item value to represent the food commodity and alternatively a higher level of aggregation for this food

commodity can be used. When the indication suggests both type or sub-type is because there is no statistical difference between the two values and the user can choose which one to use.

Level 3, SEL CF Types & SEL WF Types

In this informative level descriptive statistics is reported for CF and WF data of food types. The CF or WF data .sample data of "types" is composed by the CF or WF median value of each item that is included in the type. The value 'n' hence represents the number of items in the type. The same statistical parameters reported for the item relative to size, location and central-tendency measures and variability measures are reported for types. The flag approach is not used to test types because independently from the uncertainty there is no other meaningful footprint data at higher hierarchical level that can be attributed to a food commodity without losing it specificity. The users can choose to create different types from the ones proposed using CF and WF data provided at level 2 (items).

Level 4, SEL CF sub-Types & SEL WF sub-Types

Sub-types represent a subgroup of types, which have been used when the type refers to a wide range of food items which could have very different CF and WF values on the basis of some commodity characteristic.

An example is represented by the fresh crop products where the yield per hectare strongly influences the CF value (Figure 6).

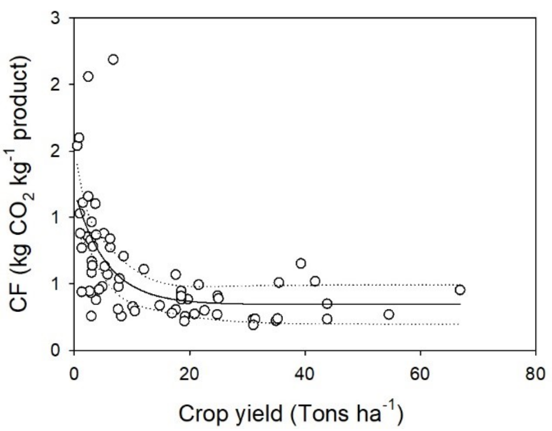

Figure 6. CF value of vegetables vs. their yield. Carbon footprint value of food items included in the type "vegetables outdoor" is plotted versus their average yield value as reported in FAOSTAT (data EU-28, year 2017).

In the SEL database only 3 types have been further divided into sub-types, as they include very different items in terms of their potential LCA outputs. These are vegetable outdoors, fruit outdoor, and shellfish. The .sample data of data used to evaluate the descriptive statistic for each sub-type is composed by the median of each item that is included in the sub-type. Additional statistical information in this informative level 4 are the output of the Kruskal-Wallis (1952) ANOVA test on ranks -all pairwise multiple comparison procedures based on Dunn's Method (1961)- to determine if the median values of the sub-types within one type were significantly different from each other, while the Mann-Whitney Rank Sum Test (Mann and Whitney, 1947) was used to determine if a sub-type footprint value was significantly different from its reference type sample data.

Step 3 - Creation of summary sheet for easy and quick consultation of CF and WF values of food commodities (SEL CF (or WF) data for users)

The two summary sheets (CF and WF data) can be considered the most interesting and innovative output of the database, as they translate the complex series of data reported in the 4 informative levels of the database into a list of footprint values of food based on statistically robust analysis. Footprint values of the food items are represented with additional information about value robustness and where the uncertainty is high alternative values with higher levels of aggregation are proposed. The summary sheets are meant to provide a scientifically robust and easy to use tool for experts and not experts who want to analyse the impact of food commodities and dietary plans. The users are free to accept the expert-based suggestions or to make their own considerations.

Data Summary

At present, the SEL database contains 3349 carbon footprint values extrapolated from 841 publications (1998-2019) and 937 water footprint values extrapolated from 88 publications (2005-2018). The CF data are summarized into a total of 85 types, 11 sub-types, 323 items. WF data are summarized into a total of 72 types, 9 sub-types, 320 items. A detailed breakdown of the CF and WF into the four food commodity groups, agricultural processed, animal husbandry, crop and fishing are reported in Table 5. Currently, based on the uncertainty analysis applied to the

	Carbon footprint			Water footprint		
	Type.	Sub-type.	Items	Type.	Sub-type.	Items
Agri. processed	41	-	100 (570)	33	-	95 (328)
Animal husb.	21	-	46 (1530)	22	-	67 (308)
Crops	18	8	117 (986)	15	8	136 (246)
Fishing	5	3	60 (263)	2	1	22 (55)
Total	*85*	*11*	*323 (3349)*	*72*	*9*	*320 (937)*

Table 5. Number of CF and WF data of food commodities reported in the database informative levels as items (level 2), types (level 3) and sub-types (level 4). Their breakdown into the 4 food commodity groups is reported. In brackets are reported the total number of data entries from level 1 used to calculate the food item values.

items, CF values of 149 items are highly reliable and 174 CF values are less reliable so that quantitative analysis based on these items should consider the uncertainty associated for the specific purpose of data use. The WF of 290 items has been considered highly reliable, while the WF values of 30 items has been evaluated as less reliable. The level of uncertainty for each item can be reduced by users including new studies that ameliorate the item sample data statistic attributes.

In terms of geographical distribution, the source data of CF have an Eurocentric prevalence while the WF data are more evenly distributed among America, Asia and Europe, the relative contribution depending on the commodity group (Table 6).

	% Geographical distribution of CF and WF data reported in level 1							
	Carbon footprint				Water footprint			
Region	**Agricultural processed**	**Animal husbandry**	**Crops**	**Fishing**	**Agricultural processed**	**Animal husbandry**	**Crops**	**Fishing**
Africa	0.5	1.4	-	2.3	0.3	-	2.0	-
America	11.9	14.6	17.9	8.0	1.5	21.1	5.7	-
Asia	3.7	2.4	11.2	7.6	0.9	16.9	13.4	-
Europe	22.4	55.5	40.4	40.4	14.6	16.5	6.1	-
Mediterranean	57.7	14.5	19.7	19.7	56.4	15.2	8.5	-
Oceania	0.5	10.4	6.4	3.8	-	9.1	1.6	-
Oceans	-	-	-	2.8	-	-	-	23.6
World	3.1	1.0	-	0.4	26.2	21.1	62.6	76.4
Not specified	-	0.1	0.3*	-				

*no EU Countries

Table 6. Geographical distribution of CF and WF data sources as reported in level 1 of the database.

Potential applications of the database

The SEL database was created based on the necessity to estimate the CF and WF of food recipes for meals served in canteens during a set of experiments run in the framework of the EU Su-Eatable LIFE project aiming at engaging citizens on healthy and sustainable diets to reduce greenhouse gas emissions and water use in EU. During the experiments, researchers and canteen managers were faced with the problem of lacking a quick tool to calculate the food-related environmental impacts based on reliable and science-based estimates. The SU-eatable database was created with this purpose and the summary tables have been used for quick decision making of sustainable recipes and data management. Following this experience, the SU-eatable database would give a significant contribution to bridge the gap between the scientific knowledge provided by the scientific community and the actors of the food system. This historical moment sees a growing attention of the food providers and food consumers to improve the sustainability of food systems. The complexity and challenges of the climate mitigation policies, aiming to reduce greenhouse gases emissions, may find in dietary shift to more sustainable patterns an additional useful element to achieve the policy targets set out by the Paris agreement.

Many data related to the impact of food commodities circulate as public or private repositories or publications, ranging from complex scientific studies to online anonymous data. The complexity to extrapolate food commodity data from scientific publications and the necessity to evaluate robustness and scientific value of the data available to users requires from the scientific community and extra effort to provide both meaningful data and a scientific methodology for stakeholders from technical, scientific and policy sectors to easily implement and expand the database with a verified and scientifically sound approach. With its different layers of information, the SEL database could hence be a valid tool for to support caterers, chefs, restaurants, nutritionists, municipalities, policy makers, to analyse different management options related to food and dietary planning.

Database flexibility and directions for database improvement

The SEL database is not an exhaustive collection of CF and WF data for all the possible food items, although with the bibliographic search we have tried to cover the majority of accessible data sources. The way the database is structured offers the possibility to implement it in many ways.

1) Missing items can be included following the methodological framework proposed.

2) Items values and uncertainty can be implemented by adding new studies and re-evaluating the items and types of interest.
3) New evaluations can be done directly using single study data from level 1.
4) Technical and scientific users might like to make different assumption to further evaluate the uncertainty of specific items, in this case the clear and transparent description of the steps done to assign uncertainty labels allows to easily accept or reject any of the assumptions made in this paper and to implement the overall scheme making new attributions and decisions about the use of the items.
5) The additional information available for the geographic sources of each CF or WF data (level 1), might allow to implement the items list based on geographical regions while the proposed methodology would allow to check if by breaking down item data into subgroups the reliability of the new item values still stands.

2.3 Data Records

The SEL database is recorded in an Excel workbook called SUEATABLE_LIFE uploaded on Figshare (Petersson *et al*., 2019 b). It is composed of an introductory sheet to guide the users through the document plus 10 data sheets, 5 for the CF data analysis and 5 for the WF data analysis. The content of the 10 data sheets is here described. All the data analyses presented were done using the software STATA 14.2.

SEL CF (or WF) for USERS is a sheet that summarizes data in an easy-to-read form for expert and not expert users. It reports for each food item:

- the food group, the type and the sub-type corresponding to each item belongs (Table 2)
- the item value of CF (or WF) corresponding to the median CF (or WF) value reported for the same item in the SEL CF (or WF) ITEM STAT sheet.
- the level of uncertainty associated to the value of the item based on the three quality flags reported in the sheet SEL CF (or WF) ITEM STAT. The uncertainty associated to the ITEM footprint value is generically summarized as *high (H)* or *low (L)*.
- The suggestion for the optimal use of the data, namely if the items data is highly reliable or the uncertainty suggest to use a higher aggregation value.
- The alternative value of CF (or WF) that can be used for that specific item at higher level of aggregation (median of type or sub-type)

CF (or WF) DATA SOURCES: reports CF (or WF) values of food commodities collected from studies reported in the literature and screened using selection criteria, and harmonized to report the same functional unit and system boundary. Information provided in this sheet for each input line are: name of group, type, sub-type, item (Table 2), CF or WF value after extraction from the publication and harmonization, type of source (journal, book, conference, EPD), full reference, publication year, system boundary at distribution, country of production, region of production, relevant notes, presence of the same value in other data collections, additional post farm gate emissions, transport (T), slaughtering (S), packaging (P) or conversion factor applied (cf).

SEL CF (WF) ITEMS STAT: reports for each food item the following statistical data: number of item values considered for the analysis (n), mean, median, standard deviation (SD), minimum (Min) and maximum (Max) observed values, Median Absolute Deviation (MAD), first quartile (Q1) and third quartile (Q3), coefficient of variation (CV), skewness (SK), kurtosis (KU) and P value of the Shapiro-Wilk normality test. Additionally, it reports the colour assigned to each quality flag (Flag 1 "size", Flag 2 "outlier", Flag 3 "adherence to normality") and the suggested median value to be used on the basis of the scheme reported in Table 4. The statistical analysis for each item reported in this sheet is based on single data of CF (or WF) classified with that specific item entry name in the sheet SEL CF (or WF) DATA SOURCES.

SEL CF (or WF) TYPES: reports for each food type the following statistical data: number of item values (median) considered for the analysis (n), mean, median, standard deviation (SD), minimum (Min) and maximum (Max) observed values, Median Absolute Deviation (MAD), first quartile (Q1) and third quartile (Q3), coefficient of variation (CV), Interquartile Range (IQR), lower fence (LF) and upper fence (UF) for the estimate of outliers related to the specific type. The statistical analysis for each type reported in this sheet is based on median value of CF (or WF) of items classified under that specific type and reported in the sheet SEL CF (or WF) ITEM STAT.

SEL CF (or WF) sub-TYPES: reports for each food sub-type the following statistical data: number of item values (median) considered for the analysis (n), mean, median, standard deviation (SD), minimum (Min) and maximum (Max) observed values, Median Absolute Deviation (MAD), first quartile (Q1) and third quartile (Q3), coefficient of variation (CV), Interquartile Range (IQR), lower fence (LF) and upper fence (UF), capital letters indicating significant difference among sub-type medians within the same type group based on the output of Kruskal-Wallis ANOVA test on ranks and pairwise multiple comparison procedures based on Dunn's Method, significant differences between the sub-type reported in the raw and the type including the analysed sub-type based on the Mann-Whitney Rank Sum test is also reported.

2.4 Technical Validation

Given the high number of inputs and interconnected steps, each step was undertaken by at least two researchers. The literature review on LCA and WF studies followed the recommendations for collecting and synthesising relevant evidence reported in PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) by Moher *et al*. (2009) and recommendations for CF data handling reported in Clune *et al*. (2017).

To classify types and sub-types that might be biologically and agronomically sound we had the specific support of biologists and agronomists.

The clarity of the “summary for users’ page” was tested with stakeholders of the food communication sector.

Concerning the choice of quality flags to attribute uncertainty to item data .sample datas different options were evaluated and a group of scientific experts with different scientific background (statisticians, agronomists, biologist, ecologists) was involved for a final agreed choice.

To further support the correct choice of the attribution of uncertainty to each item based on the three flags, numerical data were supported by visual data of the distributions. Frequency distribution plots represented by adaptative kernel (gaussian) density estimates and box and whisker plots were evaluated for each data .sample data which did not provide immediate positive or negative evidence of reliability based on descriptive statistics and tests results.

Two examples of such visualization and the consequent choices are reported in Figures 7 and 8. Fig. 7 shows the empirical distribution of data .sample data of CF values POTATO item, characterized by three green flags. Both kernel density and box-plot confirm the low level of dispersion of the empirical data range, the high level of concentration of the values around the centre of the distribution and the low density on both tails. The shape of the density function and the distance in the box-plot between Q1, Q3 and the median confirm the empirical adherence of this distribution to the normal distribution, as emerged by the SW test

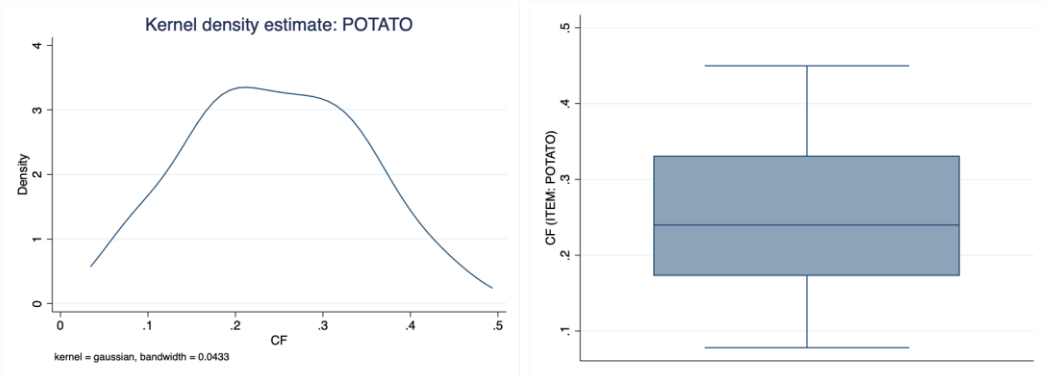

Figure 7. Kernel density estimate and box-plot of potato CF data. Empirical distribution for CF data of potato as reported in studies listed in Level 1 of the database (data analysis done with STATA 14.2).

Conversely, Fig. 8 shows the empirical distribution of the CF data .sample data for the item MAIZE characterized by the following flags: "yellow" for size, "green" for outliers and "red" for adherence to the normal distribution, which indicated a medium level of uncertainty. The number of data in the sample data (n=7) is sufficient to distinguish the mean value from the median value

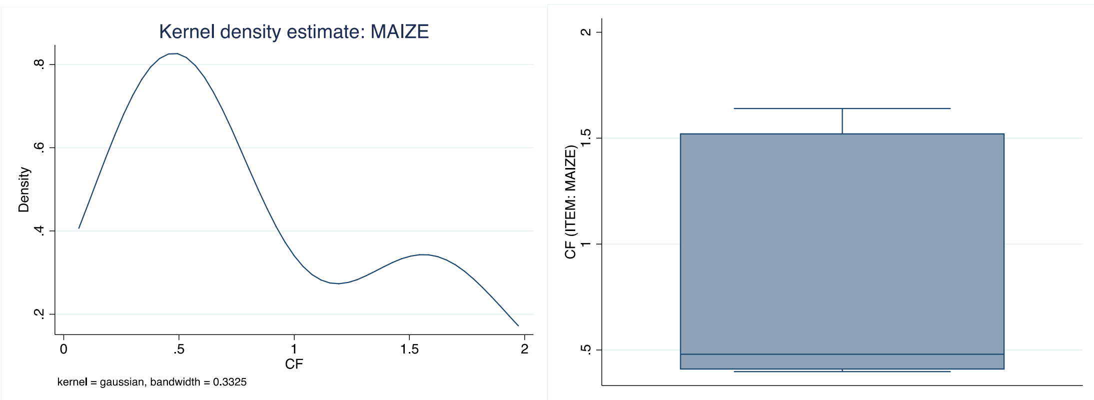

Figure 8. Kernel density estimate and box-plot for maize CF data. Empirical distribution for CF data of maize as reported in studies listed in Level 1 of the database (data analysis done with STATA 14.2).

but is not optimal to compute and evaluate variability and shape of the distribution (Flag 3). The graphic visualization of the data in this case supports the attribution of the colour to the Flag3. The strong asymmetry of the data distribution and the high level of overall and central variability, highlighted by the range and the Inter Quartile Range (IQR) of the box plot, confirm the median as the most suitable synthetic indicator of the data .sample data and confirm the choice of the red flag resulting from the results of the Shapiro Wilk test.

2.5 Usage Notes

Researchers and expert users can use any level of the database to extract information and can implement the database with additional data following the indications provided in this paper. Users that are not experts of data analysis can directly use the summary sheets 'SEL CF (or WF) data for users'. The sheet provides CF or WF values for a list of items. The users also immediately find in the same raw the CF (or WF) value of types and sub-types corresponding to each item. Each item brings a quality indication which refers to the reliability of the data they have in the table. When the user finds the indication that an ITEM value has high uncertainty it means that speculations about this item value need caution and should be supported by additional data. For these items the use of the type value might be more advisable. This could be the case for example of items represented by very few studies (1 or 2) or items represented by few studies (3, 4) with values very different from each other. If the users are looking for an item not included in the list, they can choose the median value of a type or sub-type, where it exists, of food commodity which they consider the closest to their missing object.

Users interested in using the methodological framework proposed or the derived data present in the manuscript are asked to cite this manuscript as well as the database DOI. Extraction of single studies from the study list reported in the database can directly refer to the original paper if no additional changes have been made in this database.

2.6 Author Contributions

C.S. and V.R. Conceived and designed the study strategy; C.S., P.T., S.L., designed the database; L.S. designed and performed the statistical analysis strategy with the support of C.S and P.T.; M.A. revised the food categories and provided support for agronomic data analysis; all the authors supported the literature searches and data collation; P.T. analysed the literature data for eligibility and carried out data harmonization followed by a second revision by C.S.; C.S., P.T., S.L carried out data calculations and data summary; C.S. took the lead in writing the paper with inputs and reviews from all contributing authors. All authors read, edited and approved the final manuscript.

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Competing interests

The authors declare no competing interests.

CHAPTER 3: THE GLOBAL WARMING POTENTIAL OF FOOD COMMODITIES: A REVIEW

This chapter aims at giving an overview of the GWP variability across foods as deriving from the values reported in the multilevel carbon footprint database of food commodities (Petersson *et al.*, 2021 b). For each food group, the level of carbon-intensity is determined as a tool to stir consumers towards sustainable dietary choices, thus allowing a reduction in the climate change impact of food systems through a top-down approach. Concurrently, we review the hot spots and the mitigation options of production systems that through a bottom-up approach may contribute to GHG-e reduction in the context of sustainable development.

All CF estimates are extracted from Petersson *et al.* (2021b) database, while hot spot and mitigation strategies for production processes are retrieved from the LCA studies inventory therein along with other reviewed studies.

3.1 Introduction

The dataset on GWP values of food items, as well as of sub-types, types, and groups thereof, represents thus far the widest open-source collection of estimates, based on a systematic review of LCA studies, of food's GHG-e throughout the food supply chain from production to distribution to Regional Distribution Centres (RDC). As described in detail in Chapter 2 of this thesis, the reliability of values was assessed through an innovative methodology aimed at detecting the level of uncertainty for each sample data, and is available for download on the Data Descriptor section of Nature Journal (Petersson *et al.,* 2021a). For the purposes of representing and comparing different foods, given that the median is not influenced by extreme values of the sample, we recommend the use of median values that are associated with a detected-low level of uncertainty. Researchers may access and use other summary statistics (e.g., mean, sd, min, max, 1° and 3° quartile, etc.) to describe the data for different purposes, observing caution when a high level of uncertainty is indicated. As commonly used in LCA studies, a mass-based functional unit (F.U) for CF or GWP was chosen: kg CO_2-eq/kg for food and kg CO_2-eq/litre for beverages that are packaged and transported to RDC. The present study groups foods and beverages within 4 hierarchical levels: items, sub-type, type, and group. The item is the most detailed level for aggregated data. Generally, the item name corresponds to common market definitions (i.e., carrots, wheat flour, mussels, chicken).

Group	N	Median	Min	Max	25%	75%	Anova on Ranks (P<0.001) *
Crops	117	**0.54**	0.15	7.35	0.32	0.88	**A**
Plant based processed	185	**1.36**	0.11	8.30	0.86	2.65	**B**
Animal based	46	**4.61**	0.73	71.94	3.25	8.86	**C**
Fish	64	**3.80**	0.46	20.25	2.14	6.97	**C**

Table 7. Kruskal-Wallis ANOVA test on ranks (all pairwise multiple comparison procedures based on Dunn's Method). * Significant differences were detected for P value <0.001. Different capital letters identify food groups statistically different. Values are expressed as kg CO_2-eq/kg. The letter N identifies the sample data size i.e., the number of food items comprised for which the median value was selected for this analysis.

The level of detail proposed depends on the available data source. The food sub-type is an additional hierarchal level nested in turn within one of the three food types (vegetables, fruit, shellfish) that feature a large variation of items (i.e., the type "shellfish" includes the sub-types crustacean, bivalves and cephalopods). The type is the result of grouping food items with similar biological or commercial characteristics (i.e., carrots belong to the type 'vegetables open field'; wheat flour to 'grain flour', mussels to 'shellfish', with the type 'chicken bone free-meat' including chicken-bone free meat as its unique item). Note that not every food type includes sub-types. The highest level of aggregation is represented by the 4 food groups: crops, agricultural processed, animal husbandry, and fishing. The crop group shows the lowest median CF value per kg or litre of food or beverage (0.54 kg CO_2-eq/kg), followed by agricultural processed (1.36 kg CO_2-eq/kg), fishing (3.80 kg CO_2-eq/kg) and animal husbandry (4.61 kg CO_2-eq/kg). For these food groups the output of the Kruskal-Wallis ANOVA test on ranks (all pairwise multiple comparison procedures based on Dunn's Method) is shown in Table 7 (above). For this analysis, the sample data was summarised by selecting the median values of all food items comprised within a specific food group.

Table 8 describes the symbols used for all tables in the present and following chapter.

symbol	name	description
n	numerosity	Number of data entries
$\bar{x}$	mean	Mean value of the sample data
Me	median	50^{th} percentile of the distribution
sd	standard deviation	Dispersion of the dataset relative to its mean
min	minimum	Minimum value of the distribution
max	maximum	Maximum value of the distribution
mad	median absolute deviation	Dispersion of the dataset relative to its median
25%	first quartile	25^{th} empirical quartile
75%	third quartile	75^{th} empirical quartile
cv	coefficient of variation	Relative standard deviation
IQR	interquartile range	Difference between the first and third quartile
LF	lower fence	Lower limit of the dataset, out of which values are defined as outliers
UF	upper fence	Upper limit of the dataset, out of which values are defined as outlier
S.V	Suggested value	Suggested value resulting from the uncertainty analysis

Table 8. Legend for all tables

Table 9. Descriptive statistics for Crop types and sub-types

kg CO_2 eq/ kg or litre food commodity

FOOD TYPE	n	x̄	Me	sd	min	max	MAD	25%	75%	CV	IQR	L.F	U.F
COFFEE GREEN*	8	0.49	0.49	0.14	0.29	0.71	0.09	0.4	0.55	0.28	0.15	0.16	0.78
DRIED FRUIT	3	1.07	0.81	0.52	0.6	1.8	0.21	0.71	1.31	0.49	0.6	-0.2	2.21
FRUIT HEATED GREENHOUSE	3	4.22	2.88	2.22	2.43	7.35	0.45	2.66	5.12	0.53	2.46	-1	8.81
FRUIT IMPORTED	7	1.14	1.07	0.56	0.55	2.43	0.23	0.83	1.13	0.5	0.3	0.38	1.58
FRUIT NOT HEATED GREENHOUSE [1]	4	1.41	1.43	0.11	1.24	1.55	0.06	1.38	1.46	0.08	0.08	1.26	1.58
FRUIT OPENFIELD	34	0.46	0.4	0.21	0.22	1.1	0.12	0.3	0.59	0.45	0.3	-0.2	1.04
citrus fruit (sub-type)	6	0.34	0.34	0.1	0.22	0.51	0.09	0.24	0.4	0.31	0.15	0.02	0.62
fruit (excluded other sub types) (sub-type)	13	0.43	0.32	0.23	0.26	1.1	0.06	0.27	0.49	0.53	0.21	-0	0.81
olives* (sub-type)	9	0.59	0.64	0.2	0.22	0.85	0.05	0.61	0.68	0.34	0.56	-0.2	1.52
wild berries (sub-type)	7	0.68	0.64	0.14	0.42	0.87	0.14	0.62	0.81	0.21	0.48	-0.1	1.53
GRAINS	7	0.63	0.57	0.2	0.38	0.97	0.1	0.48	0.76	0.32	0.28	0.06	1.19
LEGUMES	7	0.61	0.52	0.2	0.43	1.03	0.07	0.47	0.68	0.33	0.21	0.15	1
LEGUMES NOT HEATED GREENHOUSE [2]	4	0.31	0.28	0.08	0.24	0.43	0.03	0.24	0.34	0.25	0.1	0.1	0.48
MUSHROOMS*	6	1.78	2.06	1.09	0.2	3.09	0.86	0.82	2.64	0.61	1.82	-1.9	5.36
NUTS	9	1.17	1.11	0.56	0.44	2.06	0.49	0.8	1.6	0.48	0.8	-0.4	2.8
RICE*	35	2.54	2.19	1.44	0.24	6.45	0.74	1.65	3.08	0.57	1.44	-0.5	5.23
SEEDS	3	0.94	0.88	0.16	0.78	1.16	0.1	0.83	1.02	0.17	0.19	0.55	1.3
SPICIES	2	0.84	0.84	0.04	0.8	0.88	0.04	0.82	0.86	0.05	0.04	0.76	0.92
STARCHY TUBERS	3	0.27	0.27	0.02	0.24	0.29	0.02	0.26	0.28	0.08	0.03	0.22	0.32
VEGETABLES HEATED GREENHOUSE	5	2.7	2.55	0.55	2.12	3.73	0.12	2.43	2.67	0.2	0.25	2.06	3.04
VEGETABLES NOT HEATED GREENHOUSE	5	1.41	1.18	0.88	0.32	2.9	0.6	0.91	1.77	0.62	0.86	-0.4	3.07
VEGETABLES OPENFIELD	24	0.39	0.33	0.18	0.15	0.83	0.1	0.24	0.49	0.48	0.26	-0.2	0.88
asparagus* (sub-typ)	33	0.97	0.83	0.48	0.38	2.68	0.22	0.63	1.14	0.5	0.41	0.01	1.76
green leafy vegetables (sub-typ)	3	0.33	0.34	0.07	0.23	0.41	0.07	0.29	0.37	0.22	0.21	-0	0.7
roots & bulbs (sub-typ)	7	0.31	0.25	0.17	0.15	0.71	0.05	0.23	0.32	0.54	0.18	-0.1	0.6
vegetables (fruits, steems, flowers) (sub-typ)	12	0.39	0.33	0.17	0.19	0.7	0.12	0.26	0.5	0.42	0.14	0.05	0.71

A star (*) is assigned to types whose sample data coincides with the data of a specific food item as the only member of the corresponding type. [1]Values refer only to melons; [2]Values refer only to green beans.

Table 10. Descriptive statistics for Agricultural processed types

kg CO_2 eq/ kg or litre food commodity

FOOD TYPE	n	x̄	Me	sd	min	max	mad	25%	75%	cv	IQR	L.F	U.F
FRUIT JUICE LOCAL	2	0.48	0.48	0.01	0.46	0.49	0.01	0.47	0.48	0.03	0.01	0.45	0.51
BOTTLED WATER* (mineral water)	2	0.49	0.49	0.07	0.42	0.56	0.07	0.46	0.53	0.14	0.07	0.35	0.63
YEAST LIQUID*	1	0.50	0.50	-	0.50	0.50	-	0.50	0.50	-	-	0.50	0.50
VEGETAL MILK	4	0.57	0.54	0.16	0.41	0.78	0.12	0.42	0.69	0.28	0.27	0.01	1.10
COFFEE LIQUID	3	0.49	0.55	0.12	0.33	0.60	0.05	0.44	0.57	0.24	0.13	0.24	0.77
WINE	2	0.66	0.66	0.21	0.44	0.87	0.21	0.55	0.77	0.33	0.21	0.23	1.09
BEER	3	0.73	0.69	0.18	0.53	0.96	0.16	0.61	0.83	0.24	0.21	0.29	1.15
LEGUMES CANNED	2	0.78	0.78	0.67	0.11	1.45	0.67	0.44	1.11	0.86	0.67	-0.56	2.12
SUGAR	2	0.78	0.78	0.16	0.62	0.94	0.16	0.70	0.86	0.21	0.16	0.46	1.10
VEGETABLES FROZEN	2	0.81	0.81	0.54	0.27	1.35	0.54	0.54	1.08	0.67	0.54	-0.27	1.89
YEAST COMPRESSED*	1	0.82	0.82	-	0.82	0.82	-	0.82	0.82	-	-	0.82	0.82
BREAD**	16	0.88	0.86	0.24	0.54	1.54	0.08	0.77	0.92	0.27	0.15	0.54	1.15
GRAIN FLOUR	9	0.96	0.87	0.52	0.36	1.96	0.44	0.47	1.33	0.54	0.86	-0.82	2.62
CRACKERS**	29	1.06	0.98	0.28	0.49	1.45	0.27	0.90	1.33	0.27	0.43	0.26	1.97
FRUIT FROZEN* (raspberry)	1	1.18	1.18	-	1.18	1.18	-	1.18	1.18	-	-	1.18	1.18
TOMATO SAUCE	2	1.19	1.19	0.05	1.14	1.24	0.05	1.17	1.22	0.04	0.05	1.09	1.30
PASTA*	48	1.24	1.21	0.44	0.55	2.30	0.33	0.87	1.50	0.35	0.63	-0.08	2.45
TOMATO PUREE, PEELED, CHOPPED	3	1.27	1.30	0.18	1.03	1.47	0.17	1.17	1.39	0.14	0.22	0.83	1.72
BREAD FROZEN* (rolls)	1	1.31	1.31	-	1.31	1.31	-	1.31	1.31	-	-	1.31	1.31
LEGUME FLOUR	3	1.14	1.32	0.38	0.62	1.49	0.17	0.97	1.41	0.33	0.44	0.32	2.06
CRISPBREAD**	6	1.36	1.35	0.11	1.19	1.53	0.08	1.30	1.45	0.08	0.15	1.08	1.67
VEGETAL YOGURT* (soy yogurt)	1	1.36	1.36	-	1.36	1.36	-	1.36	1.36	-	-	1.36	1.36
MARGARINE*	6	1.43	1.39	0.24	1.10	1.80	0.21	1.26	1.61	0.17	0.35	0.74	2.14
DRESSING	3	1.53	1.46	0.39	1.10	2.04	0.36	1.28	1.75	0.25	0.47	0.58	2.46
BISCUITS**	21	1.58	1.47	0.38	1.11	2.39	0.14	1.35	1.63	0.24	0.28	0.93	2.04
VEGETABLES CANNED	2	1.48	1.48	0.12	1.36	1.60	0.12	1.42	1.54	0.08	0.12	1.23	1.72
VEGETAL CREAM* (soy cream)	1	1.62	1.62	-	1.62	1.62	-	1.62	1.62	-	-	1.62	1.62
NUTS PASTE	5	2.07	1.84	0.68	1.15	2.98	0.69	1.69	2.71	0.33	1.03	0.15	4.25
SWEETS**	23	2.13	1.99	0.39	1.45	3.09	0.25	1.93	2.44	0.19	0.51	1.16	3.20
OIL	6	2.19	2.11	0.76	0.98	3.27	0.56	1.79	2.78	0.35	0.99	0.29	4.27
LEGUMES FROZEN	2	2.26	2.26	0.49	1.77	2.74	0.49	2.01	2.50	0.22	0.49	1.28	3.23
VEGETAL PROTEINS	3	2.08	2.27	0.44	1.48	2.50	0.23	1.88	2.39	0.21	0.51	1.11	3.15
BREAKFAST CEREALS* (cornflakes)	1	2.64	2.64	0.00	2.64	2.64	0.00	2.64	2.64	0.00	0.00	2.64	2.64
PESTO SAUCE	2	2.72	2.72	0.00	2.71	2.72	0.00	2.71	2.72	0.00	0.00	2.71	2.72
FRUIT JUICE (imported ingredients)	8	2.70	2.86	0.63	1.07	3.20	0.09	2.83	2.97	0.23	0.15	2.61	3.19
EGG PASTA*	5	3.19	3.15	0.77	2.41	4.55	0.64	2.51	3.33	0.24	0.83	1.27	4.57
CHOCOLATE	2	3.16	3.16	0.45	2.71	3.60	0.45	2.93	3.38	0.14	0.45	2.27	4.05
YEAST DRIED*	1	3.29	3.29	-	3.29	3.29	-	3.29	3.29	-	-	3.29	3.29
NUTS COVERED WITH CHOCOLATE	2	4.12	4.12	0.69	3.43	4.80	0.69	3.77	4.46	0.17	0.69	2.75	5.49
ICE CREAM	3	3.97	4.30	2.29	1.02	6.60	2.30	2.66	5.45	0.58	2.79	-1.53	9.64
COFFEE GROUND & PARCHMENT	2	6.71	6.71	1.58	5.13	8.29	1.58	5.92	7.50	0.24	1.58	3.55	9.87

A star (*) is assigned to types whose sample data coincides with the data of a specific food item as the only member of the corresponding type. Two stars (**) are given to items that comprise a further level of disaggregated data.

Table 11. Descriptive statistics for animal husbandry types

kg CO_2 eq/ kg or litre food commodity

FOOD TYPE	n	$\bar{x}$	Me	sd	min	max	mad	25%	75%	cv	IQR	L.F	U.F
SNAILS*	1	0.73	0.73	-	0.73	0.73	-	0.73	0.73	-	-	0.73	0.73
MILK	3	2.10	1.44	1.04	1.31	3.57	0.13	1.37	2.50	0.49	1.13	-0.33	4.20
HONEY*	2	1.74	1.74	0.81	0.94	2.55	0.81	1.34	2.15	0.46	0.81	0.13	3.36
YOGURT	38	2.47	2.55	0.87	1.17	4.07	0.80	1.67	2.93	0.35	1.26	-0.23	4.82
EDIBLE INSECTS*	1	2.84	2.84	-	2.84	2.84	-	2.84	2.84	-	-	2.84	2.84
EGGS*	51	3.23	3.20	1.22	0.72	6.00	0.85	2.24	4.04	0.38	1.80	-0.47	6.74
POULTRY BONE FREE MEAT	4	3.34	3.88	1.08	1.50	4.10	0.21	3.13	4.09	0.32	0.96	1.70	5.52
KANGAROO*	1	4.10	4.10	-	4.10	4.10	-	4.10	4.10	-	-	4.10	4.10
RABBIT MEAT WITH BONE*	2	4.31	4.31	1.28	3.03	5.58	1.28	3.67	4.94	0.30	1.28	1.76	6.86
CHEESE FRESH	5	5.53	5.45	1.55	3.40	8.20	0.53	4.92	5.70	0.28	0.78	3.75	6.87
PORK BONE FREE MEAT*	135	5.79	5.72	1.69	2.11	11.86	1.14	4.48	6.59	0.29	2.11	1.30	9.76
PORK CURED MEAT	4	8.48	5.99	5.69	4.03	17.94	1.96	4.03	10.44	0.67	6.42	-5.60	20.07
BUTTER*	11	9.90	8.48	6.66	1.05	25.00	1.24	7.22	9.55	0.67	2.33	3.73	13.05
CHEESE HARD & SEMI-HARD	10	10.82	9.59	3.10	7.55	17.15	1.50	8.42	12.21	0.29	3.78	2.75	17.88
LAMB BONE FREE MEAT*	55	27.21	25.23	11.73	10.05	56.70	8.53	17.12	34.44	0.43	17.32	-8.86	60.42
BEEF BONE FREE MEAT*	183	27.72	25.75	12.72	2.27	109.35	4.28	21.84	31.00	0.46	9.16	8.11	44.73
BUFFALO BONE FREE MEAT*	3	71.39	78.80	11.95	54.53	80.85	2.05	66.67	79.82	0.17	13.16	46.93	99.56

A star (*) is assigned to types whose sample data coincides with the data of a specific food item as the only member of the corresponding type.

Table 12. Descriptive statistics for fishing types and sub-types

kg CO_2 eq/ kg or litre food commodity

FOOD TYPE	n	$\bar{x}$	Me	sd	min	max	mad	25%	75%	cv	IQR	L.F	U.F
FISH	34	5.97	5.19	3.95	0.82	14.51	2.58	3.09	8.31	0.66	5.22	-4.75	16.15
FISH FROZEN	12	3.19	2.2	3.51	0.9	14.28	1.03	1.23	3.2	1.1	1.97	-1.72	6.15
FISH PROCESSED	4	1.85	2.12	0.48	1.02	2.14	0.02	1.83	2.14	0.26	0.31	1.36	2.61
SHELLFISH FROZEN	2	11.47	11.47	3.59	7.88	15.07	3.59	9.68	13.27	0.31	3.59	4.29	18.66
SHELLFISH	8	6.67	5.67	5.56	0.46	20.25	1.31	4.36	6.94	0.83	2.58	0.49	10.81
bivalves* (sub-type)	7	0.94	0.46	0.86	0.12	2.54	0.35	0.33	1.39	0.92	1.06	-1.26	2.98
cephalopod (sub-type)	3	5.92	5.8	0.76	5.05	6.91	0.75	5.43	6.36	0.13	0.93	4.03	7.75
crustacean* (sub-type)	18	11.95	7.04	10.42	2.89	38	3.25	5.24	16.78	0.87	11.53	-12.1	34.07

A star (*) is assigned to types whose sample data coincides with the data of a specific food item as the only member of the corresponding type.

3.2 Fish

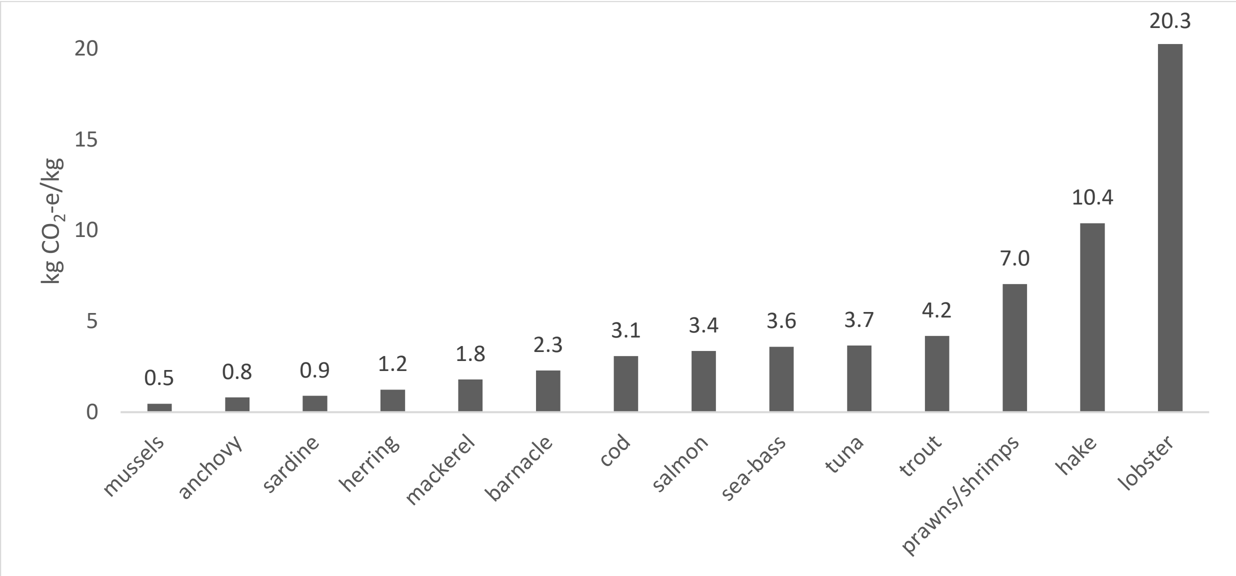
Sustainable aquaculture and fisheries are often linked to the concept of healthy and sustainable food systems. This is due to the well-documented preventive action on human health (Thilsted *et al*., 2015) exerted by the content of Ω-3 essential fatty acids -also known as polyunsaturated fatty acids n-3 (PUFA)- and to the lower environmental impact of aquaculture and fisheries compared to land animal farms (Clune *et al*., 2017). We reviewed 77 LCA studies resulting in 263 GWP values for 64 food items: (n=34) belonging to fish type, (n= 6) to shellfish, (n=2) to processed shellfish, (n=16) to frozen fish, (n=4) to processed fish. We further disaggregated data for the shellfish type into 3 sub-types: crustacean (n=3), bivalves (n=1) and cephalopods (n=3). We found 23 items associated with highly reliable median values, while 38 items were characterized by a high level of uncertainty: with regard to the latter, additional LCA should be performed to better understand the impact that their production has on climate change.

Mussels (Mytilus sp.), belonging to the shellfish type and bivalve's sub-type, emerge as the least carbon-intensive food with 0.46 kg CO_2-eq/kg median value, in turn calculated from 7 values reported for European extensive aquaculture farms or fisheries. In this respect, we found no significant differences in GWP values between wild-caught and farmed fish, since molluscan shellfish aquaculture does not require supplementary feed - the latter being identified as hot spot in aquaculture operations - due to the capability of Mytilus sp. to filter nutrient substances directly from seawater. Moreover, due to minimal chemical input (Tamburini *et al*., 2020), the environmental impact of their production per unit of protein is the lowest among all fish products with regard both to climate change and other impact categories.

Within the fish type, low GWP median values were detected for small to medium-sized pelagic wild caught fishes, such as anchovy, sardine, herring and mackerel, all of which belong to oily fish species with high content of PUFAs.

Anchovy data analysis reveals a small difference between mean (0.81 kg CO_2-eq/kg) and median value (0.82 kg CO_2-eq/kg), an overall low variability and values adhering to a normal distribution. 5 values were extracted from Peruvian industrial anchoveta fleets (Freon *et al*., 2014) and 1 for European fishery (Laso *et al*., 2018).

The 3 LCA studies on sardine (*Sardinia pilchardus*), also known as pilchard, targeted Spanish and Portuguese coastal purse seining fisheries. Almeinda *et al.* (2014) reports an average CF of 0.36



Graph 1. CF median values of fresh food commodities belonging to shellfish and fish types. Only CF values for which a low level of uncertainty was detected are represented.

kg CO_2-eq/kg for landed sardine for Portuguese fisheries; Iribarren (2010) research provides the value of 0.74 kg CO_2-eq/kg for coastal fishing activity in Galicia; while Vázquez-Rowe *et al* (2012) performed climate change impact analysis for different fishing methods and catch areas with the inclusion of discard rates: the lowest value (0.80 kg CO_2-eq/kg) was found for costal purse seining while the highest one for coastal trawling (2.28 kg CO_2-eq/kg).

All LCA studies targeting wild herring derive from N-Europe fisheries. For fresh unprocessed herring, low values were detected both by Blonk *et al* (2008) and the Danish LCA food database (www.lcafood.dk)

Schmidt, J. (2014) performed a LCA for pickled herring, including processing, transport to a wholesaler and retailer activities. The high GWP found (4.40) reflects these downstream stages, since fishing activities amounted to only 1.42 kg CO_2-eq/kg for landed fish. A similar study was conducted by Buchspies *et al*. (2011) who reported 4.55 for canned herring (including transport to Swiss retail), but only 0.47 kg CO_2-eq/kg for landed fish.

The analyses for mackerel production were performed by reviewing 8 European studies including both Atlantic mackerel (*Scomber scombrus*) and Atlantic horse mackerel (*Trachurus trachurus*) for a total of 23 GWP values ranging between 0.25 and 5.45 kg CO_2 eq/kg.

Ramos and colleagues (2011) collected data for over 8 years for Atlantic mackerel (*Scomber scombrus*) from Basque costal fisheries with purse seining fleets in order to analyse the effect of stock abundance variations on environmental burdens. In fact, stock abundance for North-East Atlantic Mackerel was inversely related to GWP (along with other impact category values), with mean values per year ranging between 0.095 and 0.445 kg CO_2 eq/kg for landed mackerel. These

results are comparable to those highlighted by Iribarren for pilchard (2010) and by Vázquez-Rowe *et al* (2010) for horse mackerel: the best performance in terms of carbon emissions was found for purse-seining fleets as opposed to coastal bottom trawling fleets (24-fold lower emissions).
On the contrary, bigger pelagic fishes such as tuna display 2-fold the GWP value of the highest small pelagic ones (mackerel), although a high variability was found among the 6 values for tuna fisheries. Irribarren provides 1.39, 1.56, and 1.89 kg CO_2 eq/kg for Indian Ocean, Atlantic Ocean and Pacific Ocean wild catch tuna fisheries (respectively), and 6.32 for Galician fisheries. The variability of GWP for different blue fishes seems to be partially related to the coastal distance of catching areas and thus to the emissions from fuel combustion that are generated.
For salmon we analysed 14 studies from which we were able to extract 26 CF values: 50% from North Europe fisheries and aquaculture, 38% from North America farming systems, and the remaining equally retrieved from Oceania, South America and World estimates. The 2-tailed T-test ($p>0,05$) with $\alpha=0.05$ resulted in no differences between the sample data of major geographical areas of production (N-America and N-Europe) nor between farmed and wild sample data, regardless of the geographical area of production, although Winther *et al*. (2009) observed higher GWP values for wild salmon (mean value: 4.41 kg CO_2-eq/kg) compared to farmed salmon (mean value: 3.8 kg CO_2-eq/kg).
For goose barnacle (*Pollicipes pollicipes*) we reviewed one Spanish study reporting 6 CF values Vázquez-Rowe *et al*., 2013). This little-known marine pedunculate cirripedes lives on rocky off-shores of the Atlantic Ocean and is commonly sold in the Spanish market, being considered a top seafood attraction in first-class restaurants. Since rocks represent their preferred ecological niche, they can be accessed both by land or sea. The study demonstrated large variation in GWP values depending on the selected means of transport for barnacle recollection: barnacles harvested by fishermen on foot ranged between 0.78 and 1.29 kg CO_2-eq/kg while marine capture by vessel ranged between 3.3 and 11.7 kg CO_2-eq/kg.
Within wild-caught demersal species, high GWP values have been attributed by different Spanish studies to hake (*Merluccius merluccius*), with a median value of 10.4 kg CO_2-eq/kg for hake packaged and delivered to RDC (Iribarren *et al*., 2010; Vázquez-Rowe *et al*., 2011, Vázquez-Rowe *et al* 2012). In fact, demersal species (e.g., hake, megrim, anglerfish, pomfret and conger eel) are captured mainly by trawling and long lining fishing gears with higher fuel use intensities. Hake and cod are both white fish having similar flavour and flesh texture with the difference that cod's median CF value is 3-fold lower than hake's value. In particular we found 10 CF values reported in LCA studies, primarily conducted in North Europe, ranging from 1.25 to 5.88 kg CO_2-eq/kg with a median value of 3,08 and a maximum attributed to Senegalese fisheries.

Studies for trout and seabass are derived primarily from aquaculture, thus showing a medium-to-high CF value per F.U, but still below the median CF value of fishing type (5.19) due to the GWP entailed by feed production, which, as highlighted by Pelletier and Tyedmers (2008), is higher when feed sources include animal-based ingredients and lower when these are replaced by plant-based proteins. The aforementioned authors demonstrated that a 50% reduction of the environmental impact associated with feed may be achieved by replacing 25% of fishmeal with soy meal and all fish oil with canola oil (Pelletier and Tyedmers, 2007). In general, life cycle research suggests that aquaculture feed often accounts for the majority of the environmental impact (Pelletier and Tyedmers, 2008). The lowest climate change impact for farmed seabass, corresponding to 1.9 Kg CO_2-eq/Kg, was found for Tunisian aquaculture farms (Jerbi *et al.*, 2012), and the highest for France (Aubin *et al.*, 2009).

On the opposite side of the ranking values, lobster production and distribution to RCD stands out as the most carbon-intensive seafood with a median value of 20.25 kg CO_2 eq/kg. Five values were encountered in the literature, ranging from 7.72 kg CO_2-eq/kg for lobster caught along the Swedish west coast by creels and conventional trawls (Ziegler & Valentinsson, 2008) up to 28.30 kg CO_2 eq/kg reported by a LCA for Galician fishing activity with economic allocation (Iribarren *et al.*, 2010). Other seafoods within the crustacean taxon exhibit relatively high values such as prawns and shrimps (median: 7.04 kg CO_2 eq/kg, calculated from 18 GWP values). Within prawns LCA studies, the lowest value was extracted from Cao *et al.* (2001) for Chinese semi-intensive farming systems targeting domestic markets, with the value for Chinese intensive aquaculture systems for export being twice as high. The maximum climate change impact (38 kg CO_2-eq/kg) was found for wild prawns from industrial trawl fisheries in Senegal, (Ziegler *et al.*, 2009), while the minimum, corresponding to artisanal fisheries, was 5 times lower than that (7.8 kg CO_2-eq/kg). For both fishing systems, the GWP included freezing, packaging and sea transport to Spain.

LCA studies on Octopus, Squid and Cuttlefish are scarcely represented and were conduct for Spanish fishing activities (Iribarren *et al.*, 2010;Vázquez-Rowe *et al.,* 2012). Although Statistics for these food commodities are highly uncertain, we found median values ranging from 5.05 to 6.91 kg CO_2-eq/kg. We recommend the use of the median value of the sub-type Cephalopods (5.80 kg CO_2-eq/kg) until new studies are published.

3.2.1 Mitigation options

We point out that climate pressure exerted by seafood production depends on fishing gears, fuel consumption, mass of landed fish and targeted species for wild-caught fish, while it depends primarily on feed composition for farmed fish. For aquaculture, the best mitigation option is to substitute animal/fish ingredients in fish feed with plant-based ingredients, whereby doing so may halve the CF of feed (Pelletier and Tyedmers, 2007, 2008).

Our analyses highlight how wild-caught fisheries targeting small schooling fishes (such as anchovy, sardine, herring and mackerel) are the least carbon-intensive, while crustacean targeting fisheries are the most carbon-intensive per tonne of landed fish. These findings are in line with results reported by Tyedmers (2015): fisheries targeting small pelagic species are amongst the most energy- and carbon-efficient forms of protein production, while the opposite is true for high-value crustacean fisheries.

In particular, the lowest fuel use intensity (FUI) values were found for fisheries targeting Atlantic herring in Iceland and Peruvian anchovy in Chile, and the highest for fisheries targeting lobster and shrimps.

From a carbon footprint perspective, fishing activities show high sustainability when wild-catch, high catch rates and low fuel intensity use (FUI) criteria are met.

Extensive farming systems targeting mussels with no supplementary feed and costal purse seining fisheries targeting small pelagic oily fishes (anchovy, sardine, herring, Atlantic mackerel, horse mackerel) where identified by the present systematic review as the least carbon-intensive activities within the fishing industry. These high-quality protein-sources may be emphasized in omnivorous or pescatarian sustainable and healthy diets, while consumption of lobster, prawns and hake should be discouraged given that production of the latter heavily exceeds sustainable CF burdens with a GWP comparable to that of hard cheese and ruminant meet.

Replacing ruminant source proteins with seafood from sustainable fisheries/aquaculture could reduce environmental burdens and enhance health benefits, particularly if beef and sheep are replaced with small pelagic fishes and bivalves.

Table 13. Descriptive statistics for fish and shellfish items

		kg CO_2 eq/ kg or litre food commodity									
FISH ITEM	**n**	**$\bar{x}$**	**Me**	**sd**	**min**	**max**	**mad**	**25%**	**75%**	**cv**	**S.V**
anchovy	6	0.81	0.82	0.03	0.77	0.86	0.02	0.79	0.83	0.04	I
sardine	5	0.9	0.9	0.3	0.5	1.41	0.12	0.78	0.92	0.33	I
herring	6	2.21	1.24	1.63	0.66	4.55	0.35	1.12	3.68	0.74	I
pollock	2	1.4	1.4	0.2	1.2	1.6	0.2	1.3	1.5	0.14	T
carp	3	1.8	1.76	0.09	1.73	1.93	0.04	1.74	1.84	0.05	T
mackerel	23	2.05	1.8	1.31	0.25	5.45	0.67	1.2	2.43	0.64	I
flathead	3	2.45	2.56	0.9	1.3	3.5	0.94	1.93	3.03	0.37	T
whiting	2	2.66	2.66	1.12	1.54	3.79	1.12	2.1	3.22	0.42	T
cod	22	3.29	3.08	1.36	1.25	5.88	1.05	2.27	4.38	0.41	I
haddock	3	3.25	3.1	0.44	2.8	3.84	0.3	2.95	3.47	0.13	T
salmon	26	3.8	3.37	1.87	1.11	8.88	0.82	2.59	4.05	0.49	I
alfonsino	1	3.49	3.49	-	3.49	3.49	-	3.49	3.49	-	T
sea-bass	5	3.59	3.6	1.26	1.91	5.76	0.66	2.94	3.74	0.35	I
tuna	6	4.68	3.68	3.59	1.39	11.44	2.2	1.64	6.11	0.77	I
eel	1	3.88	3.88	-	3.88	3.88	-	3.88	3.88	-	T
trout	21	3.65	4.2	1.14	1.37	5.95	0.34	3.02	4.3	0.31	I
fish mixed	6	4.01	4.99	2.11	0.27	6.22	0.86	2.75	5.45	0.53	I
sole	2	5.4	5.4	2.05	3.35	7.45	2.05	4.38	6.43	0.38	T
diamond fish	3	7.56	6.02	2.18	6.02	10.65	0	6.02	8.33	0.29	T
plaice	1	6.13	6.13	-	6.13	6.13	-	6.13	6.13	-	T
flatfish	2	6.41	6.41	5.21	1.2	11.61	5.21	3.8	9.01	0.81	T
ling	2	6.45	6.45	3.32	3.13	9.77	3.32	4.79	8.11	0.51	T
pomfret	2	6.63	6.63	3.14	3.49	9.77	3.14	5.06	8.2	0.47	T
rock fish	1	6.94	6.94	-	6.94	6.94	-	6.94	6.94	-	T
fork beard	2	8.01	8.01	1.76	6.25	9.77	1.76	7.13	8.89	0.22	T
rhombus	1	8.41	8.41	-	8.41	8.41	-	8.41	8.41	-	T
catfish	1	8.93	8.93	-	8.93	8.93	-	8.93	8.93	-	T
hake	6	10.12	10.4	2.52	6.88	14.15	2.18	7.88	11.47	0.25	I
porbeagle	1	11.44	11.44	-	11.44	11.44	-	11.44	11.44	-	T
shark	3	10.09	11.44	1.99	7.28	11.56	0.12	9.36	11.5	0.2	T
anglerfish	2	12.29	12.29	1.86	10.43	14.15	1.86	11.36	13.22	0.15	T
swardfish	2	12.84	12.84	1.4	11.44	14.24	1.4	12.14	13.54	0.11	T
megrim	1	14.15	14.15	-	14.15	14.15	-	14.15	14.15	-	T
turbot	2	14.51	14.51	4.89	9.63	19.4	4.89	12.07	16.96	0.34	T
SHELLFISH ITEM											
mussels	7	0.94	0.46	0.86	0.12	2.54	0.35	0.33	1.39	0.92	I
barnacle	6	4.32	2.3	4.08	0.78	11.68	1.38	1.11	6.7	0.94	I
cuttlefish	2	5.05	5.05	1.34	3.71	6.39	1.34	4.38	5.72	0.27	T
krill	1	5.54	5.54	-	5.54	5.54	-	5.54	5.54	-	T
octopus	2	5.8	5.8	1.55	4.25	7.35	1.55	5.03	6.58	0.27	T
squid	3	7.51	6.91	3.14	4	11.61	2.91	5.46	9.26	0.42	I or T
prawns/shrimps	18	11.95	7.04	10.42	2.89	38	3.25	5.24	16.78	0.87	I
lobster	5	19.3	20.25	8.19	7.72	28.3	7.81	12.44	27.8	0.42	I

3.3 Animal husbandry

The livestock sector, which includes meat, dairy and eggs, is a major contributor to climate change with roughly 7.1 gigatonnes of CO_2-eq per year, accounting globally for 14,5%-18% of anthropogenic GHG emissions (Gerber *et al*., 2013, Steinfeld *et al*. 2006; FAO, 2017 b). According to GLEAM data (FAO, 2017c), the four main processes involved in livestock supply chains emissions are enteric fermentation (44%), feed production (41%), manure management (10%) and energy use (5%). Methane accounts for approximatively half of the emissions, with the remaining share equally distributed between nitrous oxide and carbon dioxide.

As highlighted by the Intergovernmental Panel on Climate Change and by the Eat Lancet Commission, a drastic decrease both of production and consumption of animal products is urgently required as an important climate change mitigation strategy in the food sector. Yet, meat and dairy constitute the principal source of highly valuable proteins in dietary patterns (Pereira and Vincente., 2013); thus, mitigation options for sustainable livestock production must be identified by researchers and incentivized by policy makers. Meat consumption has tripled over the past 50 years (Ritchie, and Roser, 2017) with negative outcomes both on human and planet health (Willet *et al*., 2019) – a circumstance providing the theoretical underpinning for win-win opportunities for dietary shift in high-income countries, where highly valuable vegetal protein sources can easily replace animal derived products while still ensuring adequate nutrient and protein intake.

In this chapter we analyse the differences in GWP between and within different animal-derived food products, with the aim of identifying those foods or production methods that should be favoured towards achieving a more sustainable and healthy diet.

A systematic review of 344 LCA studies related to the animal husbandry food group produced 1530 CF values referring to 46 food items belonging to 21 food types.

3.3.1 Ruminant meat

Ruminant species account for 80% of the total GHGe of the livestock sector, whereby beef cattle and dairy cattle alone contribute to 65% of that total with an estimated combined 4.6 gigatonnes CO_2-eq of annual emissions (Gerber *et al*., 2013). The huge impact on global warming is linked to ruminant gut symbiosis with methanogenic-bacteria, which is responsible for methane emissions into the atmosphere, with methane having a relative global warming effect 28 times higher than that of carbon dioxide (IPCC 2014). In the case of beef as well as lamb, the reviewed studies identify enteric fermentation as the main hot spot, accounting for 30-50% of total GHG-e (Nguyen at al., 2010; Geß *et al*., 2020), followed by direct and indirect N_2O emissions deriving

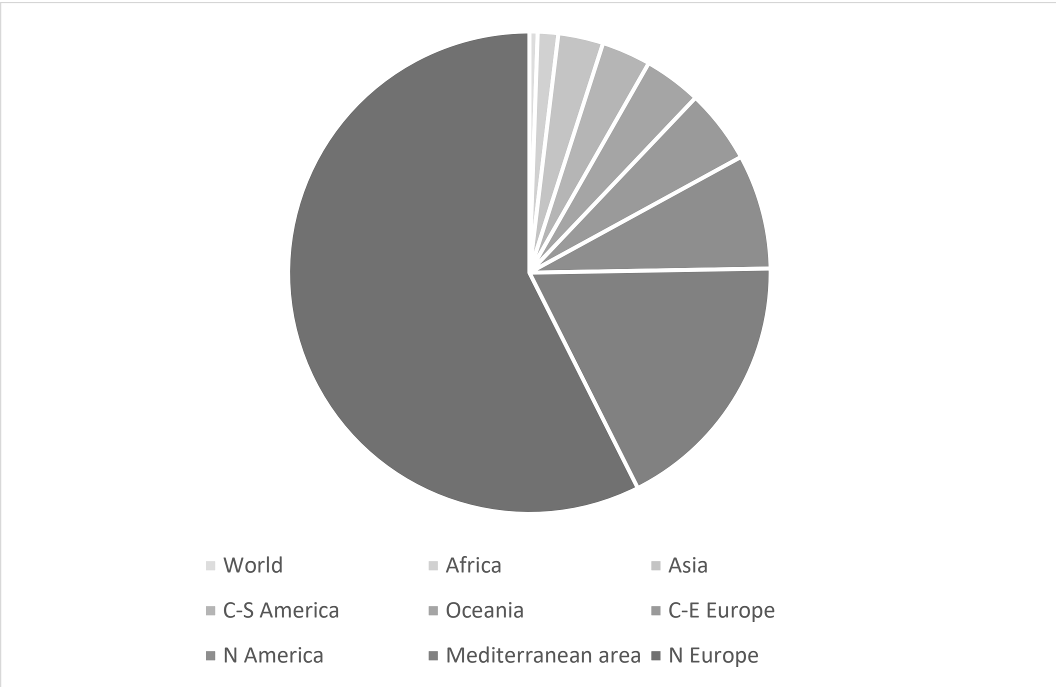
FOOD COMMODITY ITEM	n	x̄	Me	sd	min	max	MAD	25%	75%	CV
BEEF BONE FREE MEAT*	183	27.72	25.75	12.72	2.27	109.35	4.28	21.84	31.00	0.46
LAMB BONE FREE MEAT*	55	27.21	25.23	11.73	10.05	56.70	8.53	17.12	34.44	0.43
PORK HAM	4	7.93	7.95	4.04	3.00	12.84	3.90	4.54	11.34	0.51
PORK BONE FREE MEAT*	135	5.79	5.72	1.69	2.11	11.86	1.14	4.48	6.59	0.29
TURKEY BONE FREE MEAT	12	5.11	4.08	1.98	2.81	8.49	0.52	3.73	7.26	0.39
CHICKEN BONE FREE MEAT	100	4.24	3.68	2.07	1.06	16.29	0.94	2.78	5.35	0.49
CHEESE	27	9.29	8.93	2.53	5.33	14.69	1.21	8.11	10.29	0.27
BUTTER*	11	9.90	8.48	6.66	1.05	25.00	1.24	7.22	9.55	0.67
CREAM	8	5.34	5.45	2.20	2.10	8.31	1.95	3.86	7.14	0.41
YOGURT FLAVOURED**	14	2.81	2.85	0.36	2.16	3.85	0.13	2.62	2.92	0.13
YOGURT WHITE	20	2.10	1.69	0.98	1.17	4.07	0.41	1.31	2.42	0.47
BUFFALO MILK	7	3.75	3.57	0.79	2.87	5.20	0.49	3.14	4.18	0.21
COW MILK	364	1.43	1.31	0.72	0.54	8.44	0.20	1.14	1.54	0.51
EGGS*	51	3.23	3.20	1.22	0.72	6.00	0.85	2.24	4.04	0.38

Table 14. Selected statistics for animal husbandry items as an outcome of uncertainty analyses. A star (*) is given to items that also constitute types. Two stars (**) are given to items that comprise a further level of disaggregated data; or example, n= 14 for flavoured yogurt** means that its sample is represented by 14 different median values of specific flavoured yogurt commodities (i.e., cherry, apricot, chocolate, vanilla and so on), each of one deriving from a further sample data. Thus, although food items marked with two stars are presented as food items, their statistics were treated as they were food types, using median values of specific varieties of flavoured yogurt.

from animal feed production, and CH_4 and N_2O released from manure management.

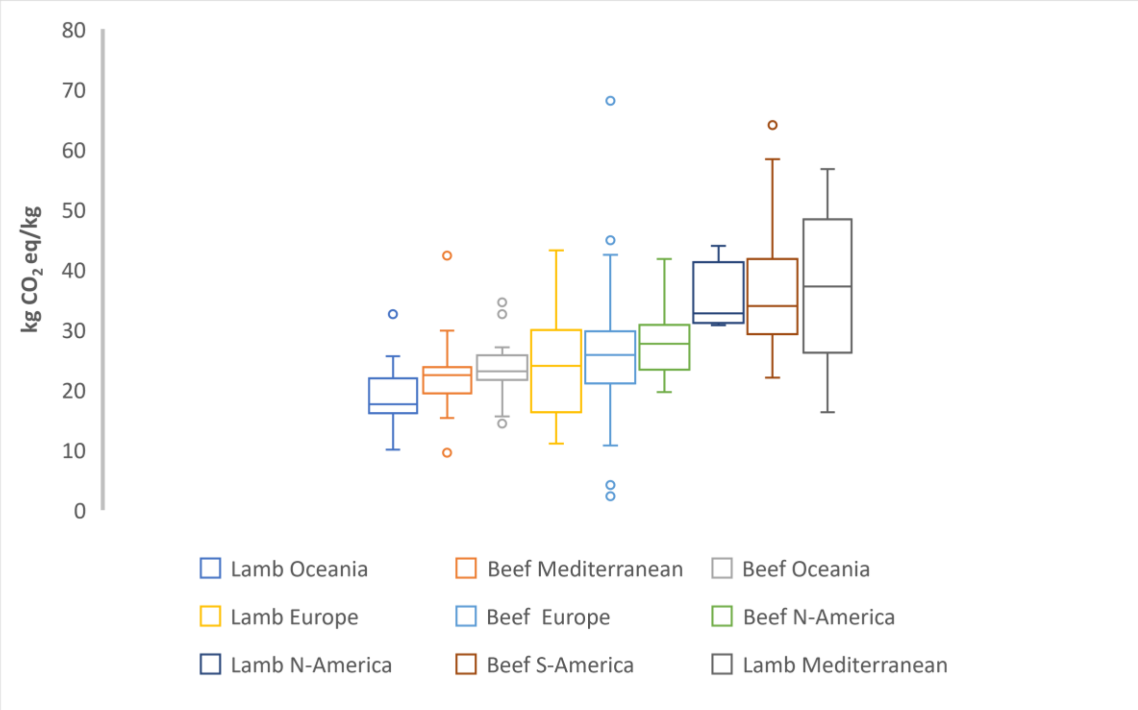
Buffalo bone-free meat, with its 8% contribution to annual GHG-e from the livestock sector (Gerber *et al.*, 2013) and a median CF value of 78.8 kg CO_2 eq/kg, is the most carbon-intensive meat product among ruminant species, although further LCA studies are warranted in this regard, given that according to the method employed in Petersson *et al.*, 2021 its emissions estimate is highly uncertain. The significantly higher intensity emissions of buffalo bone-free meat with respect to other ruminant meat products can be attributed to both a higher proportion in the concentrated feed of soy from deforested regions as well as a lower milk yield (Head *et al.*, 2013). In accordance with (Clune *et al.*, 2017), we found very high median CF values both for beef BFM (25.75 kg CO_2-eq/kg) and lamb BFM (25.23 kg CO_2-eq/kg) deriving from a robust sample data. However, the impact on global warming varies largely across farming systems and locations. De Vries *et al.* (2015) conduct a systematic review of LCA studies comparing beef systems based on the origin of calves (dairy-based vs suckler-based), production method (organic vs non-organic), and diet (concentrate-based vs roughage-based). The study highlights a significantly lower GWP (-41%) on average for dairy-based systems compared with suckler-based systems and for in concentrate-based systems (-28%) compared with roughage-based systems. No significant difference was detected for GWP between organic and conventional systems, although organic showed a 7% lower GWP on average due to reduced fertilizer input and feed concentrates (De Vries *et al.*,2015).

Gerber *et al* (2013) point to a high geographic variability in beef emission intensities worldwide. Overall ¾ of beef bone free meat GWP values within our database refer to European and Mediterranean production systems as shown in graph 2**.**, thus resulting in a Eurocentric world estimate. Therefore, we recommend, when possible, the use of specific-geographical median values for beef production for other geographical regions. For this purpose, in order to identify the variability of emission-intensity among regions for beef and lamb, we clustered data by geographical area of production, as reported in graph 3.



Graph 2. Relative abundance of CF values for beef bone-free meet food commodity on the basis of geographical area. Northern Europe (57%), Mediterranean Area (18%), North America (8%), Central-East Europe (5%), Oceania (4%), Central and South America (3%), Asia (3%), Africa (1%), World estimate (1%).

Emission intensity for beef BFM produced in the Mediterranean Area and Oceania were similar: 22.45 and 23.08 kg CO_2-eq/kg, respectively. Higher values were detected for Northern Europe (25.75 kg CO_2-eq/kg), North America (27.65 kg CO_2-eq/kg), and Central-South America (33.92 kg CO_2-eq/kg), the latter being the highest due to the inclusion of deforestation and land-use change in the sourced LCA. Data regarding beef production in Africa and Asia is scarce and not amenable to statistical interpretation ($n \leq 3$): further studies are recommended to identify possible



Graph 3. GWP of beef and lamb BFM by production area.
For Mediterranean lamb meat, includes one additional LCA value from Astori *et al* (2015) and 3 from Ibidhi *et al.* (2017) not comprised in Petersson *et al* (2021, B) LCA inventory.

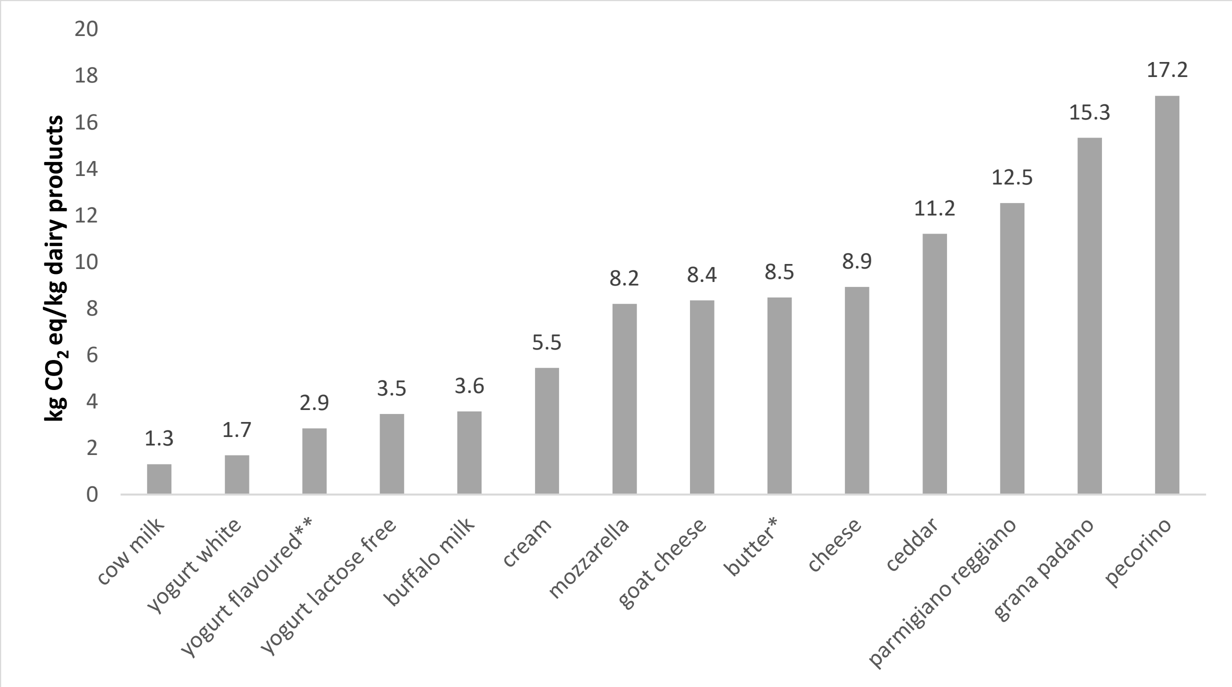
trends in undeveloped countries in light of Gerber *et al* (2013)'s findings of very high values for Africa (40.3 kg CO_2-eq/kg for North-East Africa, and 100.7 kg CO_2-eq/kg for sub-Saharan region) and for Asia (69.06 and 109.35 kg CO_2-eq/kg).

High variability among production areas can be observed for median values of lamb BFM: 17.59 kg CO_2-eq/kg for Oceania, followed by 23.99 kg CO_2-eq/kg for Europe, 32.67 kg CO_2-eq/kg for North America, with a maximum of 37.15 kg CO_2-eq/kg corresponding to the Mediterranean area. Higher values for Mediterranean production are linked to traditional extensive pasture-grazing systems which are less productive compared to intensive industrial-no grazing. Although resulting in higher GWP per kg of meat when using mass-allocation LCA methodology, silvopastoral systems are characterized by higher animal welfare and provide several ecosystems services such as biodiversity and landscape conservation and prevention of wildfires (Ripoll-Bosch *et al* 2013). In LCA studies accounting for multifunctionality in sheep meat production, pasture-based livestock Mediterranean systems showed lower mean CF values compared to industrial no-grazing systems (Ripoll-Bosch *et al* 2013). Moreover, Astori *et al* (2015) demonstrated that, if applying the economic allocation method to meat and milk in traditional Sardinian extensive systems, lower emissions per kg of meat may be achieved (16.13 kg CO_2-eq/kg).

From a systemic perspective, rather than focusing on a specific environmental indicator, ecosystems services should be accounted in the overall environmental performance and sustainability of a production system (Ripoll-Bosch *et al*., 2011), along with the inclusion of indicators of animal welfare as a determinant of consumer concern and choices (Geß *et al*. 2020). For small ruminants such as adult sheep and goat we did not conduct specific research, although we expect values in the range of lamb and beef meat. In fact, Gerber *et al* (2013) reports an average emission intensity of 23.8 kg CO_2-eq/kg for Carcass Weight (CW), with no large differences between sheep and goat meat. By applying a conversion factor of 1:0.66 (Clune *et al*., 2017) from CW to bone free meat (BFM) we obtained 36 kg CO_2-eq/kg as average goat and sheep BFM value.

3.3.2 Dairy products

The mitigation potential of reduced dairy intake is generally underestimated. Large differences were found for products across different diary types: milk, butter, fresh cheese and hard/semi-hard cheese. These differences are principally related to cheese yield from raw milk and the relative humidity (RU) of the final product. Therefore, we found increasing CF median values for decreasing relative humidity content in dairy types: milk (1.44 kg CO_2-eq/kg), yogurt (2.55 kg CO_2-eq/kg), fresh cheese (5.45kg CO_2-eq/kg), butter (8.48 kg CO_2-eq/kg), hard and semi-hard cheese (9.59 kg CO_2-eq/kg). Among dairy products raw milk production is the most significant contributor to climate change accounting for approximately 79-95% of total emissions, followed by processing operations that account for at most 18% of that (Finnegan *et al.*, 2018).
The systematic review for dairy products generated 458 CF values for 22 foods and beverages from 50 studies, comprising peer-reviewed papers, reports, Environmental Product Declarations (EPD) and conference proceedings. The majority of GWP values were found for milk (373), while most of cheese items were scarcely investigated in LCA studies, limiting the assessment of a robust CF estimate to 14 items.
The contribution of the global milk production amounts to 2,7% (FAO, 2010) of the total anthropogenic GHG emissions reported by IPCC (2007).
All dairy products derive from milk processing, thus the CF embedded in raw milk has repercussions on the final product. Milk emissions intensity is strictly related to productivity: high-yielding animals obtained by a combination of genetic selection, high quality feed and health



Graph 4. CF median values of dairy products. Only CF values for which a low level of uncertainty was detected are represented.

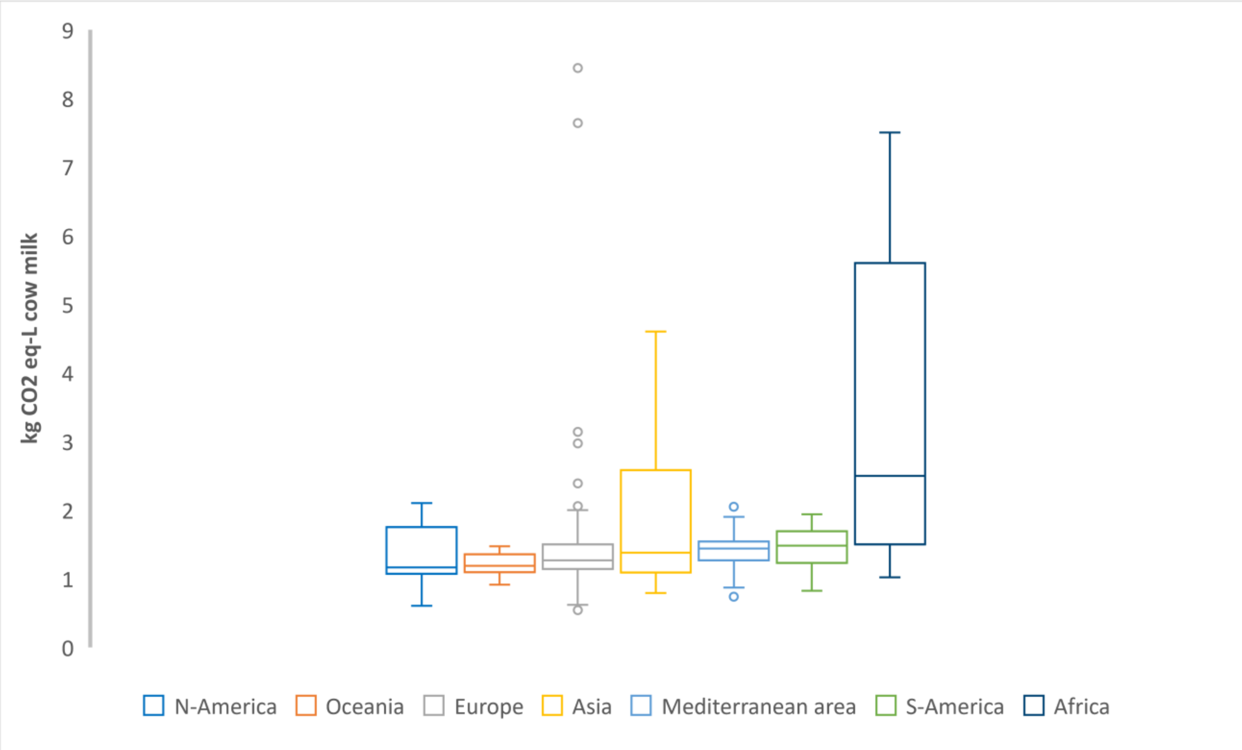
management practices, producing more milk per lactation generally exhibit lower GWP per unit. High productivity is frequent in developed countries and industrialized systems, thus exhibiting lower GWP per litre of milk compared to undeveloped countries and grazing systems (Gerber *et al*., 2011).

Cow milk commodity is widely studied and our CF inventory comprises 364 values deriving primarily from European farm systems (63%), followed by Mediterranean (18%), North America (8%), Oceania (4%) and the remaining percentage (7%) from Asia, South America and Africa.

Graph 5. shows the breakdown of emission estimates for cow milk by geographic area of production highlighting an increasing intensity emission for less developed world regions.

Cow milk has a median value in the database of 1.3 kg CO_2-eq/kg, although some variability exists among regions: we found the lowest median value for North America production (1.17 kg CO_2-eq/kg), followed by Oceania (1.19 kg CO_2-eq/kg), Europe (1.27 kg CO_2-eq/kg), Asia (1.38 kg CO_2-eq/kg), Mediterranean (1.44 kg CO_2-eq/kg), South America (1.48 kg CO_2-eq/kg), and the highest for African milk supply chain (2.5 kg CO_2-eq/kg).

The high variability of CF values for cow milk reflects differences in farming systems (intensive, extensive, mixed farms), farms dimension (small, medium, big), the recovery of energy from anaerobic digestion of slurry and manure, and the degree of feed-self-sufficiency of the farm (linear relationship between GHG-e and soymeal animal feed from deforested areas).



Graph 5. GWP of cow milk by production area.

The lowest cow milk CF value of the dataset is attributed to large scale Norwegian dairy farms (0.54 kg CO_2-eq/kg), while the highest values are found for extensive farm systems in sub-Saharan Africa with an average of approximately 7.5 kg CO_2-eq. per kg (Vellinga and Gerber., 2010).

Among milk derived products we found high variability of climate impacts per kg of product, although CF estimates should be adjusted by portion size, according to dietary guidelines, or by nutrients content. Indeed, fresh cheese has a lower fat and protein content, requiring 2-4 L of milk per kg of cheese whilst a cured cheese, with higher nutrient content, requires more milk (>4 L/kg cheese). For this reason, LARN or SINU guidelines report a portion-size of 100g and 50g for fresh and cured cheese respectively, amounting to roughly the same nutrient content per portion.

Higher values are expected for Pecorino (17.15 kg CO_2-eq/kg), Parmigiano Reggiano (12.54 kg CO_2-eq/kg), Grana Padano (15.34 kg CO_2-eq/kg) and Cheddar (11.21 kg CO_2-eq/kg), all hard cheeses subjected to dehydration due to curing processes, compared to fresh cheese. We found abnormally high values for mozzarella cheese compared to its type median value, which were in fact identified as outliers.

Butter is characterized by high variability with a CF dataset ranging from 1.05 to 25 kg CO_2-eq/kg.

Two of the highest values were reported for mountains farmer butter from Austrian production, 20.83 kg CO_2-eq/kg and 25 kg CO_2-eq/kg respectively for organic and conventional production (Lindenthal *et al*., 2010).

3.3.3 Non-ruminant meat

Monogastric species show significant lower intensity emissions compared to ruminant species. The reason lies in the lower amount of feed needed per kg of meat for monogastric animals compared to ruminants due to higher feed-use-efficiency (Schroeder and Titgemeyer, 2008) and their lower, if not irrelevant, production of CH_4. In fact, albeit negligible, some production of CH_4 in non-ruminant livestock systems may occur from enteric fermentation and manure management. Analysing several LCA studies for the livestock sector, CH_4 and N_2O were the most important GHG contributors to the GWP of ruminant products, whereas in monogastric animals N_2O alone was responsible for most of the GWP. Several authors report feed production as the hot spot for pig and poultry supply chains, ranging from 60 to 80 percent of total emissions (Gerber *et al.,* 2013, Wiedemann and McGahan, 2011).

The results of our database present significantly lower median GWP values for poultry and pork than ruminant meat, ranging from 3 to 7 times lower, all of which are below 6 kg CO_2-eq/kg with the exception of cured pork meat such as ham. Within this category we found the lowest median value for chicken bone free meat (3.68; n=100), followed by turkey bone-free meat (4.08; n=12), pork bone-free meat (5.72; n=135) and pork ham (7.95; n=4), the latter belonging to the pork cured meat type.

Chicken supply chain accounts for just 8% of total livestock emissions, including both egg and meat production (Gerber *et al*., 2013). With regard to chicken production, industrial intensive indoor systems were found to have a lower climate change impact compared to extensive outdoor or organic farming systems (Gerber *et al*., 2013; Leinonen *et al*., 2012). Leinonen et al. (2012) reported significantly higher ($P<0,05$) GHGE per kg in organic productions due to higher mortality, longer production cycle and thus greater feed consumption compared to intensive indoor systems. In contrast, pig meat production, with its 9% contribution to total livestock emissions, was found to be less carbon intensive in the case of backyard systems as compared to industrial intensive systems due to the net zero emissions of household food waste used for animal feed (Gerber *et al*., 2013).

Higher emissions per unit of turkey BFM compared to chicken BFM are due to higher emissions from manure management and housing produced by the higher feed intake associated to longer production cycles (Leinonen and Kyriazakis, 2016).

The variability in GWP assessments for chicken and pork across LCA studies may reflect the different choices among researchers in using soil N_2O emission factors, that depend on soil type and soil water content, or generic and national N_2O soil emission factors from IPCC guidelines (De Vries and de Boer, 2010)

Eggs intensity emissions range from 2.24 (1st quartile) to 4.04 (3° quartile) with a median value of 3.2 kg CO_2-eq/kg. Gerber *et al*. (2013) reports higher GWP for backyard egg production systems (4.2 kg CO_2-eq/kg) compared to industrial ones (3.7 kg CO_2-eq/kg). We divided the sample in two groups on the basis of differences in system production, that is, either conventional farming or organic/free-range. Mean values were similar and no statistical difference was detected: 3.38 for conventional and 3.54 kg CO_2-eq/kg for organic/free-range, although the latter was somewhat higher. Similar results were reported by Leinonen and Kyriazakis (2012) resulting from a comparative LCA study for conventional, organic and free-range farm systems for UK egg production: 3.59, 3.56 and 3.52 kg CO_2-eq/kg, respectively.

Extreme values within the sample data for egg ranging from 5,15 to 5,3 were identified for systems using animal protein feed (Pelletier *et al*., 2013).

The least carbon intensive values for eggs in our dataset (1.3 and 1.6 kg CO_2-eq/kg) were identified by Wiedemann and McGahan (2011) for Australian production, both in cage and free-range. By analysing this report, we understood that sustainable and low carbon agricultural practices for animal feed production may mitigate the overall climate impact of the eggs supply chain. In fact, the combination of zero or minimum tillage, low N-fertilizer input, and lower nitrous oxide emission factor for Australia (0,3%) compared to Europe (1%) reported by DCCEE (2010) as well as lower farm energy intensity (MJ/t) of Australian grain production determined a significant reduction in GWP for egg production.

Since feed production is the main determinant of GWP for non-ruminant products, the highest mitigation potential is found for agricultural management practices that transform agricultural soils from GHGE sources to sinks.

3.3.4 Mitigation options

Several options may be considered to reduce GWP in ruminant production systems by acting on the 3 main factors involved in the GHGE of ruminant livestock systems. Enteric fermentation contributes to 30-50% of total GHG-e (Nguyen at al., 2010; Geß *et al*., 2020); feed production 35-45% (Sonesson *et al*., 2009) and manure management approximatively to 10% (FAO, 2017) of total GHGE of ruminant products, including both meat and dairy. At the state of art, the least mitigation potential can be achieved for CH_4 produced by enteric fermentation, the latter being an intrinsic physiological process to ruminant species. In this regard, diet manipulation and feed additives have been identified as the most effective measures (FAO, 2013; Gerber *et al.,* 2013). Improved forage digestibility resulting from harvesting forage grasses at early stages when the lignin content is low may reduce emissions (Knapp *et al*. 2014). The use of supplementary lipids or terpenoids (linseed fatty acids and essential oils) may act as methanogenesis inhibitors (Llonch *et al.,* 2017; Grainger and Beauchemin, 2011). Genetic selection of breeds with lower emissions may be a promising avenue but requires further studies (FAO 2013; Gerber *et al*., 2013; Seijan *et al*., 2011).

Manure management and application to the soil as fertilizer generates CH_4 and N_2O emissions, accounting for 10% of the total GWP in livestock supply chains (FAO, 2017). Despite a relative low contribution to livestock GHGE, a high effectiveness for mitigation potential has been identified for different practices. One of the most effective measures is anaerobic digestion of animal sewage and animal manure entailing a 30% reduction in the relative contribution of GHG-e. In fact, up to 65% of the biogas produced is represented by CH_4: if managed properly, the latter can replace fossil fuel as an energy source within the farm system. The combustion of CH_4, otherwise emitted from manure storage, reduces GHG emissions by converting CH_4 into carbon dioxide (CO_2) and by displacing fossil fuels used to produce heat or electricity (Passos-Fonseca *et al.,* 2011).

Simultaneously, the dry digestate may be applied on agricultural soils and replace chemical fertilizer (Battini *et al*., 2014), offsetting the GHGE from fertilizer manufacturing and transport as well as the CH_4 which may be generated by undigested manure. Decreased manure storage time, storage temperature, strow covering and aerobic conditions have been identified as alternative effective mitigation measures for untreated solid manure (Gerber *et al*., 2013; FAO, 2017).

Feed contributes between 35 and 45 percent of emissions for ruminate food products, while it represents the hot spot for non-ruminant products accounting for 60.7% of total GWP of pig meat, 78% for poultry meat and 70% for eggs supply chains. The processes involved in GHGE from feed production include land use change (such as deforestation to create pasture or croplands for animal feed production), manufacturing and application of fertilizers and pesticides, emission from fuel or energy used in cultivation operations, feed processing and feed transport.

Gerber *et al.* (2013) have estimated that an 8% reduction in livestock supply chain emissions (including monogastric animal products) can be achieved by combining improved grazing management practices and legume sowing in grasslands. In fact, croplands, pastures and grasslands soils may act as carbon stocks with a reduction potential of 585 million tonnes CO_2-eq per year, although variability in the long-term carbon sequestration capability of soils raises concerns.

Among carbon-net sequestration practices for croplands and pasture, Sousanna *et al* (2004) highlight: (1) converting cropland used for animal feed production to grassland; (2) decreasing N-fertilizer use; (3) increasing the duration of grass leys and converting those leys to grass legume mixtures or to permanent grasslands; (4) privileging grazing compared to cutting of forage.

Reducing imported soybean feed from deforested areas and rice meal in animal feed is shown to have a medium mitigation potential, along with farm feed autonomy which cuts back on the transport emissions of feed. Grain-fed intensive industrialized livestock systems may have higher emission from feed than extensive grazing systems.

In general, cropland involved in animal feed production should integrate agroecological practices such as intercropping, cover-cropping, green manuring, minimum tillage, agroforestry, crop rotation, minimize fallow bear soil periods, biochar application to cropland and all other agricultural practices which have demonstrated to reduce emissions and enhance carbon sequestration and soil organic matter from agricultural soils (Altieri and Nicholls, 2017; IPCC, 2014; Toensmeier, 2016, IPCC, 2019-capter 6).

3.4 Crops

It is widely recognized that crops generate significant less GHG-e for their production, and require less land surface and water compared to animal-based products (Clune *et al*., 2017; Mekonnen and Hoekstra 2011, 2012; Collins and Fairchild 2007; Willet *et al.,* 2019). For our CF inventory, within the crop group, we reviewed 208 LCA studies resulting in 986 GWP values representing 121 food items belonging to 22 types. Data regarding fruit and vegetable open field types were further disaggregated into 8 sub-types on the basis of similar botanical characteristics. Hence, the Kruskal-Wallis ANOVA test on ranks (all pairwise multiple comparison procedures based on Dunn's Method) was performed to determine if the median values of the sub-types within one type were significantly different from each other. Moreover, the Mann-Whitney Rank Sum Test was used to determine if a sub-type footprint value was significantly different from the corresponding value of its reference type. Results are shown in Table 15 below.

In line with other systematic reviews of foods-related GHGE (Clune *et al*., 2017), within our database the crop group shows the lowest CF median value, on a mass basis, among all groups analysed.

At the broadest level (food types and sub types) we found the lowest median values for roots and bulbs sub type (0.25 kg CO_2-eq/kg), starchy tubers type (0.26 kg CO_2-eq/kg), fruit sub type (0.28 kg CO_2-eq/kg), vegetables (fruit, stems, flowers) sub type (0.33 kg CO_2-eq/kg), citrus fruit sub type (0.34 kg CO_2-eq/kg), and green leafy vegetables sub type (0.34 kg CO_2-eq/kg). Values close to the median value of the crop group (0.56 kg CO_2-eq/kg) were identified for dried legumes (0.52 kg CO_2-eq/kg), grains (0.57 kg CO_2-eq/kg), olives sub type (0.64 kg CO_2-eq/kg), and wild berries sub type (0.64 kg CO_2-eq/kg).

FOOD TYPE	FOOD SUB-TYPE	ANOVA on Ranks All Pairwise MCP	T-test sub-type vs Type Mann-Whitney
Open field fruit	citrus fruit	A	not significant
	other fruit	A	not significant
	olives*	B	significant
	wild berries	B	significant
Open field vegetables	asparagus*	A	significant
	green leafy vegetables	BC	not significant
	roots and bulbs	C	significant
	vegetables (fruits, stems, flowers)	B	not significant

Table 15. Kruskal-Wallis ANOVA test on ranks (all pairwise multiple comparison procedures based on Dunn's Method) and Mann-Whitney Rank Sum Test performed separately for open field fruit sub-types and open field vegetables sub-types.
Note: the sub-type 'other fruit' includes all fruit items not classified as citrus, wild berries or olives: apple, apricot, avocado, banana, cherry, grapes, kiwi, mango, melon, peach, pear, pineapple, carob, fig, guava, plum, pomegranate, rockmelon, watermelon. 'Citrus fruit' sub-type included in the dataset are: limes, lemon, orange, mandarin, clementine, tangerine and pomelo. 'Olives' sub-type corresponds to olives item. 'wild berries' sub-type includes strawberries, blackberries, blueberries, cranberry, currant, gooseberry and raspberry.
'Asparagus' sub-type corresponds to asparagus item. Green leafy vegetables comprise lettuce, spinach and cabbage. 'Roots and bulbs' include carrot, onion, beetroot, garlic, radish, swede and turnip. 'Vegetables (fruit, stems, flowers)' includes: broccoli, cauliflower, cucumber, eggplant, zucchini, gherkin, pepper, pumpkin, tomato, artichoke, celery and fennel.
Full details of data entries can be accessed in Petersson *et al* (2021b).

Values in the third quartile of the crops group CF distribution were detected for dried fruit (0.81 kg CO_2-eq/kg), asparagus sub-type (0.83 kg CO_2-eq/kg), dried spices (0.84 kg CO_2-eq/kg), and dried seeds (0.88 kg CO_2-eq/kg). In the fourth quartile of CF values, we found imported fruit - e.g., tropical fruit imported in European markets (1.07 kg CO_2-eq/kg), dried nuts (1.17 kg CO_2-eq/kg), vegetables and fruit grown in passive greenhouses (1.18 and 1.43 kg CO_2-eq/kg respectively).

High values were detected for cultivated mushrooms (2.06 kg CO_2-eq/kg). Unlike all other crops, marketed mushrooms are not suitable for open field cultivation and require special growth conditions such as sterilized compost substrate, indoor environments with controlled temperature

and darkness (Robinson *et al* 2019): compost production generates CH_4 emissions; additionally, electricity or fuel is required to control temperature, which explains the higher GWP of this product. Not surprisingly, for mushroom indoor production, these three processes are the largest contributor to mushroom GWP (Robinson *et al.*, 2019). Surely, on-farm compost production through anaerobic digestion may minimize emissions both by offsetting transport emissions of imported compost and by recovering CH_4 which can then be used directly as fuel or indirectly through its conversion into electricity to support the high energy requirements of mushroom plants. From a nutritional point of view, mushrooms contain up to 5,75% of proteins in fresh weight which are characterised by a high chemical score, although lysin and/or leucin were found to be limiting amino acids (Manzi *et al*, 1999) according to FAO reference protein quality (1991); thus, mushrooms play a valuable role as a source of vegetal protein in a healthy and varied diet.
Rice statistics were treated separately from other grain commodities due to a significantly higher climate change impact corresponding to 2.19 kg CO_2-eq/kg, that is, four times the median GWP of other cereal and pseudo-cereal grains. As a matter of fact, because it is cultivated in flooded croplands, the production of rice releases CH_4 from soils microbial metabolism in anaerobic conditions. The highest value among grains CF was found for Quinoa, due to lower yields compared to cereals and longer transport distances. Indeed, we retrieved all quinoa values from a study for which *Chenopodium quinoa* is cultivated in the Peruvian highland and exported to European markets by ship (Cancino-Espinoza *et al.,* 2018). That being said, the rise in demand for quinoa in recent years, prompted by the fact that quinoa is a gluten-free grain containing all essential amino acids (Janssen *et al*., 2017), has led to the cultivation of certain varieties of quinoa, such as white quinoa, in parts of Europe thus contributing to a more sustainable supply (Pulvento *et al.*, 2010; Gesinki, 2008; Brazile *et al*., 2016).
Vegetables and fruit grown in heated greenhouses are the most carbon intensive food products within the crop type and show outlying CF values of 2.55 and 2.88 kg CO_2-eq/kg respectively. Indeed, non-seasonal production requires special cultivation practices such as CO_2 enrichment, artificial lighting and heating, which are highly energy-intensive, as well as materials such as plastic houses or glasshouses for indoor cultivation whose manufacturing and distribution generates additional GHGE. Heating is found to be the hot spot of non-seasonal production. For example, Boulard *et al.* (2011) found a contribution of 80% from heating to CF for tomato production in France. When comparing different production systems, we found that tomatoes produced in heated green houses have a median CF of 2.43 kg CO_2-eq/kg, being 5 times more impacting than seasonal open-field produced tomatoes (0.45 kg CO_2-eq/kg). Trade-offs between the market demand for fresh non-season products and their environmental costs of production

should be investigated. For non-season products the most powerful mitigation option is on the demand side. Consumers are generally more informed about the health benefits of fruit and vegetable consumption than they are about the climate impact of non-seasonal production, therefore CF labelling at retailer point sale might favour a responsible purchasing choice.

For fruit, vegetables, starchy tubers, nuts, seeds and grains (excluding rice) grown in field conditions, the primary emission sources during farming are represented by CO_2 emissions from fuel for on-farm operations, CO_2 emissions from soil disturbance, emissions from fertilizer manufacturing and application to the soil (mainly associated with field N_2O emissions), and electricity for irrigation (in irrigated croplands). The contribution of the different farming stages varies greatly among studies, hence an average contribution from each stage cannot be determined. It is important to highlight that, in contrast to animal derived products, for fresh crop products the share of downstream processes within the life cycle has a relatively high impact on the total GHG-e of the product. Clune *et al.* (2017) in their review found post-farmgate emissions to be in the range of 0.01-0.21 for packaging (with a median value of 0,05), and ranging from 0.02 to 0.95 for transport (with a median value of 0.09) for each kg of food commodity. In light of the fact that CF for packaging and transport is similar across food commodities, the lower the total GWP of a product, the higher the GWP share that will be attributed to packaging and transport.

For example, relative to the median CF of fresh eggplant, i.e., 0.19, packaging and transport contributes up to 74% of that value, while the farm-stage process only about 26%, a fact that highlights the potential mitigation of reduced packaging and transport. While for pepper cultivated in heated greenhouses, which has a median CF value of 3.73, packaging and transport accounts only for 4% of the total impact.

At a more detailed level, we found 61 items characterized by median values with a low level of uncertainty, while 54 characterized by a high level of uncertainty: concerning the latter, additional LCA should be performed. Table 16 includes only reliable CF values as an output of the uncertainty analysis described in Chapter 2, while all statistics comprising skewness, kurtosis, Tukey-test and Shapiro-Wilk normality test can be found in Petersson *et a.l* (2021b).

Table 16. Descriptive statistics for crop items.

FOOD TYPE	FOOD ITEM	n	$\bar{x}$	Me	sd	min	max	mad	25%	75%	cv
COFFEE GREEN*	coffee green*	8	0.49	0.49	0.14	0.29	0.71	0.09	0.4	0.55	0.28
DRIED FRUIT	raisin	5	0.66	0.81	0.2	0.36	0.84	0.03	0.47	0.81	0.31
FRUIT HEATED GREENHOUSE	strawberry (G)	4	2.94	2.88	1.77	0.84	5.17	1.65	1.44	4.39	0.6
FRUIT IMPORTED	pineapple (i)	7	0.73	0.55	0.5	0.17	1.78	0.15	0.43	0.89	0.69
FRUIT IMPORTED	banana (i)	20	0.81	0.82	0.28	0.42	1.37	0.27	0.52	1.05	0.35
FRUIT IMPORTED	avocado (i)	4	1	1.09	0.38	0.43	1.38	0.25	0.77	1.32	0.38
FRUIT NOT HEATED GREENHOUSE*	melon (g)*	4	1.41	1.43	0.11	1.24	1.55	0.06	1.38	1.46	0.08
FRUIT OPENFIELD	apple	59	0.31	0.25	0.17	0.06	0.95	0.07	0.2	0.38	0.54
FRUIT OPENFIELD	pear	12	0.29	0.27	0.12	0.16	0.63	0.05	0.21	0.31	0.41
FRUIT OPENFIELD	orange	31	0.35	0.3	0.16	0.18	0.87	0.07	0.25	0.42	0.44
FRUIT OPENFIELD	apricot	7	0.36	0.3	0.12	0.23	0.56	0.06	0.26	0.45	0.34
FRUIT OPENFIELD	grapes	15	0.39	0.31	0.22	0.15	0.88	0.1	0.27	0.42	0.55
FRUIT OPENFIELD	mango	6	0.33	0.31	0.07	0.25	0.44	0.05	0.27	0.36	0.2
FRUIT OPENFIELD	banana	9	0.38	0.34	0.18	0.15	0.78	0.13	0.32	0.47	0.46
FRUIT OPENFIELD	peach	12	0.43	0.39	0.19	0.23	0.83	0.06	0.29	0.43	0.44
FRUIT OPENFIELD	mandarin	7	0.4	0.45	0.11	0.22	0.51	0.06	0.31	0.49	0.27
FRUIT OPENFIELD	cherry	7	0.49	0.46	0.19	0.26	0.88	0.09	0.39	0.52	0.38
FRUIT OPENFIELD	kiwi	12	0.65	0.49	0.42	0.27	1.61	0.21	0.33	0.84	0.64
FRUIT OPENFIELD	avocado	4	0.54	0.54	0.22	0.25	0.84	0.19	0.39	0.69	0.4
FRUIT OPENFIELD	melon	6	0.56	0.61	0.19	0.3	0.76	0.61	0.37	0.74	0.35
FRUIT OPENFIELD	strawberry	27	0.68	0.61	0.33	0.2	1.5	0.26	0.39	0.9	0.49
FRUIT OPENFIELD	olives	9	0.59	0.64	0.2	0.22	0.85	0.05	0.61	0.68	0.34
FRUIT OPENFIELD	blueberry	8	0.64	0.78	0.29	0.19	0.97	0.15	0.39	0.86	0.45
GRAINS	barley	17	0.53	0.48	0.25	0.11	1.11	0.14	0.34	0.62	0.47
GRAINS	wheat	44	0.67	0.57	0.43	0.18	3.08	0.18	0.44	0.77	0.65
GRAINS	oat	5	0.7	0.67	0.26	0.38	1.1	0.21	0.47	0.88	0.38
GRAINS	quinoa	12	0.96	0.97	0.19	0.53	1.2	0.16	0.86	1.13	0.19
LEGUMES	bean	14	0.67	0.43	0.48	0.22	1.55	0.21	0.26	1.09	0.71
LEGUMES	pea	12	0.58	0.45	0.63	0.15	2.6	0.11	0.27	0.5	1.08
LEGUMES	cowpea	4	0.48	0.49	0.11	0.33	0.61	0.1	0.4	0.57	0.23
LEGUMES	green bean (fresh)	11	0.73	0.52	0.51	0.2	1.55	0.27	0.29	1.14	0.69
LEGUMES	soybean	5	0.6	0.56	0.22	0.38	1.01	0.1	0.46	0.61	0.36
LEGUMES NOT HEATED GREENHOUSE*	green bean (fresh) (g)*	4	0.31	0.28	0.08	0.24	0.43	0.03	0.24	0.34	0.25
MUSHROOM*	mushroom*	6	1.78	2.06	1.09	0.2	3.09	0.86	0.82	2.64	0.61
NUTS	peanut	10	0.89	0.83	0.3	0.28	1.35	0.12	0.8	1.05	0.34
NUTS	hazelnut	5	1.07	1.11	0.35	0.43	1.5	0.09	1.1	1.2	0.33
NUTS	cashew nut	11	1.56	1.38	0.92	0.35	3.44	0.84	0.86	2.25	0.59
NUTS	pistachio	4	1.6	1.6	0.65	0.88	2.33	0.65	0.99	2.21	0.41
NUTS	almond	13	1.9	1.88	0.94	0.51	3.71	0.73	1.11	2.61	0.5
NUTS	walnut	5	1.75	2.06	0.88	0.63	3.03	0.97	0.89	2.13	0.5
RICE*	rice*	35	2.54	2.19	1.44	0.24	6.45	0.74	1.65	3.08	0.57
STARCHY TUBERS	potato	35	0.25	0.24	0.1	0.08	0.45	0.07	0.18	0.33	0.39
VEGETABLES HEATED GREENHOUSE	tomato (G)	36	2.89	2.43	1.31	1.16	6.12	0.71	1.94	3.66	0.45
VEGETABLES HEATED GREENHOUSE	cucumber (G)	8	2.59	2.55	1.02	1.3	4.51	0.84	1.72	2.89	0.39

(*cont.*)

FOOD TYPE	FOOD ITEM	n	x̄	Me	sd	min	max	mad	25%	75%	cv
VEGETABLES HEATED GREENHOUSE	lettuce (G)	7	2.69	2.67	1.55	0.45	4.73	1.37	1.4	4.1	0.58
VEGETABLES HEATED GREENHOUSE	pepper (G)	4	4.6	3.73	3.35	0.9	10.05	1.45	2.96	5.36	0.73
VEGETABLES NOT HEATED GREENHOUSE	tomato (g)	28	0.94	0.91	0.56	0.2	2.14	0.45	0.44	1.28	0.6
VEGETABLES OPENFIELD	eggplant	5	0.45	0.19	0.44	0.1	1.3	0.1	0.19	0.5	0.98
VEGETABLES OPENFIELD	gerkin	7	0.23	0.21	0.06	0.13	0.33	0.05	0.19	0.28	0.28
VEGETABLES OPENFIELD	onion	12	0.24	0.22	0.14	0.06	0.52	0.12	0.13	0.34	0.58
VEGETABLES OPENFIELD	cabagge	9	0.3	0.23	0.15	0.12	0.64	0.11	0.21	0.37	0.49
VEGETABLES OPENFIELD	carrot	16	0.23	0.24	0.12	0.04	0.45	0.1	0.13	0.33	0.54
VEGETABLES OPENFIELD	pumpkin	12	0.38	0.24	0.35	0.09	1.31	0.08	0.16	0.47	0.9
VEGETABLES OPENFIELD	cucumber	15	0.32	0.27	0.16	0.08	0.8	0.07	0.22	0.38	0.52
VEGETABLES OPENFIELD	cauliflower	6	0.32	0.31	0.13	0.09	0.52	0.08	0.27	0.4	0.42
VEGETABLES OPENFIELD	spinach	4	0.48	0.34	0.32	0.18	0.93	0.16	0.26	0.63	0.67
VEGETABLES OPENFIELD	lettuce	27	0.4	0.41	0.15	0.13	0.62	0.09	0.3	0.5	0.37
VEGETABLES OPENFIELD	tomato	68	0.48	0.45	0.3	0.15	2.29	0.1	0.35	0.56	0.61
VEGETABLES OPENFIELD	broccoli	19	0.67	0.57	0.36	0.22	1.87	0.12	0.48	0.7	0.53
VEGETABLES OPENFIELD	pepper	8	0.58	0.65	0.23	0.19	0.87	0.22	0.37	0.71	0.4
VEGETABLES OPENFIELD	zucchini	8	0.65	0.7	0.42	0.09	1.31	0.41	0.22	0.98	0.64
VEGETABLES OPENFIELD	asparagus	33	0.97	0.83	0.48	0.38	2.68	0.22	0.63	1.14	0.5

A star (*) is given to items that also constitute types. Two stars (**) are given to items that comprise a further level of disaggregated data.

3.4.1 Mitigation options

The GWP or CF associated to the farm stage of a crop is calculated as the ratio between the total GHG-e of the process and the corresponding mass yield. Therefore, a first improvement opportunity can be identified in the sustainable intensification of agriculture (SIA). Within SIA practices, intercropping has been widely proven to increase yields by an estimated 12–32% relative to monoculture (Ren *et al*., 2014; Aziz *et al*., 2015; Bedoussac *et al*., 2015; Yu *et al*., 2015, 2016; Himmelstein *et al*., 2017), as well as to increase carbon sequestration in soils (Chapagain and Riseman 2014); it may also offset emissions from N-fertilizers production when N-fixing intercrops are used (Crews and Peoples 2005, Martin-Guay *et al.,* 2018).

Conversion from plough till to no-till or minimum tillage is a viable option for soil organic matter (SOC) sequestration (Lal 2004). Many agricultural practices can potentially mitigate GHG emissions, the most prominent of which are related to increasing soil carbon stock in the form of soil organic matter: a) mulching, b) using cover crops (between successive crops or between rows of plantations) and avoiding bare fallows, c) crop rotation with high diversity, d) integrated nutrient management with compost, green or animal manuring (Mandal *et al*. 2007, 2008), e) precision farming techniques (in the case of chemical fertilizers use), and last, but not least, f) agroforestry, which integrates perennial crops with annuals and livestock systems (Smith *et al.,* 2019; Niggli *et*

al., 2009; Altieri and Nicholls 2017). Together, all these practices have shown rates of soil C sequestration ranging from 0.05 to 1 t/ha/year (Lal 2004).
Moreover, several studies have been highlighting the beneficial effect of biochar soil application on soil carbon sequestration, soil fertility and yield increase (Sohi *et al*., 2010; Zhang *et al*., 2012; Liu *et al*., 2014; Li *et al*., 2015; Cornelissen *et al*., 2018). A meta-analysis of biochar application to soil aimed at evaluating its impact on yield-scaled greenhouse gas intensity (GHGI) – another indicator of Climate change impact (Mosier *et al*., 2006; Zhang *et al*., 2012) – found that biochar or lime application significantly reduced GHGI (-29% on average), with higher reductions in dry lands (-41%) compared to paddy fields (-17%) (Liu *et al*., 2019).
Decreasing emissions from fuel biodiesel instead of petroleum gasoline and diesel resulted in a 32% reduction in the total farm CF (Adewale *et al.,* 2016), although raising issues related to competition for land.
Downstream stages within a life cycle of a crop product contribute significantly to the GWP (I Canals *et al.,* 2008). Packaging and transport emissions may contribute up to 74% of the CF of a crop product. Studies aimed at investigating GWP mitigations options for packaging materials and transport means are scarce. Options for limiting GHG-e from packaging may include minimum packaging, bulk unpackaged foods, plant-derived biodegradable materials, and recycled cellulose-based materials such as cardboard (Escursell *et al*., 2021). Research is urgently needed considering both the environmental and human health hazards related to the production and disposal of fuel-based packaging materials (Thompson *et al.,* 2009). As part of its 'Green Deal', the European target of reducing by 90% emissions from the transport and mobility sector by 2050 has been set. This target will be met by incentivizing zero emission transport means, such as electricity or hydrogen powered vehicles (European Union, 2019). Until that happens, the currently less emission-intensive transport means, such as train and ship freight, should be involved in the supply chains.
As part of the demand-side strategy, consumers may contribute in avoidable GHG-e by both choosing seasonal and locally produced plant-based products, since transportation contributes on average to 16% of the total carbon footprint of a food and heating for indoor production up to 90% of that (Stoessel *et al*., 2012; Wakeland *et al*., 2012; Hospido *et al*., 2009). When non seasonal foods are produced locally in intensive-heating systems, the consumption of imported crops from regions where those same crops can be grown in open field conditions may be preferred since GHG-e from rail, road or ship are generally lower than the ones emitted by heating systems (Theurl, 2014), except for the case of air freight transport means (Smith *et al*., 2005; Weber & Matthews 2008; Wakeland *et al*., 2012)

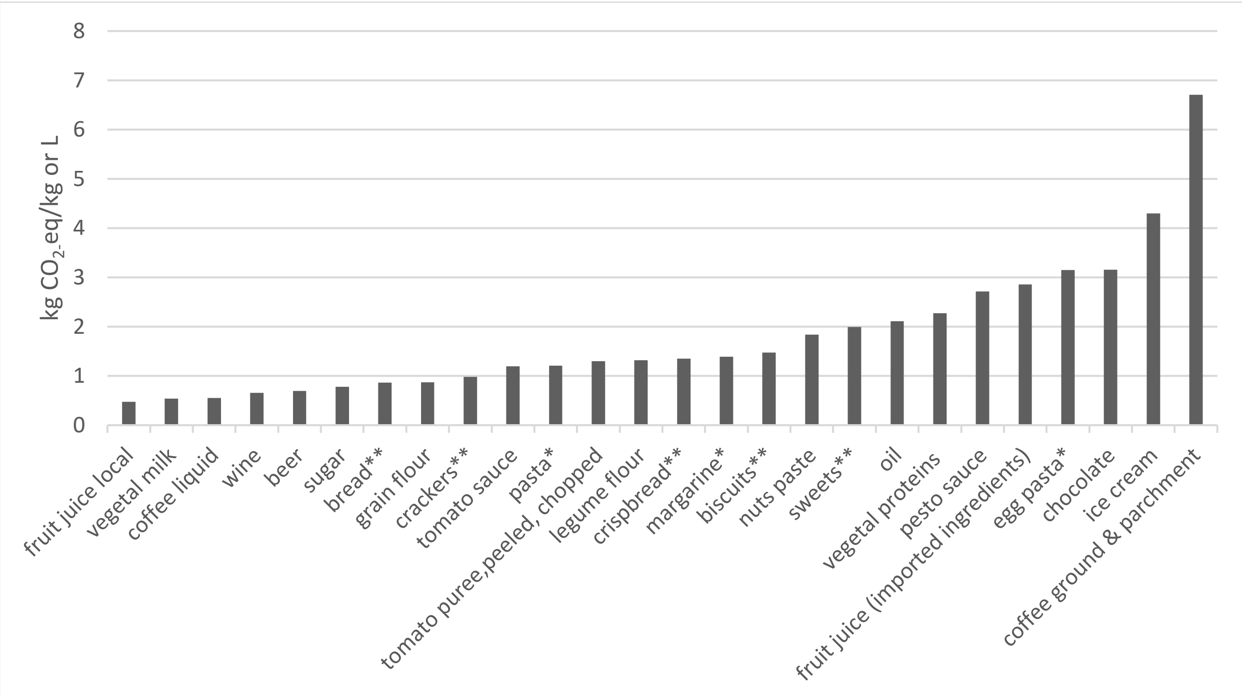
3.5 Processed foods

At present, there is a relative lack of LCA studies addressing processed foods, a circumstance which would be important to remedy given that the consumption of agricultural processed foods has been on the rise over the past decades and has become the primary energy source in western diets (Zinöcker and Lindseth, 2018). To our knowledge, this is the first attempt to review the available studies on processed food products that rely on LCA procedures. The production of processed foods includes post-farm energy-intensive industrial processes aimed at extending shelf life (such as drying, crushing, grinding, fractioning, roasting, boiling, pasteurisation, milling and baking). Processed foods are typically industrial branded-foods, and for this reason most of the CF included in this review derives from Environmental product declaration (EPD), i.e., a standardized (ISO 14025) LCA-based tool to assess the environmental performance of a product (Grahl and Schmincke, 2007).

To address the CF of processed foods, we reviewed 298 studies among EPD (n=210), conference proceedings (n=12), books (n=2), peer-revied papers (n=58), reports (n=11), and the Danish LCA database on food (www.lcafood.dk). The majority of the EPD were retrieved from the International EPD system available online (www.environdec.com), which collects worldwide updated EPD from spontaneous initiatives of private food companies. Indeed, the industrial food system in developed countries is changing as the result of increased consumer concerns about the environmental impact of consumption (Borin *et al*., 2011). 570 primary CF data points were collected in this domain, referring to 100 food items, further grouped into 41 food types. Most values refer to Mediterranean area food industries (58%), followed by European industries (23%), and North America (7%), with the remaining continents being scarily represented.

Excluding items for which highly uncertain values were found (Petersson *et al*., 2021 a and b), the lowest CF value was identified for wholegrain wheat flour (0.36 kg CO_2-eq/kg), while the highest for coffee parchment (8.29 kg CO_2-eq/kg), with the 25th, 50th and 75th percentile CF values for processed foods group being 0.82, 1.36 and 2.26 kg CO_2-eq/kg respectively.

Among beverages types, we found very similar values, all of which within the first quartile of the processed foods sample distribution: fruit juice (0.48 kg CO_2-eq/L), bottled water (0.49 kg CO_2-eq/L), vegetable milk (0.54 kg CO_2-eq/L), coffee (0.55 kg CO_2-eq/L), wine (0.66 kg CO_2-eq/L), and beer (0.69 kg CO_2-eq/L). The only solid food found within the first quartile of the processed foods distribution was sugar (0.78 kg CO_2-eq/kg), which includes both beet sugar (0.94 kg CO_2-eq/kg) and cane sugar (0.62 kg CO_2-eq/kg). Higher values, falling in the second quartile of the CF distribution, were detected for bread (0.86 kg CO_2-eq/kg), grain flour (0.87 kg CO_2-eq/kg), crackers (0.98 kg CO_2-eq/kg), tomato sauce (1.19 kg CO_2-eq/kg), pasta (1.21 kg CO_2-eq/kg), tomato puree/peeled/chopped (1.3 kg CO_2-eq/kg), legume flour (1.32 kg CO_2-eq/kg), and crispbread (1.35 kg CO_2-eq/kg). The median value of the processed foods category is represented by soy yogurt (1.36 kg CO_2-eq/kg). Values in the third quartile were detected for: margarine (1.39 kg CO_2-eq/kg), biscuits (1.47 kg CO_2-eq/kg, nuts paste (1.84 kg CO_2-eq/kg), sweets (1.99 kg CO_2-eq/kg), and oil (2.11 kg CO_2-eq/L). Fourth quartile values were detected for vegetable proteins such as soy burger, soy meal and tofu (2.27 kg CO_2-eq/kg) along with pesto sauce (2.72 kg CO_2-eq/kg), fruit juice produced through imported fruit (2.86 kg CO_2-eq/kg), egg pasta (3.15 kg CO_2-eq/kg), chocolate (3.16 kg CO_2-eq/kg), and ice-cream (4.3 kg CO_2-eq/kg), the latter corresponding to the upper fence of the processed foods category. Parchment/ground coffee is the most climate impacting processed ingredient found through this review (6.71 kg CO_2-eq/kg), with the Tukey test identifying it as an outlier.



Graph 6. Comparison between median CF values of processed food types.
Note: food types derived from less than 4 primary data values are not shown (values for yeast, breakfast cereals, frozen legumes, vegetable yogurt, vegetable cream, frozen bread, frozen fruit, frozen vegetables, dressing, canned legumes, canned vegetables, nuts covered with chocolate).
A star (*) is given when a type comprises a single item, thus they both correspond.
Two stars (**) are attributed to types represented by items whose sample data is constituted by a further level of disaggregate data.

Coffee production requires drying, roasting and grinding of green coffee, whose cultivation is highly carbon intensive owing to its low yields and high nitrogen inputs (Kilian *et al.*, 2013;

Birkenberg and Birner 2018). This results in high emission intensities compared to other crops, ranging from 1.9 to 7.30 kg CO_2-eq/kg for green coffee at farm gate (depending on cultivation methods). Moreover, GHG-e of coffee increases as a function of shipping distance from Central-South America, where it is typically produced for export to countries such as European ones. Higher energy intensity in the case of coffee is not only associated to milling and roasting operations but also to secondary packaging, given that the latter is generally made of plastic polymer and aluminium (C-LDPE 90) which have a higher GWP compared to other packaging materials (Birkenberg and Birner, 2018). Humbert *et al*. (2009) analysed coffee at further life stages, and determined the CF of coffee beverage to be 0.33 kg CO_2-eq/L for soluble coffee, 0.55 kg CO_2-eq/L for espresso, and to 0.73 kg CO_2-eq/L for filtered drip coffee.
Similarly, cacao is cultivated in tropical and subtropical areas of the world and mainly imported from other countries for industrial chocolate manufacturing. With respect to Italian dark chocolate production, Recanati *et al.* (2018) found that 42% of total emissions were attributable to farm stage, followed by 28% to chocolate manufacturing (which is highly energy intensive), 13% to aluminium folium packaging production and transport to the chocolate manufactory plant, 9% to shipping of cocoa beans across global distances, with the remaining 8% attributable to other processes such as production and transportation of jute and packaging and sugar transportation. The value for dark chocolate reported in the aforementioned study coincides with the median value for dark chocolate found in Petersson *et al*. (2021b) dataset: 2.71 kg CO_2-eq/kg. The contribution of farm stage increases for milk chocolate, due to the associated GHG-e of livestock systems, and results in higher GWP (Busser and Jungbluth, 2009): 3.6 kg CO_2-eq/kg for milk chocolate, and 4.1 kg CO_2-eq/kg for white chocolate.

In accordance with other studies (Korsaeth *et al.*, 2012) and EPDs (environdec.com) on main carbohydrate sources deriving from minimally processed wheat, we found a positive correlation between the number of processing phases required to obtain a product (e.g., milling, refining, baking and cooking for bread; mixing and drying for pasta) and its GWP. Whole wheat flour requires milling and grinding of wheat grain resulting in a median CF value of 0.36 kg CO_2-eq/kg. Plain wheat flour additionally requires refining, resulting in an increased CF (0.47 kg CO_2-eq/kg). Baking and cooking take place in bread production, resulting in 0.77 kg CO_2-eq/kg for wholegrain bread and 0.89 kg CO_2-eq/kg for plain bread. Additional processing phases take place in pasta production, such as mixing, extruding and drying, which explain the higher median value attributed to pasta: 1.21 kg CO_2-eq/kg.

In so far as global warming is concerned, sunflower oil is the best performing vegetable oil (0.98 kg CO_2-eq/kg), followed by soybean oil and rapeseed oil (1.79 kg CO_2-eq/kg), palm oil (2.43 kg CO_2-eq/kg) and extra virgin olive oil (EVO) (3.27 kg CO_2-eq/kg).

The high variability of GWP for EVO, whose values range from 0.63 and 17.5, is mainly linked to differences in: a) the practices and techniques for the agricultural production of olives (low input vs. high input), b) olive yield (kg//ha), c) EVO yield (kg oil/kg olives), d) the power system of the harvesting equipment (electric vs. fuel powered devices), e) the power system of the oil mill, along with the transport facilities chosen by the producers for distribution to the market (Salomone and Ioppolo, 2012; Rinaldi *et al.,* 2014). The highest CF value of our dataset is retrieved from an Italian study on the distribution of extra virgin olive oil to other EU countries by means of air-freight (Rinaldi *et al.,* 2014).

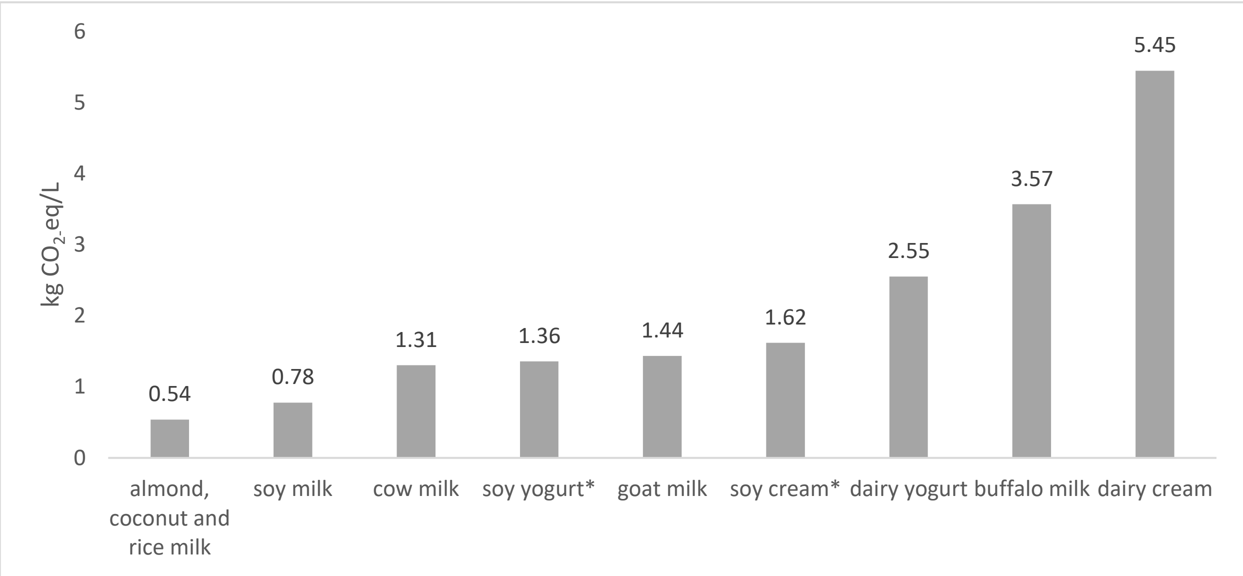
Pattara *et al.* (2016) identified N-fertilizers and pesticides, applied at the farm-level in intensive conventional agricultural systems, as a major contributor to GHG-e from olive production, alongside glass bottle packaging. Olive oil plants are energy intensive and require different processing phases, such as washing, grinding, heating, extracting, centrifugation. To reduce the impact of the olive oil milling plant both the use of waste as energy source and the shift toward green energy are a feasible solution (Romero-Gámez *et al*., 2017; Christoforou and Fokaides, 2016). According to the reviewed literature, traditional extensive low-input agriculture coupled with more sustainable packaging materials and transport would allow a significant reduction in the CF of olive oil (Tsaroushas *et al* 2015; Pattara *et al* 2016; Rinaldi *et al* 2014). Moreover, the percent of oil in olives varies both with the olive cultivar (some cultivars may have higher content in oil) and with the olive ripening stage / harvesting timing, ranging from 10% to 25% on mass basis. Harvesting at peak maturity may reduce significantly the CF of oil. Proietti *et al*. (2017) demonstrated that the extra virgin olive oil supply chain may be carbon negative under certain conditions: organic or low input agricultural management, the use of electrical instruments for harvesting and pruning operations, and local transformation and distribution (farm-to-table product).

Among alcoholic beverages, wine (0.66 kg CO_2-eq/L) and beer (0.69 kg CO_2-eq/L) have similar CF values. For red wine, five journal papers were reviewed focusing primarily on Italian wine production (Vázquez-Rowe *et al*., 2013; Pattara *et al* 2012; Bosco *et al* 2011; Petti *et al*., 2006; Aredente *et al*., 2006). The production and distribution of 1L of bottled red wine produced GHGe in the range of 0.32 - 2.13 kg CO_2-eq/L. Vázquez-Rowe *et al*. (2013) calculate the CF of 9 different types of wine in Italy, Spain and Luxembourg, highlighting how the variability of CF values is linked to a number of factors, such as grape yields, agricultural practices (organic vs. conventional), wine ageing, and optimization of inputs. In this study, the lowest CF value - coinciding with the minimum of our sample data for red wine - was found for an Italian organic wine, whilst the highest for a Spanish conventional, the latter owing to higher fuel emissions, fertilizers and pesticide application during the farming stage. As regards post-farm gate emissions, a large variability was found for the winemaking process, with values in the range of 0.16 - 1.55 kg CO_2-eq/L coupled with a high positive correlation between emissions and aging time (r^2 = 0.83). Moreover, production emissions for 1 L of glass bottle ranged between 0.23 and 0.67 kg CO_2-eq as an increasing function of bottle weight. According to the reviewed studies, a significant reduction in the CF of wine may be achieved through organic cultivation or management practices aimed at reducing chemical fertilizers and pesticides (Vázquez-Rowe *et al*.,2013; Ardente *et al.,* 2006) as well as minimizing energy inputs and materials in wine production and packaging (Vázquez-Rowe *et al*., 2013; Bosco *et al.,* 2011; Ardente *et al.,* 2006).

For beer production we retrieved 19 values from different EPDs, journal papers and conferences. We found a direct correlation between packaging type and CF values: lowest values were detected for beer in 10-20 L modular cans (0.50-0.59 kg CO_2-eq/L), followed by beer in 33-44 cc cans (0.51-0.9 kg CO_2-eq/L), and beer in 33 cc glass bottles (0.42-2.27 kg CO_2-eq/L). These findings are consistent with the reviewed literature, which agrees in attributing the hot spot of beer industries to packaging production (Amieno *et al*., 2016; Cimini and Moresi 2016).

Graph 7 shows the median CF values in increasing order of emissions for various plant-based and dairy-based milk, yogurt and cream products. Despite the increasing availability and demand for dairy substitutes worldwide, LCA studies on plant-based analogues are scarce. Floren *et al.* (2013)'s LCA analysis reports emissions in the range of 0.24-0.34 kg CO_2-eq/L 1 L for packaged oat milk at Swedish retailers. For 1 L of packaged almond milk Winans *et al.* (2020) report the value of 0.5 kg CO_2-eq/L (transport to RDC not included). Among studies excluding both packaging and transport, Henderson and Unnasch (2017)'s LCA study estimated emissions for pea, almond and soy milk at 0.31, 0.27, 0.30 kg CO_2-eq/L respectively, while Grant & Hicks (2018) found 0.28 kg CO_2-eq/L for almond milk and 0.17 kg CO_2-eq/L for soy milk (values not included in Petersson *et al*., 2021).

For almond and coconut milk we extracted values of 0.39 - 0.44 kg CO_2-eq/L from a conference paper (Feraldi *et al*., 2021), while 3 Italian EPD's reported rice milk values ranging between 0.64 and 1.09 kg CO_2-eq/L. Since data for rice and coconut milk included in the database shows high uncertainty, mainly due to low sample size (n<4), we used the median value of vegetable milk type as a better estimate (0.54 kg CO_2-eq/L); the latter figure is consistent with the aforementioned studies provided the addition of a standard share of CF for packaging and transport to RDC (0.14 kg CO_2-eq/L) as described by Petersson *et al.* (2021a). Within the vegetable milk type of our database, the median value of soy milk can be taken as a reference value: low uncertainty is present in its estimation, having been derived from 22 normally distributed underlying values (results of



Graph 7. CF values among plant based and animal-based dairy products. Data extracted from Petersson *et al* 2021b.

Shapiro-Wilk normality test). The higher value for soybean milk reflects the inclusion in the original LCA of the GWP of land use change and deforestation to create soybean fields in South America. In sum, vegetable milk, yogurt and cream types are 2 to 3 times less carbon intensive than their dairy analogues.

The majority of processed food items (55) is associated with highly uncertain values: substitution thereof with the median value of the reference type is highly recommended. 34 out of the 100 processed food items show low uncertainty values. Among the remaining 11 items, each uniquely representing an overarching type (i.e., egg pasta, margarine, soy yogurt, soy cream, mineral water, frozen raspberries, frozen bread, cornflakes, dried yeast, compressed yeast, liquid yeast), only margarine and egg pasta were associated with low estimate uncertainty. For the majority of EPD analysed, the hot spot is identified as the ingredients production at farm stage, which contributes to roughly 50% of the CF from cradle to distribution, followed by industrial production which represent the core phase of the life cycle of processed foods.

Table 17. Descriptive statistics for processed foods.

FOOD TYPE	FOOD ITEM	n	kg CO_2-eq/ kg or litre food commodity $\bar{x}$	Me	sd	min	max	mad	25%	75%	CV
BEER	beer modular can	5	0.54	0.53	0.03	0.50	0.59	0.03	0.52	0.58	0.06
BEER	beer in can	5	0.69	0.69	0.14	0.51	0.90	0.12	0.58	0.77	0.20
BEER	beer in glass	9	1.03	0.96	0.52	0.42	2.27	0.29	0.67	1.17	0.50
BISCUITS	simple cookies**	12	1.50	1.39	0.35	1.11	2.35	0.18	1.25	1.60	0.23
BISCUITS	chocolate or cream filled cookies**	9	1.69	1.53	0.38	1.33	2.39	0.13	1.45	1.69	0.23
BOTTLED WATER*	mineral water*	2	0.49	0.49	0.07	0.42	0.56	0.07	0.46	0.53	0.14
BREAD	bread whole**	5	0.78	0.77	0.13	0.55	0.91	0.12	0.76	0.89	0.17
BREAD	bread plain**	9	0.97	0.89	0.25	0.61	1.54	0.06	0.85	0.98	0.26
COFFEE GROUND & PARCHMENT	coffee parchment	4	8.47	8.29	1.74	6.34	10.94	1.40	7.17	9.59	0.21
CRACKERS	flavored crackers**	4	1.01	0.93	0.15	0.91	1.26	0.02	0.91	1.02	0.15
CRACKERS	wholegrain crackers**	17	0.99	0.97	0.31	0.49	1.43	0.29	0.71	1.32	0.31
CRACKERS	plain crackers**	8	1.24	1.35	0.20	0.97	1.45	0.08	1.02	1.39	0.16
CRISPBREAD**	crispbread**	6	1.36	1.35	0.11	1.19	1.53	0.08	1.30	1.45	0.08
EGG PASTA*	egg pasta*	5	3.19	3.15	0.77	2.41	4.55	0.64	2.51	3.33	0.24
FRUIT JUICE LOCAL	orange juice	13	0.62	0.46	0.46	0.24	2.00	0.06	0.42	0.52	0.74
GRAIN FLOUR	whole wheat flour	6	0.38	0.36	0.09	0.27	0.51	0.09	0.29	0.45	0.24
GRAIN FLOUR	durum wheat	4	0.48	0.47	0.06	0.40	0.57	0.05	0.43	0.51	0.13
GRAIN FLOUR	wheat plain flour	16	0.61	0.52	0.23	0.33	1.18	0.11	0.47	0.72	0.38
GRAIN FLOUR	oat meal	5	1.13	0.87	0.61	0.69	2.32	0.14	0.74	1.01	0.54
MARGARINE*	margarine*	6	1.43	1.39	0.24	1.10	1.80	0.21	1.26	1.61	0.17
OIL	sunflower oil	5	0.99	0.98	0.08	0.90	1.12	0.05	0.94	1.03	0.08
OIL	rapeseed oil	9	2.40	1.79	1.27	0.40	4.30	1.38	1.54	3.63	0.53
OIL	soybean oil	6	2.30	1.79	1.24	1.07	4.30	0.63	1.28	3.26	0.54
OIL	palm oil	5	2.32	2.43	0.76	1.01	3.32	0.27	2.16	2.65	0.33
OIL	olive oil	45	3.84	3.27	2.85	0.63	17.53	1.05	2.58	4.56	0.74
PASTA*	pasta*	48	1.24	1.21	0.44	0.55	2.30	0.33	0.87	1.50	0.35
SUGAR	cane sugar	7	0.67	0.62	0.37	0.28	1.51	0.20	0.42	0.70	0.56
SUGAR	beet sugar	9	0.89	0.94	0.30	0.26	1.31	0.27	0.67	1.05	0.34
SWEETS	cocoa cakes and croissant**	9	1.97	1.94	0.37	1.45	2.62	0.22	1.83	2.16	0.19
SWEETS	cakes and croissant**	14	2.23	2.14	0.38	1.64	3.09	0.23	1.96	2.47	0.17
TOMATO PUREE, PEELED, CHOPPED	tomato puree	7	1.17	1.03	0.22	0.96	1.56	0.07	0.99	1.33	0.19
TOMATO PUREE, PEELED, CHOPPED	tomato chopped	4	1.41	1.47	0.16	1.14	1.56	0.04	1.39	1.49	0.11
TOMATO SAUCE	tomato & basil	4	1.15	1.14	0.12	1.02	1.29	0.11	1.04	1.25	0.10
TOMATO SAUCE	tomato arrabbiata	4	1.26	1.24	0.14	1.07	1.46	0.11	1.16	1.34	0.11
VEGETABLE CREAM*	soy cream*	1	1.62	1.62	-	1.62	1.62	-	1.62	1.62	-
VEGETABLE MILK	soy milk	22	0.85	0.78	0.26	0.28	1.40	0.14	0.70	0.95	0.31
VEGETABLE PROTEINS	tofu	4	2.33	2.27	0.96	1.07	3.72	0.73	1.77	2.84	0.41
VEGETABLE YOGURT	soy yogurt*	1	1.36	1.36	-	1.36	1.36	-	1.36	1.36	-
WINE	wine red	17	1.02	0.87	0.48	0.32	2.13	0.38	0.71	1.38	0.47

A star (*) is given to items that also constitute types. Two stars (**) are given to items that comprise a further level of disaggregated data.

3.5.1 Mitigation options

Although food processing and packaging contribute only to 3.5% and 5.5% of Foods systems annual GHG emissions, respectively (Crippa *et al*., 2021), food processing industries are still highly energy and resource-intensive, thus more sustainable options should be implemented within this sector. The mitigation potential of industrial production may involve both farm-stage mitigation practices as well as improving the energy efficiency of production plants in the core processes, such as by limiting energy losses, increasing the amount of renewable energy sources or allocating waste products as resources for other industries or for energy recovery. Improving waste management practices for biofuel and electricity production is a feasible option to reduce the global warming potential of the food processing sector (Hall and Howe, 2012). Indeed, biogas, owing to its carbon neutrality, is a more sustainable energy source compared to fossil fuels. Bacenetti *et al*. (2015) demonstrated a 6% GHGe reduction by using crop discards and residues from tomato processing for biogas production in combination with a Heat and Power engine for energy production, compared to residue returned to soil. The adoption of grid-connected roof-top solar photovoltaic systems (PV) by the processing industries is a promising avenue for reducing both energy cost and GHG-e emissions (Cucchiella et al., 2015). Although photovoltaic systems cannot be regarded as 100% carbon neutral, since environmental impact occurs during their production, they are nonetheless more sustainable energy sources when compared to fossil fuels. Tawalbeh *et al*. (2021) found CFs of PV systems during LCA to be in the range of 14-73 g CO_2-eq/kWh, which is 10 to 53 orders of magnitude lower than the emissions reported from the burning of oil (742 g CO_2-eq/kWh). Another study estimated a saving of 2-3 tons of CO_2 annual emissions for each square meter of concentrating solar power (CSP) systems, compared to energy produced though fossil fuels (Shahsavari and Akbari 2018). Moreover, packaging was found by the present review to contribute significantly to the GWP of products, in some cases being identifiable as the hot-spot stage (Amieno *et al*., 2016; Cimini and Moresi 2016); therefore, studies aimed at highlighting alternative and less carbon-intensive packaging options should be incentivized (Birkenberg and Birner, 2018; Vázquez-Rowe *et al*., 2013; Bosco *et al.,* 2011; Ardente *et al.,* 2006). A recent implemented initiative regards reverse logistic practices especially for glass packaging. This practice consists in incentivizing customers to return glass bottles and jars to producers, allowing their reuse. The rationale is that washing and transport operations not only reduce resource depletion but also produce lower emissions compared to transport to landfill sites or recycling (Almeinda *et al*., 2017; González-Torre and Adenso-Díaz, 2006).

CHAPTER 4: COMPARING THE GLOBAL WARMING POTENTIAL OF PROTEIN SOURCES

In this chapter we explore the use of alternative functional units (FU), such as CF expressed as protein content and serving size for main protein sources, which this study identifies as the variable enabling the greatest mitigation potential by food choices.

4.1 Introduction

The use of alternative FU to compare environmental performance of food products is increasing. A number of authors have examined the effects of applying alternative FU to the commonly used mass FU: serving-based (Kägi *et al*., 2012), average daily intake (De Vries and de Boer, 2010) nutrient-based (De Vries and de Boer, 2010; Williams *et al*., 2006; Heller and Keoleian, 2012; Kägi *et al*., 2012), energy density (Heller and Keoleian, 2012).

Indeed, when addressing the sustainability of food or dietary patterns, the use of mass functional units, which are common in LCA studies, might not be appropriate given that they account neither for nutrient variation nor differences in standard serving size across foods.

Meat, dairy and fish are appreciated for their high content (ranging between 3.3% and 33.9%) of highly valuable proteins that are well balanced in their amino acid composition. On the contrary, legumes and cereals show generally lower relative protein percentages, lower digestibility and unbalanced amino acidic profile, although with some exceptions. Lupin and soybean, for example, have shown on average 38-40% of protein content (Duranti, 2006). Pseudo-cereals such as quinoa (Chenopodium spp.), amaranth (Amaranthus spp.) and buckwheat (Fagopyron spp.) have a complete and well-balanced amino acid profile (Janssen *et al*. 2017). Moreover, legume and cereal proteins are nutritionally complementary, thus essential amino acid deficiencies are overcome by integrating legume-based dishes with cereal foods within a daily diet (Young and Pellet, 1994; Mariotti and Gardner, 2019).

4.2 Materials and methods

With the aim of enabling comparisons of foods' environmental performance on the basis of nutritional value and recommended meal serving-size, we recalculated the FU as protein content (kg CO_2-eq/Kg protein) and standard serving size (kg CO_2-eq/ serving).

Median CF values on mass-basis FU for high protein rich food commodities reported by Petersson *et al.* (2021b) dataset are taken as primary data. We obtained GWP in terms of kg CO_2eq/kg protein applying specific food conversion factors on the basis of average % protein content (PC)

Protein source	(SPS) standard serving size (g)	(PC) protein content (%)	FU Kg CO_2-eq/Kg	FU Kg CO_2-eq/Kg protein	FU Kg CO_2/serving size
soybean	50	36.9	0.56	1.52	0.028
bean	50	24.0	0.43	1.79	0.022
pea	50	23.9	0.45	1.88	0.023
cowpea	50	25.2	0.49	1.94	0.025
sardine	150	21.5	0.90	4.19	0.135
anchovie	150	18.5	0.82	4.43	0.123
tofu	100	49.5	2.27	4.59	0.227
herring	150	21.5	1.24	5.77	0.186
mussel EF	150	14.9	0.46	6.04	0.069
quinoa	80	15.4	0.97	6.30	0.078
mackerel	150	21.4	1.80	8.41	0.270
salmon	150	23.0	3.37	14.68	0.506
tuna	150	23.6	3.68	15.59	0.552
chiken BFM	100	23.3	3.68	15.79	0.368
turkey BFM	100	24	4.08	17.00	0.408
cod	150	17.8	3.08	17.29	0.462
trout	150	20.8	4.20	20.22	0.630
sea-bass	150	17.8	3.60	20.22	0.540
egg[1]	100	12.4	3.20	25.81	0.320
pork BFM	100	21.3	5.72	26.85	0.572
parmigiano reggiano	50	32.4	12.54	38.70	0.627
cow milk	125	3.3	1.31	39.70	0.164
cheddar	50	26.7	11.21	41.99	0.561
mozzarella	100	18.7	8.20	43.85	0.820
yogurt white	125	3.8	1.69	44.47	0.211
grana padano	50	33.9	15.34	45.25	0.767
prawn/shrimp	150	14.0	7.04	50.29	1.056
pecorino	50	28.8	17.15	59.55	0.858
hake	150	16.5	10.40	63.03	1.560
lobster	150	18.0	20.25	112.50	3.038
beef BFM	100	20.5	25.75	125.61	2.575
lamb BFM	100	20	25.23	126.15	2.523

Table 18. Protein content of food items was extracted from: FAO/INFOODS Global food composition database for fish and shellfish – version 1.0 (uFiSh1.0) – 2016; FAO/INFOODS Global Database for Pulses on Dry Matter Basis – version 1.0 (PulsesDM1.0) – 2017; Bhardwaj *et al* (1999); www.crea.gov.it/alimenti-e-nutrizione.
Legumes are considered in dry weight; all meat products and mussels are expressed as bone-free meat (BFM) or edible fraction (ED). Standard serving sizes are extracted from SINU LARN (2014).
[1]Eggs serving size was increased by 2-fold (e.g., 100g) compared with LARN standard serving size (50g).

reported by FAO/INFOOD database, CREA dataset on food and nutrition and peer-reviewed papers. On the other hand, serving size FU (kg CO_2-eq/serving) is determined with reference to standard serving size (SPS) of common protein sources provided by SINU-LARN guidelines (2014).

4.3 Results and discussion

With the exception of rice and egg pasta, sources of complex carbohydrates display consistently low GHG-e (0.48-1.35 kg CO_2 eq/kg), with the lowest impact found for wholegrains. On the other hand, oils and fats are usually employed in meal preparation as dressings, that is, in small amounts, thus cannot account for a significant share of food-related GHG-e. Contrastingly, high amounts of protein-containing foods must be consumed in order to meet protein daily requirements (0.8 g protein/kg body weight according to WHO guidelines), given that food protein percentages are relatively low (see PC percentages in Table 18). Moreover, a large variation in GHG-e is present across different protein sources, spanning between 0.45 to 25.75 kg CO_2 eq/kg. These facts combined point to protein source as harbouring the highest environmental impact mitigation potential for food consumption.

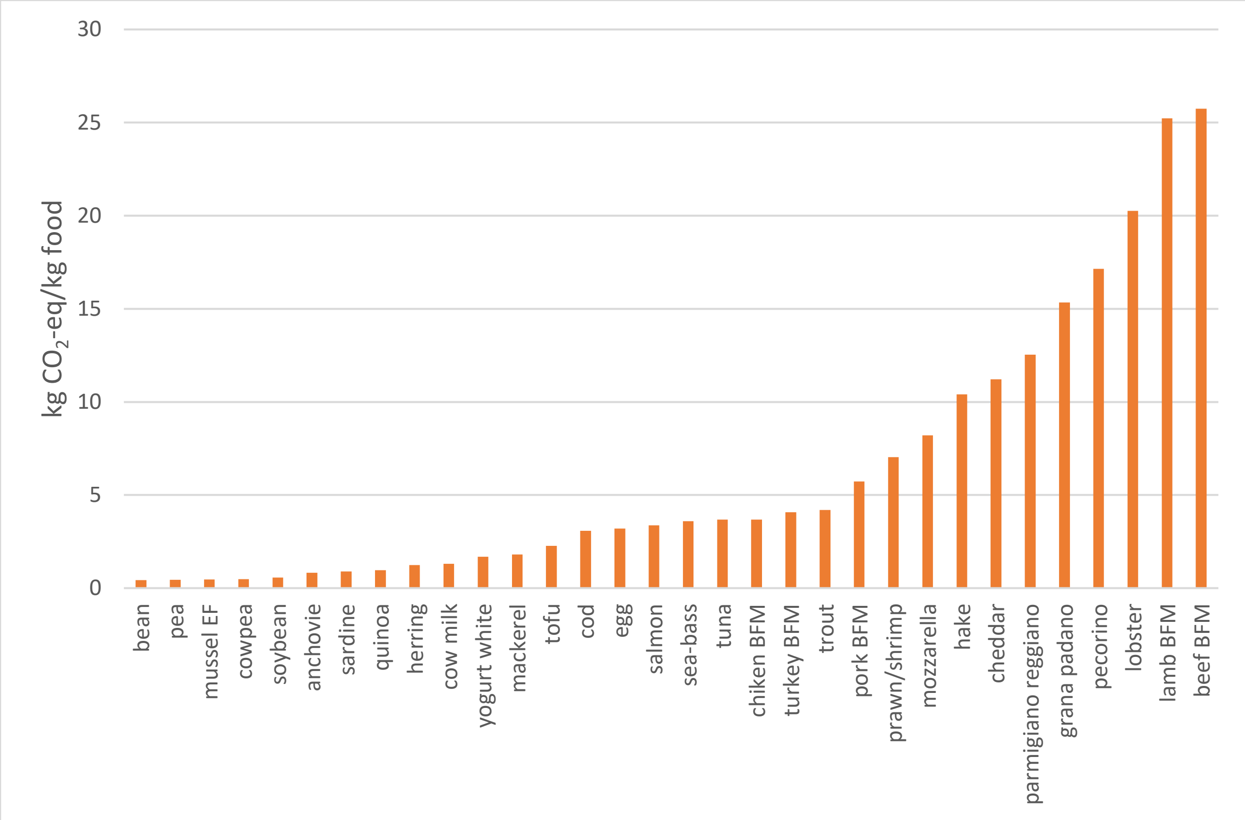
The relative sustainability of plant-based protein rich food compared to animal derived foods increases when comparing their GWP both on the basis of equivalent protein content or meal servings. For example, on a mass-basis FU, legumes are 50 times less carbon intensive than beef and lamb meat, 19 times lower than hard and semi-hard cheese, 12 times lower than pork meat, 11 times lower than fresh cheese and approximately 7 times less impacting than poultry meat and eggs. Adopting a protein FU, legumes have an average value of 1.78 kg CO_2-eq/kg protein, 70.7 times lower than the average value of beef and lamb (125.89 kg CO_2-eq/kg protein), whereas from a serving-based FU the contrast is even starker being the emissions of legumes 106 times lower than those of beef/lamb (0.024 vs 2.55 kg CO_2-eq/serving). Indeed, for bean, pea, soybean and cowpea alternative FU range between 1.52 and 1.94 kg CO_2-eq/kg protein and between 0.022 and 0.028 kg CO_2-eq/serving.

Sardine, anchovy, mussels, quinoa, herring and tofu have a similar climate impact both on protein-basis and serving-basis FU, with values in the range of 4.19-6.30 kg CO_2-eq/kg protein (lowest for sardine and highest for quinoa) and 0.08-0.23 kg CO_2-eq/serving (lowest for quinoa and highest for tofu). Mackerel has slightly higher emission values with 8.41 kg CO_2-eq/kg protein and 0.27 kg CO_2-eq/serving.

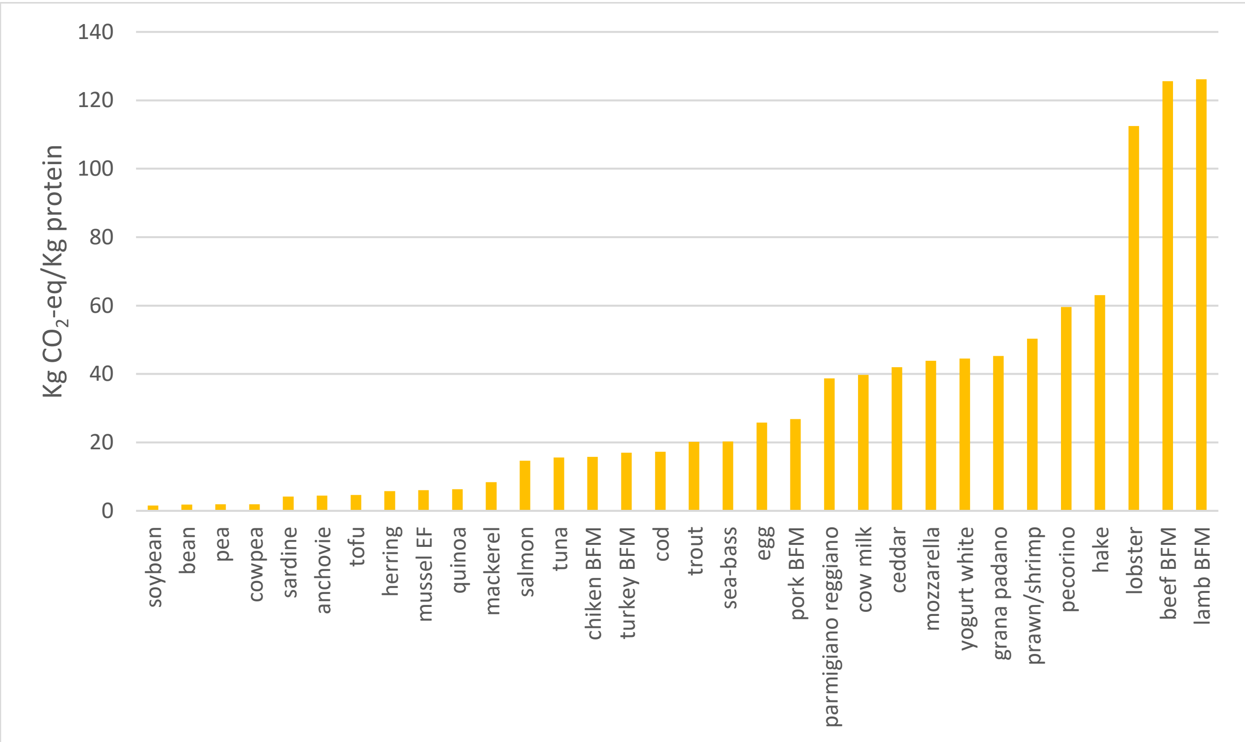
The GHG-e for producing 1 kg of protein from certain fish (salmon, tuna and cod) are found to be similar to poultry meat (chicken and turkey BFM) ranging from 14.7 to 17.3 kg CO_2-eq. Higher emissions are attributed to trout and seabass (20.22 kg CO_2-eq/kg protein for both) although with lower emissions on serving-basis for seabass.

Eggs and pork meat are similar in terms of protein FU (25.8 and 26.81 kg CO_2-eq/protein, respectively) but differ on serving-basis FU: 0.32 kg CO_2-eq/serving for eggs and 0.57 kg CO_2-eq/serving for pork meat.

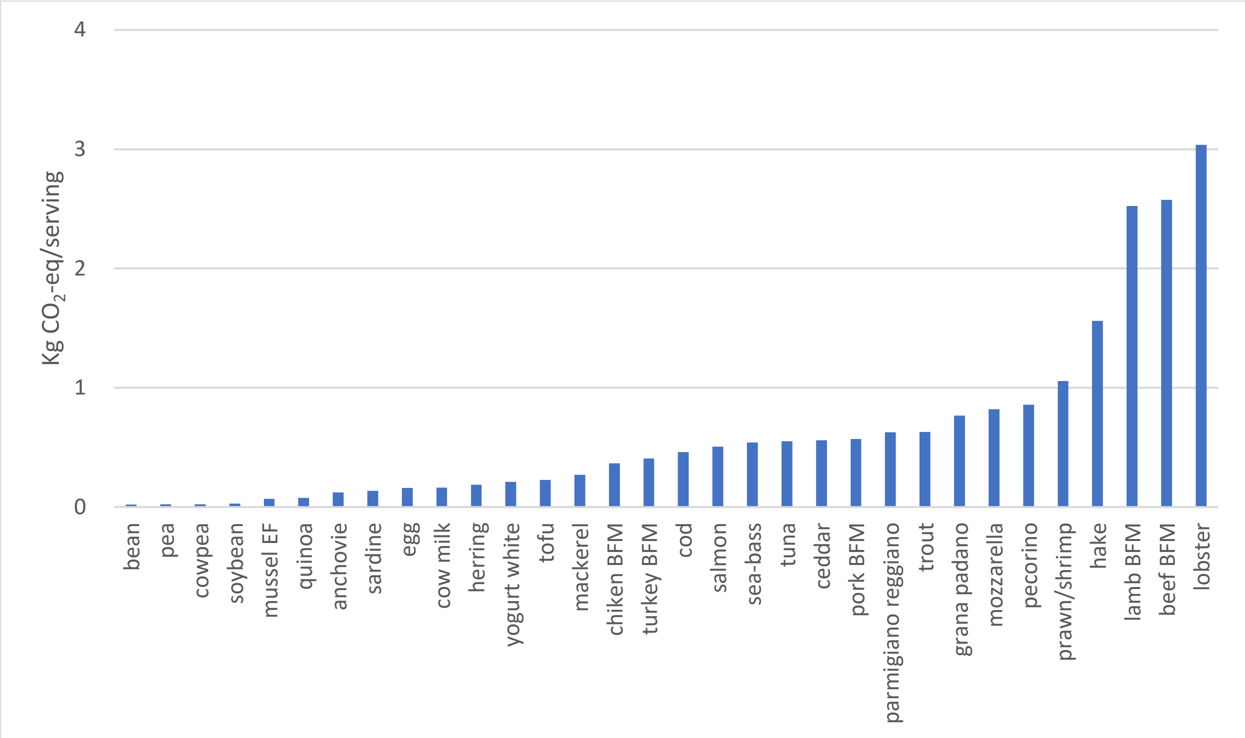
Cow milk and yogurt should be treated separately since they are generally consumed in breakfasts and snacks rather than in main meals. Nerveless, when comparing milk and yogurt footprints, the CF of yogurt was 30% higher than that of milk when reported per kilogram of product (1.69 vs. 1.31 kg of CO_2eq/kg), but only 12% higher when reported per kilogram of protein because of the higher protein density in yogurt than in fluid milk. Moreover, the beneficial effects of probiotics in yogurt are highly valued for the well-being of the human intestine microbiome and immune system (Adolfsson, 2004) and trade-offs between human health and climate impact should be well balanced. All cheese displays high GWP irrespective of the FU considered. Carbon-intensity for cheese ranges between 38.70 and 59.55 as kg CO_2-eq/kg protein and between 0.63 and 0.86 kg CO_2-eq/serving, highlighting a great GHG-e reduction potential from diets that limit cheese intake. Among seafoods, prawns, shrimps, hake and lobster should be discouraged and rather treated as an occasional food. For 1 kg of protein intake from fresh prawn or shrimp more than 50 kg of CO_2-eq are released into the atmosphere, with more than 1 kg CO_2-eq being generated from a 150g serving. Lobster supersedes/displaces the record hold by beef and lamb for being the most climate impacting food on serving-based FU with more than 3 kg CO_2-eq/serving (buffalo meat not considered). Beef and lamb meat can be considered equivalent food items both from a nutritional standpoint as well as with respect to their GWP values (irrespective of the FU considered): 1 kg of meat generates 25.5 ± 0.25 kg CO_2-eq, 1 kg of protein 125.9 ± 0.28 and a meal serving 2.55 ± 0.026 kg CO_2-eq.



Graph 8. CF expresses as mass FU for different protein sources. For detailed values see Table 18.



Graph 9. Equivalent protein content FU applied for main protein sources. For detailed values see Table 18.



Graph 10. Serving-based FU applied for main protein sources. For detailed values see Table 18.

4.4 Conclusions

This study highlights how protein source plays a central role in determining diet sustainability; lesser mitigation potential can be achieved among fat sources, which have a moderate recommended daily intake, or among principal carbohydrate sources, which are all plant-based. This analysis shows how, whether by using mass FU, protein FU or serving FU, the lowest negative climate impact of food choices is achieved by legumes and the highest by beef, lamb, and lobster. Moreover, the low GWP of small-to-medium wild pelagic fish and mussels is consistently revealed by all the alternative functional units tested, therefore identifying them as valuable food commodities to be included in omnivorous diets aimed at reducing the climate change pressure of food systems. The high protein content (15,4%) of Quinoa along with well-balanced amino acid composition (Janssen *et al*. 2017) and the low CF per kg (0.97) renders this pseudo-cereal a promising sustainable and healthy alternative to animal-based foods. With the exception of crustaceans and hake, other fish products and poultry meat show a moderate GWP both on mass, protein, and serving size FU, and might still be part of well-planned sustainable, healthy and varied nutritional patterns, provided they do not exceed meal serving-sizes and recommended week-intake.

The most effective mitigation option from diets is to avoid all ruminants' products, both dairy and meat, when attempting to meet human body protein requirements, given that this study identifies several valuable alternatives.

CHAPTER 5: SU-EATABLE LIFE: ENGAGING CITIZENS IN THE ADOPTION OF SUSTAINABLE AND HEALTHY DIETS

Here we present the Su-Eatable Life project (LIFE16 GIC/IT/000038), a three-year project financed by the EU LIFE program, aimed at reducing greenhouse gas emissions and water consumption related to food choices by incentivizing EU citizens to adopt a healthier and more sustainable diet. As part of the project, a series of engagement activities were carried out at company canteens located in Italy during 6/8-months-long pilot experiments. We reviewed the latest definitions of sustainable and healthy diets as well as best practices aimed at engaging citizens in sustainable behaviours. On this basis we defined and promoted healthy and sustainable dietary guidelines and developed engagement tools to be applied during the pilot experiments. We monitored customer food choices at baseline and during the experimental phase that followed, and determined the WF and CF reduction as both the average monthly difference from baseline values and the difference from baseline observed at the last experimental month alone (end-point analysis). The research highlights the effectiveness of experiments in reducing greenhouse gas emission (GHG) and water consumption, especially when sustainable dishes meet consumer tastes and local gastronomic culture.

5.1 Engaging citizens in sustainable behavior

Making the environment a priority begins at the individual level (OECD, 2013). Indeed, behavioural choices that people take on a day-to-day basis play a fundamental role in enhancing global sustainability. However, successful and purposeful engagement of individuals in climate action and sustainability activities is an ambitious challenge, particularly because economic, technological, cultural and psychological barriers need to be overcome. Despite established sustainable food consumption targets (Willet et *al*., 2019), there is still the need to identify effective measures and interventions for social engagement. People are generally not knowledgeable of the extent to which food products differ in their climate impact. There are also some misconceptions regarding the nutritional value of plant-based foods compared to animal-derived ones (Shi *et al*., 2018). Moreover, there is a certain disbelief about the effects of personal food choices in mitigating climate change (Macdiarmid *et al*., 2016; Mäkiniemi and Vainio, 2014). Lack of awareness, information and knowledge have been recognized as major barriers preventing from participating in pro-environmental behaviours (Schultz, 2002); indeed, as demonstrated by Peschel *et al*. (2016), high knowledge levels drive environmentally sustainable food choices. Most programs aimed at fostering sustainable behaviour rely upon information campaigns consisting of lectures, printed brochures, TV broadcasts and interviews. According to the Center for Climate and Energy Solutions, successful engagement programs often incorporate four main components, namely:

- *Education*: people must be aware of a problem and/or the opportunity for action before any engagement can occur; providing accessible and credible information will help avoid dismissal or scepticism and ensure understanding;
- *Empowerment*: people can respond positively to a call to action if they have the capacity and possibility to engage; if there are obstacles to action, the program should seek to empower by illuminating options and setting out a clear path forward;
- *Call to action*: a successful call to action is inviting, clear, and well-communicated;
- *Recognition*: people stay more engaged when they have a clear indication of the impact of their actions and are given positive reinforcement for changing their behaviour.

5.1.1 Experimental engagement activities

In order to raise awareness/knowledge on the issue of diet sustainability as well as to measure resulting environmental impact reductions, a series of dietary choice experiments and related engagement activities were implemented. At the core of the experiments are the following tenets:

• Dietary choices should be based on a balanced and healthy diet standard, as defined by the world leading experts. Among the latter are the World Health Organization (WHO 2018), the Joint WHO/FAO Expert Consultation on diet, nutrition and the prevention of chronic diseases (Geneva 2002), the British Dietetic Association (BDA), and the EAT-Lancet Commission on Food, Planet, Health. In this regard, healthy diets are generally considered to include a diversity of nutrient-rich foods, such as vegetables, fruits, whole grains, pulses (beans, legumes, nuts and seeds), unsaturated vegetable oils, with modest amounts of meat, fish, eggs and dairy (Willet *et al*., 2019; GLOPAN 2016).

• Dietary choices should bring clear and recognized benefits to the environment, in particular to GHG emission reduction and water footprint reduction. In this regard, there is compelling evidence of environmental benefits from reducing consumption of bovine and ovine meat as well as dairy products, while increasing plant-based food nutrients (Willet *et al*., 2019; Poore and Nemecek, 2018; Vanham, 2018; Clune *et al*., 2017).

- Dietary options at canteens and in everyday life should also bear in mind side actions which might have a minor, although still recognizable impact on the targeted environmental issues. Examples are preference for fresh food, reduction of food waste, avoiding the use of bottled water, and recycling.

5.2 Su-Eatable Life project

The experimental engagement activities were carried out as part of the broader project 'SU-EATABLE LIFE' (SEL), that is, a three-year project (Nov. 2018 – Apr. 2022), financed by the EU LIFE program, aimed at reducing food-related GHG emissions and water consumption by encouraging EU citizens to adopt a healthier and more sustainable diet. The project is coordinated by Riccardo Valentini, Full Professor of Forest Ecology at Tuscia University, Italy, and member of the Intergovernmental Panel on Climate Change (IPCC). The leading project partner is Barilla Centre for Food and Nutrition (BCFN), an independent multidisciplinary think tank promoting research and interventions in the field of food and environmental sustainability. Other partners of the project include: a) TheGreenApes, a Benefit Corporation whose mission is to foster sustainable lifestyles through the development of the greenApes app; b) Wageningen University's department of Social Science, specialized in innovative approaches to health and nutrition promotion; c) the Sustainable Restaurant Association (SRA), a NGO supporting 8,000 restaurants and food service providers in the UK engaged in promoting sustainability in the food service industry.

5.2.1 Location and timeframe of experiments

The pilot experiments/engagement activities were originally designed to involve 6 company and university canteens, located throughout Italy and England, for a period of 8 months (Dec. 2019 – Jul. 2020). Due to the COVID-19 health emergency and limitations, the experiments were forcibly interrupted at the beginning of March 2020. Hence, a new implementation plan was designed and the experiments were rebooted in Autumn 2020. Unfortunately, due to protracted COVID-19 restrictions, 4 out of the 6 canteens initially adhering to the project were unable to engage in the reboot of the experiments: for these locations the experiments are still ongoing and will end in April 2022. The remaining 2 canteens that have completed the experimental phase both belong to Italian companies: *Pavesi* and *Ducati Motors*. *Pavesi* is a food company located in Piedmont Region, Italy that is part of *Barilla* group and operates in the confectionary industry; its canteen is managed by *Felsinea* catering service and features a daily average flow of 350 employees; both customers and catering staff at this canteen were previously engaged in a health food campaign promoting the adoption of healthy food choices. *Ducati Motor* is an Italian motorcycle manufacturer; it has its headquarters in Bologna, in the Borgo Panigale district; its canteen is also managed by *Felsinea* catering service and has a daily flow of 1155 employees on average.

5.2.2 Participants

A printed or online baseline survey (delivered by newsletter or e-mail) was submitted to a total of 1500 experimental subjects, that is, all Ducati and Pavesi canteen-attending employees. The survey aimed at gauging participants' initial knowledge of healthy diets and/or sustainable diets, the principal perceived barriers and drivers towards effecting dietary change as well as basic socio-demographic information. The survey characterized the experimental subjects as having an age ranging from 20 to 60 years, a low-to-middle educational level and low-to-middle income depending on company role. In Pavesi canteen, the gender ratio was close to one, while in Ducati there was a preponderance of male gender. Additionally, while for Ducati employees background knowledge of healthy diets was heterogenous and reflected differences in life-style, all Pavesi customers had a robust knowledge of healthy diets, as a result of the information campaign on healthy diets (Mediterranean Diet) that had been conducted within Pavesi canteen environment during the preceding year.

5.3 Preparation phase

During the preparation phase (Sep. - Nov. 2019) three main activities were performed: the development of the information/engagement campaign tools, CF and WF assessments from canteen procurement time series, and the analysis/adjustment of canteen menus to meet healthy dietary guidelines.

5.3.1 Engagement tools

Several printed and digital educational materials were produced/made available for the experimental phase: a) SEL dietary guidelines (printed and digital), b) the sustainable cookbook (digital), c) symbols to label sustainable dishes on canteen printed/on-screen menus, d) the Green Apes app (digital), e) various canteen set-up material displayed during the information campaign: posters, banners, table talkers (printed), as well as two educational videos played on canteen screens during the first 2 experimental months (topics: food & climate / sustainable diets).

a) With the aim of enhancing motivation for dietary shift we developed the SEL dietary guidelines highlighting the linkage between sustainable diets and healthy diets. The SEL guidelines were further summarized in 8 key principles and actions; indeed, as highlighted by Schulte-Mecklenbeck *et al*. (2013), synthetic decision-making rules may better stir consumers towards lower environmental impact food choices. The 8 key principles were promoted during the engagement phase in the form of table talkers and brochures. A majority of these principles focuses on actions reducing foods GHG-e and water footprint, with positive or neutral effects on health. However, principles 7 and 8 target other environmental issues. Hereunder are the Su-Eatable Life key principles:

1. **Champion plant-based food in your diet**
Make vegetables, legumes, nuts and fruit the basis of your daily diet

2. **Treat meat as a luxury**
Enjoy meat in moderate amounts, especially red and processed meat

3. **Enjoy dairy products in moderation**
Consume dairy products, including milk, in moderation

4. **Avoid too much**
Avoid too much food on your table and in your daily diet to avoid excess calories and food waste

5. **Celebrate variety**
Explore the biodiversity that nature offers. Vary your diet with the seasons and try local varieties or heritage breeds

6. **Fresh is best (for you, and the environment)**
Favor fresh and minimally processed foods in your diet

7. **Drink tap water whenever possible and safe**
Drink plenty of water, chasing tap over bottled wherever it is possible and safe

8. **Reduce single-use!**
Reduce/reuse/recycle food packaging by carrying along your own bags, cups and cutlery whenever feasible. Choose food with minimum packaging and recycle/reuse materials wherever possible.

Explanations of the 8 principles as well as scientific evidence in support of each statement are reported in Appendix I.

b) Providing examples of sustainable, healthy and tasty dishes might favour the adoption of plant-based meals in daily food routines. Thus, we developed the online sustainable cookbook on the SEL website (https://www.sueatablelife.eu/en/cookbook/) with about 200 sustainable recipes. Each recipe card contains: a description of the ingredients used along with the execution process, the environmental impacts (carbon and water footprints) and the nutritional values of the dish, “chef's advice” as well as both nutritional and environmental messages/tips.

c) The project developed two symbols that were used to label sustainable dishes on canteen menus during the experimental phase: ‘My Plate 4 the Future’ (MP4F) and the ‘Chef's Plate’. In line with results reported by Castaldi *et al*. (2022) and Capone *et al*. (2013), SEL project identified CF and

WF threshold for sustainable and healthy meals of 1 kg CO_2-eq and 1000 L of water per capita per meal per person, respectively, calculated as the sum of meal course contributions (main, second and side-course). The 'My Plate 4 the Future' symbol was attached to menu dishes identified as being both healthy and sustainable (CF sustainable threshold was set to 0.5 kg CO_2 eq). If the dish exceeded 0.50 kg CO_2 eq., the recipe was not considered sustainable. The 'Chef's Plate' symbol was given to special MP4F courses whose preparation was overseen by the canteen's chef with an eye for seasonal ingredients and/or traditional recipes. This symbol was accompanied by the Chef's plate card providing information on nutritional value (Kcal), the recipe and the level of sustainability as follow:

3 MP4F planets: highly sustainable recipe - CO_2 eq. less than 0.2kg

2 MP4F planets: very sustainable recipe - CO_2 eq. between 0.2 and 0.4 kg

1 MP4F planet: sustainable recipe - CO_2 eq. between 0.4 kg and 0.5kg

Figure 9 - The 'My Plate 4 the Future' symbol.

Figure 10 - The 'Chef's Plate' symbol.

d) The GreenApes corporation developed a digital platform, i.e., the GreenApes App, as an alternative tool - more suitable for young employees - to motivate, engage and educate customers through a playful and rewarding approach. For each of the focus themes of the project (i.e., GHG-e, health, water consumption, sustainable diets, seasonality, local purchase), the digital platform offers multiple interactive challenges with the chance of being rewarded upon completion.

5.3.2 Procurement data analysis

For each experimental site, we retrieved and analysed procurement data from canteen catering services reporting the list of food items and their purchased quantities for a reference period of 1 year prior to the experiment. Subsequently, SEL CF and WF database (Petersson *et al*., 2021 b) was used to calculate the carbon and water footprint of the canteen food purchase. This analysis provides an estimate of canteen WF and CF impacts throughout an extended period (1 year) prior to the experiments. The calculation (indirect method) was based on the analysis of quality (grouped by type/item) and quantities (kg) of foods purchased by caterers over a number of working days, multiplied by their correspondent CF and WFs. The value obtained (i.e., the total CF and WF of canteen purchase), was then divided by the number of meals offered and the average flow of customers for the reference period. The result was expressed as kg CO_2eq-meal^{-1}per capita. The calculation was performed as follows:

$$kg\ CO_2\ eq\text{-}\ capita^{-1}\ meal^{-1} = \Sigma_i\ (kg_i \times CF_i)\ /\ M \times C$$

i= food item or food type purchased; **kg** = kg of food purchased; **CF** = CF value for each food item or food type; **M** = number of meals; **C** = number of customers

This value does not represent the experimental baseline CF canteen value - calculated during Dec. 2019 and Jan. 2020 - in that it derives from an indirect measurement of CF and WF for the food types purchased; it was instead used as a reference value for customer food consumption which enabled the planning and adjustment of canteens menus. Moreover, this analysis gave us an insight into the ‘business-as-usual’ canteen environmental impact.

5.3.3 Menu analysis

In accordance with LARN guidelines (SINU, 2014), we revised canteen menus by directly collaborating with chefs and catering staff in order to ensure a balanced and healthy food offering throughout the experimental period. Unsustainable dishes were mostly identified for second courses containing beef, pork and cheese. Second courses based on chicken, fish, turkey and eggs were found to be sustainable when not exceeding 100g protein source (150g for fish). All side dishes, being plant-based, were found to be both healthy and sustainable, with the exception of fried potatoes (unhealthy) and potato puree (unsustainable due to the contribution of milk, cheese and butter). Serving size for protein sources was harmonized with SINU-LARN reference serving-size. The proportion of unhealthy or unsustainable dishes was not altered; instead, their occurrence was uniformly distributed across daily menus in order to ensure the presence of sustainable and healthy alternatives at every meal. Indeed, the aim of the pilot experiments was not that of determining a reduction in the environmental impact by limiting the canteen offering of unsustainable dishes, but rather that of testing the response of consumers to the information campaign: when it comes to social programs, restrictive and limiting interventions might well be counterproductive. These menu-related modifications were put in place at the beginning of the baseline month and were maintained during the entire experimental phase.

5.4 Materials and methods

With the goal of evaluating the CF/WF mitigation potential of promoting sustainable and healthy diets we conducted a dynamic evaluation though time starting from a time zero (T_0) corresponding to the business-as-usual behaviour (taken as counterfactual), to a time one (T_1) corresponding to either one of two subperiods of the experimental phase (treatment), i.e., the last experimental month or the entire experiment duration. More specifically, T_0 corresponds to the bimester preceding the launch of the Su-Eatable Life information and engagement campaign (i.e., Dec. 2019 - Jan. 2020). T_1 corresponds to 8 months of engagement activities for Ducati canteen (i.e., Feb. 2020; Nov. - Dec. 2020; Jan. - May 2021) and 6 months for Pavesi canteen (i.e., Feb. 2020; Jan. - May 2021). For each canteen, the CF and WF values at T_1 were computed as mean per capita per meal values observed alternatively during the last experimental month (May 2021) and over all 8 (or 6) experimental months (Feb. 2020 - May 2021).

5.4.1 Canteen setup

The project principles were launched in February 2020 during the Su-Eatable Life Communication Campaign. A presentation Conference was held both in Ducati and Pavesi canteen by Su-Eatable project partners involving both worksite employees/managers and canteen catering staff. Canteen environments were set up with all the engagement tools developed during the preparation phase. The project poster Manifesto (A1) and banner (80 x 200cm) were visible at the entrance. Notice boards presenting the concept of ‘My Plate for a Future’ and the ‘Chef’s plate’ (both in A1 and banner format) were placed on walls in proximity of the food line. “My Plate 4 the Future (MP4F)” badge as well as the mascot identifying dishes meeting the sustainability criteria were introduced with the aim of helping the user to identify sustainable meals, in accordance with the principles of a healthy and varied diet. The symbols were placed both on the menu board and at the counter where the meals were served. The video on food and climate was played on screen. Table talkers were used as reminders of the key principles of a sustainable and healthy diet. Moreover, the consumers were encouraged to download and subscribe to the Green-Apes app on their personal mobile phones so to engage in different challenges focusing on the project topics.

5.4.2 Carbon and Water footprints assessment for dish servings and per capita per meal

A total of 1400 recipes were collected for all the involved canteens, representing the dishes served throughout the entire observational phase (T_0, T_1) referring to the autumn, winter and spring menus offered to customers. These recipes consist of main courses, second courses and side dishes while dessert, fruit and bread were excluded. The recipes were provided by the cooks and chefs of the involved catering service. Each recipe reported the recipe name and ingredient quantities (g). SEL database (Petersson *et al*., 2021 b) was used to calculate the CF and WF for each recipe. Only reliable CF and WF median were used in the calculations. When ingredients were not comprised in the database or showed high uncertainty values the correspondent type or sub-type median values were adopted. Salt and ingredients present in negligible amounts (<3 g), such as spices and vegetable stock, were not accounted for. When not specifically reported by catering staff we assumed all vegetables to be fresh, not processed (frozen or canned), and coming from national open field productions.

Pizza margherita

Ingredients	g-serving $^{-1}$	CF kg CO_2 eq -serving $^{-1}$	WF L serving^{-1}	% CF	% WF
Wheat plain flour	85	0.044	157.2	5.2%	21.5%
Mozzarella cheese	90	0.738	472.8	86.4%	64.7%
Tomato puree	40	0.052	28.5	6.1%	3.9%
Olive oil	5	0.016	72.1	1.9%	9.9%
Yeast	4	0.003	0.2	0.4%	0.0%
TOTAL		**0.854**	**730.7**	100%	100%

Table 19. Example of CF and WF determination for dishes. The relative contribution of ingredients highlights the hot spot for dishes. Reducing the quantities of the most impactful ingredients may bring the CF and WF of a serving to a sustainable level for a main course/first course.

Excepting the 2-month baseline period, which was purely observational in nature, all first and second course that did not exceed the sustainable threshold of 0.5 kg CO_2 eq and 500 L of water were labelled with the 'My Plate 4 the Future (MP4F)' badge so to help the user to identify sustainable meals during the experimental/engagement phase. In addition, every 2 weeks a seasonal or traditional Italian dish - i.e., the 'Chef's plate', accompanied by the Chef's card - was incorporated in the menu.

The impact assessment compared differences between the baseline period (Dec. 2019 - Jan. 2020) and the experimental phase (Feb. 2020; Nov. 2020 - May 2021), and was determined by combining data on CF and WF of dishes with catering sales data. Sales data included the daily flow of customers (number of customers) and the number of sales per dish during a specific timeframes of canteen activity (e.g., days, weeks).
The results were expressed as kg CO_2-eq per capita per meal and L of WF per capita per meal. The calculation was performed as follows:

$$kg\ CO_2\ eq\text{-}capita^{-1}\ meal^{-1} = \Sigma_i (n_i \times CF_i) / C$$

i = dish type purchased; **n** = number of purchases for each dish type; **CF** = CF value for each dish; **C** = number of customers for the reference timeframe

5.5 Results and Discussion

Table 20 shows the main results for the experiment conducted at Pavesi-Barilla canteen.
The difference between the baseline value (b.) and the sustainable reference value (d.) represents the scope for improvement. Pavesi canteen customers showed a positive reaction to the project, reaching on average 111% of the CF reduction target and 151% of the WF reduction target over the course of the experiment (respectively 113% and 157% at end-point, i.e., during the last experimental month). This corresponds to an average reduction in their diet-related GHG-e and WF of 35% and 32% respectively (36% and 33% respectively at end-point). With the exception of the mean impact value observed for April 2021, which was slightly above the sustainable

Table 20 *Average per-capita impacts for Barilla Pavesi*-Novara

	Carbon footprint kg CO_2 eq. per person per meal	**Water footprint** Litres of water per person per meal
a. Year 2019 impact (procurement data)	1.06	954
b. Baseline impact (Nov. 2019)	1.46	1272
c. Average European impact	1.75	1619
d. Sustainable reference impact	1.00	1000
Scope for improvement := **b** - **d**	0.46	272
e. Month I (Feb. 2020) impact	0.95	895
f. Month II (Jan. 2021) impact	1.01	913
g. Month III (Feb. 2021) impact	0.79	718
h. Month IV (Mar 2021) impact	0.96	904
i. Month V (Ap. 2021) impact	1.04	884
j. Month VI (May 2021) impact	0.94	846
Impact reduction at end-point := **b** - **j**	0.52	426
End-point reduction as % of *scope for improvement*	113%	157%
Experimental impact := mean(**e**, **f**, **g**, **h**, **i**, **j**)	0.95	860
Mean impact reduction := **b** - experimental impact	0.51	411
Mean reduction as % of *scope for improvement*	111%	151%

reference value for CF, customers impact value not only decreased throughout the experiment but remained consistently below the sustainable threshold.

Considering a total of 119 working days and an average daily flow of 205 employees, each decreasing on average his/her own environmental meal impact by 0.51 Kg of CO_2eq and 411 L of WF per meal (as can be seen in Table 20), the project success allowed a total saving of 12.4 tons of CO_2eq. and 10.023 m^3 of water.

Table 21 highlights the main results for the experiment conducted at Ducati company canteen. The performance of Ducati canteen-goers was variable throughout the entire project, although consistently below baseline values. On average, only 70% and 53% of the reduction target for CF and WF were reached respectively. The highest impact value was detected during the resumption of activities (Nov. 2020), followed by a reduction trend reaching 100% of the scope for improvement during the last month (Apr. 2021). As a result of the intervention, Ducati customers decreased on average their diet-related GHG-e and WF by 17% and 10% respectively (by 21% and 16% respectively at end-point).

Considering a total of 140 working days and an average daily flow of 950 employees, each decreasing on average his/her environmental meal impact by 0.21 kg of CO_2-eq and 111 L of WF per meal, the project allowed a total saving of 27.9 ton of CO_2eq. and 14,700 m^3 of water.

These positive results by way of replication are consistent with further improvements in the effort to reach the per-capita per meal thresholds recommended by SU-EATABLE LIFE, i.e., 1 kg CO_2

Table 21. *Average per-capita impacts for Ducati-Bologna*

	Carbon footprint kg CO_2 eq. per person per meal	**Water footprint** Liters of water per person per meal
a. Year 2018 impact (procurement data)	1.48	1338
b. Baseline impact (Dec. 2019 - Jan. 2020)	1.33	1230
c. Average European impact	1.75	1619
d. Sustainable reference impact	1.00	1000
Scope for improvement: = **b** - **d**	0.33	230
e. Month I (Feb. 2020) impact	1.11	1118
f. Month II (Nov. 2020) impact	1.26	1307
g. Month III (Dec. 2020) impact	1.11	1148
h. Month IV (Jan. 2021) impact	1.16	1184
i. Month V (Feb. 2021) impact	1.06	1092
j. Month VI (Mar. 2021) impact	1.14	1118
k. Month VII (Apr. 2021) impact	0.92	863
l. Month VIII (May 2021) impact	1.05	1033
Impact reduction at end-point := **b** - **l**	0.28	198
End-point reduction as % of *scope for improvement*	87%	86%
Experimental impact = mean(e, f, g, h, i, j, k, l)	1.10	1108
Mean impact reduction := **b** – experimental impact	0.23	122
Mean reduction as % of *scope for improvement*	70%	53%

eq. and 1000 litres of water. Although Ducati canteen showed a lower mean impact reduction per-capita, the higher employee flow and longer experiment duration resulted in higher net water and GHG savings compared to Pavesi canteen. This highlights the potential for achieving a substantial reduction in the environmental impact of the European catering sector through large scale, coordinated interventions.

5.5.1 Reduction trends in the consumption of beef

For both canteens we analysed the reduction in the consumption of beef-based second courses as difference between values observed during the baseline month(s) and the last experimental month (May 2021).

At baseline (Dec. 2019 - Jan. 2020) in Ducati canteen, beef-based second courses represented 16% of total second courses purchased by customers, accounting for 35% of CF and 24% of WF of the canteen. Equivalently, relative to the CF and WF per capita per meal observed during baseline months (CF=1.33 Kg CO_2-eq, WF=1230 L), beef consumption contributed for 0.46 kg CO_2eq-per capita per meal and 291 L per capita per meal.

In Pavesi canteen during the baseline month (Nov. 2019), beef-based second courses represented 23% of total second courses purchased by customers. The consumption of beef-based second courses amounted to 31% of CF and 22% of WF of Pavesi canteen. Put differently, relative to the CF and WF per capita per meal found at baseline (CF=1.46 Kg CO_2-eq, WF=1272 L) beef consumption contributed for 0.45 kg CO_2eq-per capita per meal and 279 L per capita per meal.

With reference to food choices made at Ducati canteen during the last experimental month alone (May 2021) (end-point analysis) we observed a 54% reduction of consumed beef-based second courses (from 16% at baseline down to 7.4% in May 2021), whilst holding constant beef food offering. This reduction corresponds to a saving of 0.25 kg CO_2-eq and 154 L of WF per capita per meal, representing 89% of the overall CF per capita per meal reduction (= 0.28 kg CO_2eq-capita^{-1}meal^{-1}) and 78% of the overall WF reduction (= 198 L capita^{-1}meal^{-1}) observed during that same month. This means that the majority of reduction trends observed for Ducati customers are strongly linked to the reduction of beef intake.

Similarly, during the last experimental month (May 2021) Pavesi customers reduced beef-based second dishes consumption by 54% (from 23% at baseline down to 10.7%), allowing a saving 0.23 kg CO_2eq-per capita per meal and 143L of WF per capita per meal. These reductions correspond to just 44% and 34% of the delta value observed between baseline and end-point for CF and WF respectively. This implies that for Pavesi canteen the decrease in the consumption of second courses based on beef is not the only factor behind the large decrease in the environmental impact observed at the end of the experimental phase: to the latter has probably contributed the concurrent decrease in the consumption of other first or second courses with medium / high impact.

5.6 Conclusions

The project results highlight that a small variation in the consumption frequency of animal protein sources, within an omnivorous diet, can be achieved by performing successful engagement programs. Since animal husbandry contributes up to 70% of the world's food-related GHGe (Spingmann *et al*., 2016), adopting sustainable and healthy diets on a large scale represents an auspicious strategy for climate change mitigation. Thanks to the project's success, communication and networking, different actors have been engaged for future replication and scaling-up activities. All private companies and caterers involved in the pilot experiments have expressed their interest in resuming the project protocol in a permanent form. Other 12 actors, including European Universities, catering agencies and private companies, signed a letter of engagement for future replication. In order to contribute to keeping the European GHGe targets by 2050 within the "planet boundary", we recommend future research aimed at identifying socio-economic and cultural drivers/barriers to collective sustainable dietary transition.

STUDY LIMITATIONS

Although we acknowledge that the concept of sustainable diets should be approached systemically by merging economic, social, and ethical issues with all burdens of anthropogenic environmental pressure and degradation, this study focuses primarily on GHG-e reductions and, secondarily, on anthropogenic pressure on water resources. Inevitably, some trade-offs occur when limiting attention to single environmental indicators, thus we invite readers to investigate the topic from a wider perspective. One example is the case of traditional grazing systems for sheep that, while associated with higher animal welfare and pasture biodiversity conservation, were found to exert higher global warming pressure - on a CF basis - compared to intensive-industrialized livestock systems. This finding does not suggest ignoring animal welfare or other environmental, social, economic and ethical issues that may be relevant when addressing sustainable consumption. Moreover, promoting sustainable and healthy diets in a manner similar to the one experimentally explored in this research is clearly limited to developed and industrialized countries where carbon- and water-intensive food systems are linked to unsustainable and unhealthy consumption patterns, such as overconsumption and food waste. Another limitation of our approach is represented by the fact that in the Su-Eatable Life experiments food kitchen waste was not taken into account, and thus was not factored in the CF and WF reduction assessments. As a matter of fact, the experimental design focuses on incentivizing and measuring canteen footprint reductions in terms of customer purchases, and is not concerned with the overall catering performance: targeting caterer purchases' environmental impact reduction would require a totally different project design. From the customer standpoint, plate waste is part of the overall consumption choice and is correspondingly reflected in the CF/WF purchase footprint.

CONCLUSIONS AND FUTURE PERSPECTIVES

This research makes a contribution by building a database of CFs and WFs for food commodities based on a systematic review of LCA and WF studies, to the inclusion of CFs for processed foods and WFs for farmed fish that are lacking in other databases. In addition to an inventory of primary data sources, the database provides descriptive statistics at three hierarchical levels of information: food type, food sub-type, and food item. At the item level, quality flags are further assigned to each of three data dimensions (sample numerosity/normality, and outlier position relative to the sample distribution of the corresponding food type) in order to inform users about the most reliable level of CF/WF estimation and proxy use. The database construction methodology ensures replicability and further expansion through additional environmental indicators and literature data for both currently included and missing food items. The database can be readily used to associate Eurocentric CF and WF values to food ingredients, courses and diets.

A comparative assessment of food CFs in light of dietary recommendations highlights the pivotal role of protein source in determining the sustainability of dietary patterns. The maximum GHG emissions are identified for beef and lamb meat irrespective of functional unit, i.e., mass (25.23-25.75 kg CO_2 eq/kg), protein (125.6-126.0 CO_2 eq/kg protein) or serving (2.52-2.57 CO_2 eq/serving). In addition, our findings suggest that other animal-derived products, i.e., lobster, hake and cured cheese, are also responsible for very high GHG emissions, thus sustainable diets should call for a reduction in the amounts/frequency of these products as well. We draw attention to healthier and more sustainable food protein sources, including fish and other animal products; notably, poultry meat and eggs may still be included in a sustainable, healthy diet if not exceeding weekly maximal intake as defined by WHO or Italian dietary guidelines, as well as fish, most of which fall in the same GHG-e impact range of poultry products (i.e., 3.1-4.2 kg CO_2-eq/kg food, 14.7-25.8 kg CO_2-eq/kg protein, and 0.37-0.55 CO_2-eq/serving). According to Italian dietary guidelines (IDGs, 2018), the consumption of red meat should be limited to one portion (100 g) per week, or preferably replaced by poultry meat; in the latter case, up to three portions of poultry per week could be consumed (Rossi *et al.*, 2022). As expected, consumption of plant-based foods exerts a very low impact on global warming whenever crops are fresh, seasonal and locally produced; on the contrary, non-seasonal crops cultivated in heated greenhouses exhibit CF values 5 to 12 times higher than their seasonal equivalents, generating as much GHG-e as poultry. Plant-based protein sources are found to be much less GHG intensive than animal derived proteins when compared on the basis of equivalent protein content as opposed to mass FU: counter to common beliefs, legumes and their minimally processed derivatives represent valuable protein sources, with average protein content exceeding that of animal products, and deficiencies in some essential amino acids that can be offset by including sufficient amounts of wholegrains. Interestingly, we found low CFs for farmed mussels as well as certain wild fish, such as anchovy, sardine, herring and mackerel, provided the latter are captured via pure-seining fleets in areas proximate to the coast: these CF values range between 0.46 and 1.80 kg CO_2-eq, and are at most 4 times higher than CFs for legumes, while being 2 to 9 times lower than CFs for poultry meat and eggs (on mass basis).

Encouraging results were obtained from 6 and 8 months-long engagement experiments conducted at 2 Italian company canteens (Ducati, Pavesi) involving a total of 1500 customers. Educating canteen customers about the win-win benefits for both human and planetary health stemming from the adoption of sustainable diets, by means of simple, playful, concise messages conveyed by videos, posters, banners and table talkers, spurred an openness to dietary change. Labelling sustainable courses with the SEL project logos incentivized their purchase especially when those courses were carefully prepared and hallmarked by the chef for being seasonal/traditional. Unfortunately, the download/use of the GreenApes social network app on personal mobile phones found limited support among canteen goers. At end-point (i.e., May 2021), we observed a decrease meal for Ducati canteen food purchases from 1.33 to 1.05 kg CO_2-eq and from 1230 to 1033 L of WF-equivalents per, corresponding to a 21% and 16% reduction in CF and WF respectively. This reduction was entirely driven by a decrease in the preference for red meat-based courses, having purchases of red-meat courses decreased while the supply (frequency and serving-size) thereof was kept constant at baseline values. The mean CF and WF per person per meal observed during the entire follow-up experimental months for Ducati employees were 1.10 kg CO_2-eq and 1108 L respectively, corresponding to an average reduction of 17% for CF and 10% for WF, and total experiment-induced savings of 27.9 ton of CO_2eq. and 14,700 m^3 of water. Throughout the 6 experimental months, Pavesi employees lowered on average their CF from 1.46 to 0.95 kg CO_2-eq per meal and their WF from 1272 to 860 L per meal, corresponding to a reduction from baseline of 35% and 32% respectively, that generated total savings of 12.4 ton of CO_2-eq and 10.023 m^3 of water. The maximum impact reduction was achieved during February 2021, with -46% GHG-e and -43% WF, while the 36% CF and 33% WF reductions observed at end-point, i.e., during May 2021, were similar to the average experimental reductions: the latter were related to a diminished preference for unhealthy and/or unsustainable animal-based courses and not only to beef purchase. We hypothesize that greater environmental impact reductions achieved for Pavesi customers compared to Ducati may be connected to synergies with the educational Mediterranean-diet health campaign run previously in Pavesi canteen. The implementation of the Su-Eatable experimental protocol demonstrates that a moderate but consistent reduction in GHG-e and water withdrawals of food consumption can be achieved by implementing engagement protocols for work-place canteens. In this regard, the SEL project highlights the importance of an interdisciplinary approach to the question of food sustainability, involving experts in health care, environmental and social sciences. While many scientists call for an urgent need to shift to sustainable and healthy diets, drastic changes in eating habits are challenging: informing citizens about the health- and environment-related benefits and risks of dietary choices can create the basis for enabling dietary shift. That being said, considerably more attention should be devoted to identifying drivers and motivations for collective behavioural change.

In sum, this PhD research project emphasizes how consumers, with their choices, have the power/potential to reverse the currently unsustainable trend of food systems that is implicated in multiple environmental and human hazards. Nevertheless, the Great Food Transformation, that is urgently needed to reconcile and safeguard human and planetary health, calls for the cooperation between all stakeholders of the food supply chain as well as for no less than a global paradigm shift in agriculture and nutrition.

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LIST OF PAPERS

Scientific articles and conference proceedings

1. Petersson, T., Secondi, L., Magnani, A., Antonelli, M., Dembska, K., Valentini, R., Varotto, A & Castaldi, S. (2021 a). A multilevel carbon and water footprint dataset of food commodities. Scientific Data, 8(1), 1-12.
2. Petersson, T., Secondi, L., Magnani, A., Antonelli, M., Dembska, K., Valentini, R., Varotto, A & Castaldi, S. (2021b) SUEATABLE_LIFE: a comprehensive database of carbon and water footprints of food commodities. figshare https://doi.org/10.6084/m9.figshare.13271111
3. Petersson T. Reducing GHG-e and water footprint in the EU through sustainable and healthy diets. Proceedings of XXIV Workshop on the developments in the Italian PhD research on food science, technology and biotechnology (Florence, 11-13 September 2019)
4. Castaldi, S., Antonelli, M., Dembska, K., Magnani, A., Varotto, A., Petersson, T., & Valentini, R. (2019). Su-Eatable Life Project: reducing carbon emissions and water use pressure through sustainable diet. In E3S Web of Conferences (Vol. 119, p. 00024). EDP Sciences.
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APPENDIX I

The 8 key principles of the SU-EATABLE DIET – THE WHY

The following boxes report the scientific evidence in support of the 8 principles on which the SU-EATABLE LIFE diet is based. Environmental impact is specifically addressed with reference to the two main indicators of the SU-EATABLE Life Project: CO_2 emissions equivalents, and water quality and quantity. The amount of CO_2 emitted per kg or liter of food product is referred to as Carbon footprint, or is reported as CO_2 equivalents. The amount of water used per kg or litre of food product is indicated as Water Footprint – WF.

1. **Champion plant-based food in your diet**

Environment: Plant-based food emits on average significantly less CO_2 equivalents (0.2 to 2.7 kg CO_2-eq/kg), compared to animal-based food (3.5 to 28 kg CO_2-eq/kg), with the exception of milk and eggs which are in the range of plant-based food (Clune *et al*. 2017, Poore and Nemecek 2018, Willet *et al*. 2019). The WF of vegetables, grains and fruit are about 25 times lower when compared to beef meat; as a protein source, legumes have a WF which is between 2 to 4 times lower than beef WF and similar to the WF of chicken and eggs (Mekonnen and Hoekstra, 2010). The optimal daily diet for health and the environment, ensuring sustainable resource use, should consist (by volume) of approximately half a plate of vegetables and fruits and a significant source of protein obtained from legumes, nuts and cereals (Willet *et al*. 2019). To date, in industrialized countries, people tend to consume too much sugar, oils and fats, and red meat as well as milk and cheese, while not enough fruit and vegetables (Vanham *et al*., 2018, *Willet et al*., 2019).
Health: According to the World Health Organization, a healthy diet includes: fruit, vegetables, legumes, nuts and whole grains, with at least 400 g (i.e., five portions) of fruit and vegetables per day (WHO, 2018). Emphasizing nutrient-dense, plant-based foods such fruit, vegetables, legumes and nuts, is associated with significantly better health outcomes (Tuso *et al*., 2013; Satija *et al*., 2016; BDA, 2017; Satija *et al*., 2017; Toumpanakis *et al*., 2018).

2. Treat meat as a luxury

Environment: Meat production significantly affects climate change, as the "impacts of the lowest-impact animal products typically exceed those of vegetable substitutes" (Poore and Nemecek 2018). At the highest end of CO_2 eq. emissions, we have ruminant meat, i.e., beef and lamb, which can be almost 10 times higher than poultry, eggs, rabbit and most of fish meat and 4 to 5 times higher than pork meat (Clune *et al*. 2017, Poore and Nemecek, 2018). In terms of pressure on freshwater resources, meals that include beef have 3 times the WF as those that include other meat protein sources (pork, chicken) or legumes, and twice the WF of eggs (Mekonnen and Hoekstra, 2010). The big WF impact of beef is mainly related to the production of animal feed over the lifetime of the animal (Hoekstra 2015). A WF reduction of up to 35% could be reached by adopting the common guidelines for healthy diets (Vanham *et al*.2018). A good compromise for protein intake is represented by fish, both in terms of CO_2 equivalent emissions and water saving (Mekonnen and Hoekstra, 2010, Clune *et al*., 2017). A full shift to a pescatarian (or vegetarian) diet could reduce the WF per capita by approximately 33-55% (Vanham *et al*., 2018).

Health: Following reclassification in 2015 by the International Agency for Research on Cancer of the World Health Organization, processed meats (such as hot dogs, ham, sausages, corned beef, canned meat, and meat-based sauces) eaten daily may increase the risk of colorectal cancer and stomach cancer. A completely safe intake of this type of food cannot be defined. Similarly, also red meat consumption (i.e., all muscle meat, such as beef, veal, pork, and lamb) is associated with an increased risk of colorectal, pancreatic, and prostate cancers (IARC, 2015) and cardiovascular diseases (Abete *et al*., 2014) as well as higher risk of stroke and type 2 diabetes (Chen *et al*., 2013, Feskens *et al*., 2012). Such risks can be significantly diminished by substituting red meat with other protein sources (Pan *et al*., 2012).

According to the EAT-Lancet commission (Willet *et al*., 2019): "Because intake of red meat is not essential and appears to be linearly related to total mortality and risks of other health outcomes in populations that have consumed it for many years, optimal intake might be 0 g/day, especially if replaced by plant sources of protein. Because data on risk of low intakes of red meat are imprecise, we have concluded that an intake of 0 g/day to about 28 g/day of red meat is desirable and have used a midpoint of 14 g/day for the reference diet. Since consumption of poultry has been associated with better health outcomes than has red meat, we have concluded that the optimum consumption of poultry is 0 g/day to about 58 g/day and have used a midpoint of 29 g/day for the reference diet".

3. Enjoy dairy products in moderation

Environment: Plant-based milk, except rice milk, have a lower Carbon Footprint (CF) than dairy milk (Clune *et al*., 2017). The difference is even more significant for Water Footprint (WF of soy milk is 296.9 L/kg vs cow milk 1050 L/kg, Ercin *et al*. 2011). Yogurt has a value similar to milk, while cheese - due to the high concentration of milk used for its production - can have a CF and WF up to 6 times higher than that of the original milk. When compared with other protein sources, cheese has twice the WF of soy-based proteins, and both the CF and WF of cheese can be higher than that of many meat sources, including chicken, pork and fish (Clune *et al*., 2017, Mekonnen and Hoekstra, 2010).
Health: High intake of dairy products (i.e., at least three servings per day) has been widely promoted in western counties for bone health and fracture prevention, primarily because of the associated high calcium content. However, the optimum calcium intake remains uncertain (Willett *et al*., 2019), while there is evidence that the adverse effect of protein of animal origin might outweigh the positive effect of calcium intake on calcium balance (FAO and WHO, 2002). Animal-based dairy fat, like butter conveys higher risk of cardiovascular disease than unsaturated plant oils: the latter should hence be preferred whenever possible for cooking and preparation of meals (EAT Lancet Commission, Willett *et al*., 2019).

4. Avoid too much

Environment: every kilogram of food incorporates the environmental impact generated during its production, processing, packaging and transportation (Willet *et al*., 2019, Ercin *et al*., 2011, Clune *et al*., 2017, Vanham and Bigoglio, 2013). To reduce pressure on the environment, we need not only to balance the composition of our diet, but also to reduce the food quantities we purchase for consumption. Every time we trash food into the waste-bin we are basically vaporizing resources and we have generated unnecessary environmental pressures. The wasted environmental value is higher for meat and animal-based food (Clune *et al*., 2017, Willet *et al*., 2019). A dietary shift combined with reducing our food waste might help us to reach important sustainability targets in terms of climate change and water use (Willet *et al*,. 2019). In Spain, for example, the WF of food waste accounts for 2095 hm^3, equivalent to 131 liters per person per day (Blas *et al*., 2018).
Health: Energy intake (calories) should be in balance with energy expenditure (WHO, 2018). Excess energy intake (i.e., energy-dense unhealthy dietary patterns) has been identified as the most important dietary factor in relation to weight gain and the development of obesity (Roberts *et al*., 2002).

5. Celebrate variety

Environment: Agro-biodiversity is an important strategy to face the challenges of climate change, as it offers more flexible climate adaptation strategies thus supporting food security and resource savings (Fischlin *et al*., 2007). Widening food choices allows for more creativity into our diet making it easier to plan more sustainable diets. Coupling variety with valorization of seasonal and local productions might help to booster local economies and save resources. Seasonality is also important. Vegetables and fruit grown in heated greenhouse can increase their CF by 4 times (Clune *et al*., 2017). Refrigerated transport of plant-based food and long term refrigerated storage of "out of season food" vegetables/fruit in warehouses can be a significant source of CO_2 equivalents (Hospido *et al*., 2009, Wakeland *et al*., 2012). In general, only when local markets are affected by seasonal constraints which strongly limit food variety (cold climates), long-distance supply chains may be more advantageous compared with greenhouse food production or with long term food storage through the seasons (Wakeland *et al*., 2012).
Health: Dietary diversity has long been recognized as a key element of high-quality diets. Increasing the variety of foods across and within food groups is recommended in most dietary guidelines internationally, as a means to ensure adequate intake of essential nutrients and to promote good health (Ruel, 2003). Simplification of human diets associated with increased accessibility of inexpensive commodities and erosion of agrobiodiversity, leads to nutrient deficiencies and excess energy consumption (Johns & Eyzaguirre, 2006). Fruits, minor vegetables, and leaves used as condiments, spices, or sauce ingredients can be grown in small quantities and add variety and essential nutrients to diets otherwise dominated by staple foods. Agrobiodiversity is an underexplored avenue for giving both food producers and consumers access to greater dietary diversity (Johns & Eyzaguirre, 2006).

6. Fresh is best (for you, and the environment)

Environment: Food processing can add further pressure on the environment. The more complex is the processing, the higher amount of energy and materials required, which leads to higher CO_2 eq. emissions and resource consumption per kilogram of product (Notarnicola *et al*. 2017). For example, the CF of fresh peas increases by a minimum of 60% to possibly more than 100% when purchased canned, jarred or frozen (Clune *et al*., 2017, Carbon footprint frozen food Report 2012). The GWP of processed tomatoes (copped, peeled, purée) can be twice that of fresh tomato due to energy use for processing and packaging (Del Borghi *et al.* 2014).
Health: The increasing proportion of ultra-processed foods in diets has been identified as a driver of excess energy intake (Monteiro, 2010). Also, the evidence so far shows that displacement of minimally processed foods and freshly prepared dishes and meals by ultra-processed products is associated with unhealthy dietary nutrient profiles (Monteiro *et al*., 2018).

7. Choose tap over bottled water wherever possible and safe

Environment: When safe tap water is available, the consumption of water in plastic bottles results in an unnecessary burden on the planet. An analysis of 6 different Italian water providers proved that consumers can save 163.50 kg of CO_2 equ per capita on a yearly basis by drinking 2 liters of tap water instead of PET-bottle water (Botto *et al.* 2011). In terms of water savings, bottling 1.5L of water requires around 1.9 extra liters of water for bottling operations, processes, packaging and transport (Nicolucci *et al.*, 2011), compared with 0.5 L of extra water if using tap water responsibly in efficient municipal systems. Bottled water in plastic materials poses a further environmental burden as plastic production relies heavily on oil (Foolmaun & Ramjeawon 2008) and even among EU countries the amount of plastic recycled is still less than 50% of the total plastic produced (Plastic Europe 2017).
Health: Good hydration is vital for good health and well-being. Water safety and quality are fundamental to human development and well-being, and 71% of the global population uses a safely managed drinking-water service (WHO, 2017). The reason for the increase of bottled water consumption is not straightforward; one of the most common factors seems to be the dissatisfaction of consumers with tap water organoleptic, i.e. the water characteristics that affect the senses of taste, odor and sight (Miguel, 2006). However, the quality of bottled water in not necessarily superior when compared with the municipal tap water, as shown by Rosa *et al*. (2011) in a study conducted on 37 bottled waters available in the market and 15 municipal water pipelines.

8. Reduce single-use!

Environment: Food packaging represents an important fraction (25%) of the plastic materials that leak into the environment. The estimated annual input of mismanaged plastic waste into the ocean is about 13 million metric tons (Jambeck, 2015). This plastic remains in the ocean for centuries causing harm to natural systems. Shopping food in hypermarkets has been shown to have 3 times the CF per food basket than shopping in local food markets, due to the higher amount of packaging in the hypermarket food (Sanyé *et al*. 2012). Retailers might save a great deal of CO_2 emissions by reducing food packaging, while users might significantly reduce the environmental footprint of their food basket by recycling or bringing their own shop bags (Sanyé *et al*. 2012).

APPENDIX 2

The following table lists some of the sustainable first and main courses offered during the SU-EATABLE LIFE pilot experiments. Side dishes are not shown, but for those prepared only with plant-based ingredients, the CF/serving was found to be < 0.1 kg CO_2-eq. Combinations of one first course with one main course (plus a plant-based side dish) of the list hereinbelow never exceed 1 kg of CO_2-eq, which is the sustainable threshold set by SU-EATABLE LIFE. For all main courses, protein-bearing ingredients reflect standard serving size (SPS) indicated in table 18 of chapter 4 of this thesis. Carbon and Water footprints assessment for dish servings is described in section 5.4.2 of this thesis. CF is expressed as kg CO_2-eq/serving and WF as litres of WF/serving. Note: "w/" abbreviates "with".

Table 22. Sustainable Menu

FIRST COURSES	CF	WF	MAIN COURSES	CF	WF
carrot purée	0.02	79	vegetarian burgers	0.03	55
barley, carrots, capers and olives	0.03	97	cabbage, potato and beans salad	0.05	246
pea purée	0.03	133	pea and carrot salad	0.05	179
cannellini beans purée w/ sage	0.03	274	spicy peas	0.05	221
barley soup w/ pumpkin	0.03	100	cauliflower and chickpea salad	0.06	217
carrots and cinnamon velouté	0.04	48	broccoli and beans salad	0.07	264
pumpkin purée	0.04	67	vegetable flan	0.08	107
spelt and spinach soup	0.04	92	truffle tart	0.08	267
cereal and vegetable soup	0.04	79	stewed chickpeas	0.09	325
chickpea purée	0.04	62	steamed mussels w/ black pepper	0.09	n.a
bean and carrot soup	0.04	273	sautéed legumes	0.09	502
cauliflower velouté	0.05	101	sautéed mussels	0.09	n.a
barley, chickpeas and rosemary	0.05	239	*fagioli all'uccelletto*	0.11	542
barley, peppers, arugula, and olives	0.05	104	potato and spinach pie	0.12	143
leak and potato purée	0.05	131	tuna w/ potatoes and olives	0.14	254
cannellini beans and radicchio purée	0.05	296	vegetable fricandeau	0.14	215
carrot velouté	0.05	124	tuna w/ beans and potatoes	0.17	293
peasant soup	0.05	324	stewed lentils	0.19	704
potato and borlotti beans soup	0.05	298	mackerel *alla zingara*	0.21	100
cannellini beans and radicchio velouté	0.05	550	vegetarian tart	0.23	247
flavored couscous	0.06	153	mackerel *au gratin*	0.24	148
onion velouté	0.06	83	stewed mackerel	0.25	172
onion soup	0.06	83	eggs *alla pizzaiola*	0.26	252
potage Parmentier	0.06	150	vegetable mix w/ scamorza cheese	0.32	427
potato velouté	0.06	171	vegetable tart	0.33	520
barley and pumpkin soup	0.06	174	baked omelette	0.34	399

carrot and curry velouté	0.06	149
spelt salad and green beans	0.06	163
Tuscan-style spelt soup	0.07	282
Tuscan-style spelt soup	0.07	221
legumes velouté	0.07	391
spelt soup w/ vegetables	0.07	177
lentil soup	0.07	378
barley and lentil soup	0.08	265
couscous w/ chickpeas and aubergines	0.08	302
lentil soup w/ turmeric and ginger	0.08	425
potato and tomato purée	0.08	142
couscous w/ tomatos and zucchini	0.08	165
chickpeas and peas purée	0.08	316
zucchini and basil soup	0.08	152
spelt and Swiss chard soup	0.08	168
cucumber and yogurt cream	0.08	140
aurora purée	0.09	152
vegetable soup	0.09	141
couscous w/ chickpeas and curry	0.09	329
zucchini and basil purée	0.09	135
pasta w/ chickpeas	0.09	260
beetroot and pepper purée	0.09	98
Provençal soup w/ barley	0.10	126
barley and zucchini soup	0.10	222
spelt and vegetable salad	0.10	223
pasta w/ pesto	0.10	128
chickpea and zucchini purée	0.10	357
chickpea and zucchini soup	0.10	357
beetroot and ricotta purée	0.11	166
legumes velouté	0.11	535
potato and mussels velouté	0.11	204
zuchini and spelt velouté	0.12	175
pasta w/ garlic and oil	0.12	202
rice w/ Savoy cabbage	0.12	92
peasant pasta	0.12	175
rainbow couscous salad	0.12	192
asparagus purée	0.13	345
vegetable soup w/ croutons	0.13	158
baked ricotta	0.34	247
carpaccio alla tartara	0.35	448
salt cod w/ potatoes	0.36	165
salt cod in potato crust	0.36	165
artichoke tart	0.36	434
Savoy cabbage and potato pie	0.37	405
cod fillet w/ curry	0.37	268
potato and spinach pie	0.38	360
escalope w/ artichokes	0.39	502
chicken breast *alla sassi*	0.39	502
chicken supreme w/ lemon	0.39	508
chicken w/ pumpkin and rosemary	0.40	517
capers and olives pie	0.40	332
scrambled eggs	0.40	467
cabbage and taleggio salad	0.40	450
stew w/ artichokes and potatoes	0.40	539
Sicilian-style chicken escalope	0.40	513
escalope w/ asparagus	0.40	545
grilled chicken meat	0.40	463
chicken supreme w/mustard	0.41	472
poultry w/ hazelnuts and mushrooms	0.41	505
salad niçoise	0.41	440
eggs and peas	0.41	579
scrambled eggs w/ bacon	0.41	461
frittata w/ tuna	0.42	367
potato flan	0.42	418
supreme w/balsamic vinegar	0.42	544
escalope w/ marsala wine	0.42	544
escalope w/ black pepper	0.42	544
escalope w/ lemon	0.42	546
baci di ricotta	0.42	327
flan w/ carrots	0.43	377
spring roast	0.43	438
sliced turkey w/ arugula	0.43	506
salt cod *alla vicentina*	0.43	207
chicken *alla cacciatora*	0.43	499
redfish fillet w/ potatoes and olives	0.44	205
tuna salad	0.44	663

pasta w/ artichokes	0.13	226
spaghetti bella Napoli	0.13	262
pasta w/ cannellini velouté and arugula	0.13	355
pasta w/ Savoy cabbage	0.14	220
pasta w/ borlotti beans and tomatoes	0.14	403
tagliatelle w/ butter and sage	0.14	150
orecchiette w/ rapini	0.14	193
pasta w/ Swiss chard and ricotta	0.14	229
pasta w/ asparagus	0.14	265
spelt and champignon salad	0.15	154
orecchiette w/ broccoli	0.16	239
pasta w/ crispy bread	0.16	216
pasta w/ parmesan	0.16	172
pasta w/ artichokes	0.16	321
pasta w/ vegetables	0.17	219
pasta w/ ricotta and walnuts	0.17	237
spaghetti alla carrettiera	0.17	263
pasta w/ cauliflower and cheek lard	0.17	273
spaghetti alla puttanesca	0.18	197
pasta w/ beans	0.18	612
pasta alla palermitana	0.18	268
pasta w/ rapini	0.18	321
chickpeas and seafood velouté	0.19	396
pasta w/ tuna and tomatos	0.20	223
pasta w/ aromatic herbs	0.20	251
rice w/ egg	0.20	234
pasta alla sanremese	0.21	266
pasta all'arrabbiata	0.21	252
pasta w/ tomato and basil	0.21	253
pasta w/ tomato sauce	0.21	253
pasta alla corsara	0.21	254
pasta alla livornese	0.21	254
pasta alla pizzaiola	0.21	254
pasta alla napoletana	0.21	255
plain rice	0.22	163
pasta w/ calamari and arugula	0.22	190
pasta w/ tomato and olives	0.22	281
pasta alla caruso	0.22	262

turkey burger w/ sesame	0.44	609
carpaccio w/ arugula and parmesan	0.44	517
salt cod *all'anconetana*	0.44	233
eggs *alla fiorentina*	0.44	473
eggs w/ bacon	0.44	510
frittata w/ vegetables	0.44	500
roasted chicken	0.45	572
cod *au gratin*	0.45	198
grilled turkey	0.45	476
escalope w/ mushrooms	0.45	517
grilled chicken breast	0.46	577
chicken breast w/ curry	0.46	586
tomato flan	0.46	416
chicken nuggets w/ orange	0.47	599
broccoli flan	0.47	453
escalope w/ mustard	0.47	582
frittata w/ tomato	0.47	443
escalope w/ speck and arugula	0.47	606
frittata w/ leek and salmon	0.48	397
frittata w/ onion	0.48	438
baked perch w/ vegetables	0.48	141
carrot flan	0.49	445

pasta w/ leeks	0.22	262
pasta alla fiaccheraia	0.22	355
pasta w/ capers and olives	0.22	287
pasta w/ tomato and pesto	0.22	259
pasta w/ green olives	0.22	313
pasta alla zingara	0.23	262
pasta ai sette peccati	0.25	430
pasta w/ mushrooms and cherry tomato	0.25	181
pasta w/ artichokes and baked ham	0.25	381
black rice w/ crab	0.25	215
pasta w/ spinach and bacon	0.25	395
pasta w/ salmon	0.25	286
pasta w/ tuna and capers	0.26	268
pasta w/ tuna and peas	0.26	282
pasta alla pescatora	0.26	143
basmati rice w/ yogurt and cucumber	0.26	267
pasta w/ mushrooms	0.26	260
pasta alla dorè	0.26	366
fantasia couscous salad	0.26	429
rice w/ tomato sauce	0.26	236
pasta w/ zucchini	0.26	321
venere rice w/ avocado and cuttlefish	0.26	179
pasta alla norma	0.27	296
pasta w/ peas and ham	0.28	407
pasta alla riminese	0.29	272
pasta all'amatriciana	0.29	374
risotto w/ speck and spinach	0.29	375
pasta alla medici	0.29	340
pasta w/ mushrooms and arugula	0.29	270
pasta all'amatriciana	0.30	699
pasta w/ clams	0.30	363
carbonara	0.32	348
pasta w/ calamari and arugula	0.33	240
pasta w/ gorgonzola and radicchio	0.34	453
pasta alla tirolese	0.34	393
pasta alla vogherese	0.34	405
pasta w/ mussels	0.34	463
pasta w/ grouper and olives	0.35	329

pasta w/ chickpeas and shrimp	0.35	351
couscous w/ fish	0.36	356
pasta w/ calamari, shrimps and peas	0.36	277
pasta w/ speck and arugula	0.36	473
pasta w/ mushrooms	0.37	283
pappardelle w/ mushrooms	0.37	500
pasta alla boscaiola	0.37	726
cold pasta salad	0.37	552
pasta w/ pumpkin, hazelnuts, pine nuts, and bacon	0.37	505
risotto alla milanese	0.37	252
pasta alla gigi	0.38	447
pasta alla sorrentina	0.38	442
pasta w/ gorgonzola and pear	0.38	350
Genoese-style spelt salad	0.40	499

Note: meat dishes include only poultry meat.