Environmental and health-related external costs of meat consumption in Italy: estimations and recommendations through life cycle assessment

Alessandro Arrigoni[a,b,*], Davide Marveggio[b], Francesca Allievi[a,c], Giovanni Dotelli [d], Guido Scaccabarozzi[a,b]

[a] SIMBIO Sistemi Innovativi di Mantenimento della Biodiversità, 23889 Santa Maria Hoè, Italy

[b] Demetra Società Cooperativa Sociale Onlus, 20842 Besana Brianza, Italy

[c] JAMK University of Applied Sciences, 40200 Jyväskylä, Finland

[d] Department of Chemistry, Materials and Chemical Engineering "G.Natta", Politecnico di Milano, 20133 Milano, Italy

*Corresponding author at: SIMBIO ONLUS, 23889 Santa Maria Hoè, Italy. E-mail address: a.arrigonim@gmail.com

ABSTRACT

The literature on the external costs of food consumption is limited. This study aims at advancing in this field by translating the environmental and health-related impacts generated by the life-cycle of meat into external costs via monetization. The main types of meat consumed in Italy are used as a case study. The potential external costs are estimated via attributional life cycle assessment (LCA), using: i) the ReCiPe method for the environmental impact assessment (fourteen impact categories), ii) the population attributional fractions for the health damage from meat ingestion, and iii) the CE Delft environmental prices for monetization. Results show that processed pork and beef generate the highest costs on society, with an external cost of approximately 2€ per 100g. Fresh pork and poultry follow, with a cost of 1€ and 0.5€ per 100g, respectively. For comparison, the potential external costs of legumes (i.e., a plant-based alternative to meat) are estimated to be from eight to twenty times lower than meat (around 0.05€ per 100g of legumes). In 2018, meat consumed in Italy potentially generated a cost on society of 36.6 bn€. The burden arises almost equally from impacts generated before meat ingestion (mainly associated with the emissions arisen from farming), and after the ingestion (due to diseases potentially associated with meat consumption). A sensitivity analysis on the main parameters revealed a large uncertainty on the final yearly cost, ranging from 19 to 93 bn€. Although more research is needed to improve the accuracy and the validity of the models used in the study (e.g., human health impact assessment, monetization) and to include potential external costs currently unaccounted for (e.g., water use, animal welfare, occupational health), results show unequivocal significant costs associated with meat consumption. We thus advocate for policies aimed at reducing these costs and allocating them properly.

1. INTRODUCTION

Nowadays it is almost common knowledge that food consumption is linked with significant environmental impacts: food production uses 40% of Earth's land, and it accounts for about 70% of Earth's freshwater withdrawals (Clark et al., 2019; Willett et al., 2019). Moreover, a third of global greenhouse gas (GHG) emissions (18 Gt CO_2eq/yr) comes from the food system -from production to consumption-, with industrialised countries being responsible for 27% of it (Crippa et al., 2021). However, the costs in terms of natural resources' use and harmful emissions remain mostly hidden from consumers (Nguyen et al., 2012; Pieper et al., 2020). These costs are known under the name of external costs or externalities, because they are not included in the final market price. Externalities arise when an activity generates an impact on someone without compensating them, leading to welfare losses to society as a whole (Pigou and Aslanbeigui, 2017). This study uses a holistic approach to estimate the potential external costs of a food product, providing a potential framework to policymakers for future assessments.

The main meat types consumed in Italy (beef, pork, processed pork, and poultry) are used as a case study. Meat -in particular meat from ruminants- is one of the foods with higher impact on global warming and other environmental categories, such as acidification and eutrophication (Clune et al., 2017; Poore and Nemecek, 2018). Meat consumption has consequences in terms of animal welfare and human health too (Bonnet et al., 2020). The International Agency for Research on Cancer (IARC) has classified the consumption of red and processed meat as probably carcinogenic and carcinogenic (for colorectal cancer) to humans, respectively (Bouvard et al., 2015). Moreover, epidemiological studies found a correlation between meat consumption and other diseases, such as type 2 diabetes and coronary heart disease (Bechthold et al., 2019; Schwingshackl et al., 2018, 2017). As a consequence, a null or low consumption of red and processed meat is recommended to achieve the sustainable development goals and to remain within safe planetary boundaries for the Earth system (Springmann et al., 2020; Willett et al., 2019). Nevertheless, meat has always been part of the human diet (Leroy and Cofnas, 2020) and it remains the major source of protein for Europeans (26 g of protein/capita/d). While the supply of beef proteins declined in Europe in the past 20 years (from 8 g/d in 1990s to 6 g/d in 2013), pork meat supply remained constant (11 g/d) and the supply of proteins from poultry increased from 2 g/d in 1960s to 9 g/d in 2013 (Bonnet et al., 2020; FAO, 2021). Meat plays a relevant role in the Italian diet too: although the Italian protein supply from poultry meat is 17% lower than the European average, an excess of beef (30%) and pork (7%) proteins have been supplied in Italy in the period 2014-2018 compared to an average European country (FAO, 2021). Notwithstanding, the number of vegetarian and vegan people is on the rise, reaching almost 9% of the Italian population (Eurispes, 2020). All these reasons make the consumption of meat in Italy an ideal case study to suggest a new way to look at the external costs of food and at how these should be accounted for food policies.

The approach proposed in this study is based on the monetization of the environmental and health impacts generated by a food product throughout its entire life cycle. To assess the potential environmental impact of food, the LCA methodology is typically adopted in the literature, since it allows to quantify all the impacts from the extraction of the raw materials until the end of life (McLaren et al., 2021; Notarnicola et al., 2017a). On the other hand, the estimation of the health impacts typically relies on epidemiological studies associating a disease to the ingestion of food (Springmann et al., 2018; Stylianou et al., 2021). A framework was proposed by Stylianou et al. (2016) to combine the nutritional and environmental health impact of food products. This framework was applied to change in diets, such as the substitution in the US of beef and processed meat with fruits, vegetables, nuts, legumes, and selected seafood (Stylianou et al., 2021). Results suggest that a substitution of only 10% of the daily caloric intake could offer substantial health improvements (48 min gained per person per day) and a 33% reduction in the dietary carbon footprint (Stylianou et al., 2021). Recently, a similar framework was used to compare a vegan diet, a Mediterranean diet, and the national dietary guidelines in the German federal state of North Rhine-Westphalia (Paris et al., 2022). The authors highlight the health benefits of increasing the share of plant-based foods in the diet, and they recommend including animal welfare and human health indicators in LCAs of food. Our study follows the same methodological framework (i.e., including human health-related impacts in the LCA), but we applied it to a single food portion (i.e., 100 g of meat). The impacts were then monetized and upscaled to the national level, in order to estimate the overall potential cost on society caused by meat consumption in Italy.

Different monetization methods of the environmental impacts (e.g., Stepwise 2006, EPS, Environmental Prices) are available in the literature (Pizzol et al., 2015). The methods differ in the geographical scope and the cost perspective (e.g., damage cost, abatement cost), leading to different monetary valuation coefficients (Amadei et al., 2021). Studies that assessed the external costs of meat and other food products already exist in the literature, but no study was found that quantified both the environmental and health-related costs. For instance, Weidema et al. (2008) assessed the potential external costs and benefits of reducing the environmental impact of meat and dairy products in the EU, but the health-related costs were not assessed. The authors concluded that the social costs of meat and dairy could be 20% lower if the environmental impacts were reduced. Using the same monetization method (Weidema, 2009), Nguyen et al. (2012) quantified the external environmental cost of pork production in the EU. The cost was estimated to be around 1.9 € per kg of pork produced, mainly due to land occupation and GHG emissions. Other studies focused just on the climate costs of food products, asking for policy measures to close the gap between current market prices of food products and their true costs. The external climate cost estimated for meat varies among the different studies. Pieper et al. (2020) estimated for the German context a cost of 1.7 € per kg of pork, 2.8 € per kg of poultry, 6.6 € per kg of ruminant, and 0.02 € per kg of plant-based product. In their study, an emission cost rate of 180 € per tonne of CO_2eq from the German Federal Environment Agency was used. Gren et al. (2019) quantified the climate cost for beef and tomatoes in Sweden using the actual Swedish tax

on CO_2 (~115 €/t CO_2). The resulting costs vary from few euro cents per kg of Swedish tomatoes to 5-7 € per kg of Swedish beef. Springmann et al. (2017) assessed the climate cost of food across the globe and investigated the health consequences of a taxation based on the climate impact. With an emissions price for GHG of ~46 €/t CO_2eq (assumed to correspond to the net present value of future climate damages), average climate costs were 2.5 € per kg beef, 0.3 € per kg of pork and poultry, and less than 0.1 € per kg of most crops. The authors concluded that climate taxes on food commodities would also promote health if properly designed. Finally, in another study, Springmann et al. (2018) estimated the health-related costs to society attributable to red and processed meat consumption, and concluded that including these costs in the price of red and processed meat could lead to significant health and environmental benefits.
Despite this growing body of research on the external costs of food production, the quantification of the environmental and health-related costs of a national food supply chain based on LCA is lacking in the literature. This study provides for the first time an estimation of the total external cost of a single portion of meat and of all meat consumed in a year in a developed country, proposing a framework for the assessment of these costs that could be adopted in the future for other food products in different contexts.
The paper is structured as follows: first the amount of meat actually consumed in Italy is estimated. Then, the potential environmental and health impacts are quantified through LCA. The impact of the last step of the meat life cycle (i.e., ingestion) is estimated via the number of years that are potentially lost or gained due to its consumption. The environmental and health impacts are translated into monetary values using the external costs proposed in the Environmental Prices handbook by the CE Delft research centre (Bruyn et al., 2018). The results are finally interpreted to provide insights and recommendations for the public and the policymakers.

2. MATERIALS AND METHODS

In the study, the potential monetary cost for society due to the life cycle impacts of meat consumption in Italy is estimated. The cost includes the hidden economic consequences from the impact of meat production and distribution on several environmental categories (e.g., climate change, acidification, etc.), and the human health cost (positive or negative) of eating meat. Other potential external costs and benefits to society (e.g., animal welfare, occupational health, cultural and hedonistic aspects) were excluded for lack of robust data in the scientific literature. Although concerns about occupational health and foodborne illnesses at slaughterhouses have been reported in the recent literature (Ciambrone et al., 2020; Jerie and Matunhira, 2022; Qekwana et al., 2017), with the Covid-19 pandemic increasing the attention on this issue (Herstein et al., 2021; Larue, 2022; Ursachi et al., 2021; Winders and Abrell, 2021), few quantitative data are available (Li et al., 2019). Following the framework proposed in previous LCAs of dietary changes (Paris et al., 2022; Stylianou et al., 2021, 2016), the health-related impact of the food is included in the LCA. The methodology adopted is described in detail in the next sections: estimation of meat consumption in Italy in 2018 (2.1), LCA of meat consumption (2.2), quantification of the health impacts linked to meat ingestion (2.3), monetization of the environmental and health impacts (2.4), and interpretation (0).

2.1. Italian meat consumption

Italian apparent meat consumption is estimated from the FAOSTAT database, adding up production and imports, and subtracting the exports (FAO, 2021). Since FAOSTAT data include bones, cartilages, and other by-products, the amount of fresh bone-free meat per kg of apparent meat is calculated using the conversion factors from Springmann et al. (2020): 0.715 for beef, 0.68 for pork, and 0.71 for poultry. The amount of meat waste along the supply chain is subtracted to account for the actual amount consumed by the Italian omnivorous population: 5% of waste during processing and packaging, 4% during distribution, and 11% during consumption (FAO, 2011). From a total apparent consumption in 2018 of approximately 5 kt (i.e., 77 kg per capita), the actual daily consumption per Italian omnivore results to be approximately 130 g/d. A population of 60.5 million was assumed for Italy in 2018 (Eurostat, 2020), with 4.3 million vegetarian and vegan (Eurispes, 2018). Consumption results for the different types of meat are reported in Table 1. On average, an Italian omnivore consumes 82 g/d of unprocessed (i.e., "fresh") meat, mainly poultry (41%) and beef (34%), and 46 g/d of processed meat, mostly (97%) in the form of processed pork meat. Data for processed meat are collected from the annual report of the Italian association of meat producers (ASSICA, 2019). Processed meat data do not include frozen meat, due to its very low consumption in Italy (IIAS, 2019). Finally, poultry meat is assumed to be entirely unprocessed in our study.

Table 1. Meat consumption in Italy in 2018. Elaboration on data from FAOSTAT and ASSICA (ASSICA, 2019; FAO, 2021). *Pc: per capita; pc_o: per omnivore; d: day.*

Meat type	**Production**	**Export**	**Import**	**Consumption (apparent)**		**Consumption mode**	**Consumption (bone-free meat)**		**Average consumption (actual)**	**Average omnivores' consumption (actual)**
	kt	kt	kt	kt	kg/pc		kt	kg/pc	g/(pc*d)	g/(pc_O*d)
Beef	809	140	347	1,016	16.8	Fresh	695	11.5	25.5	27.5
						Processed	31.7	0.5	1.2	1.3
Pork	1,470	302	1,100	2,268	37.5	Fresh	409	6.8	15	16.2
						Processed	1,134	18.7	41.7	44.8
Poultry	1,270	176	88.5	1,182	19.5	Fresh	840	13.9	30.9	33.1
Other	115	10.9	65.6	170	2.81	Fresh	119	2.0	4.3	4.7
Total	***3,660***	***628.9***	***1,601***	***4,636***	***76.6***		***3,228***	***53.3***	***118.6***	***127.7***

2.2. LCA methodology

The environmental impacts of meat production are assessed via LCA following the recommendations of the ISO 14040 and ISO 14044 (ISO, 2006a, 2006b). In the following sections, the goal and scope definition (2.2.1) and the life cycle inventory (2.2.2) are presented.

2.2.1. Goal and scope

The goal of the LCA is to assess the potential cost on society due to the environmental and health impacts of meat consumption in Italy, using 2018 as reference year. The assessment is a snapshot of the potential impacts generated in a specific (past) time, and it does not try to assess, for instance, the potential consequences from a dietary shift. For this reason, the assessment falls under the umbrella of the so-called attributional LCAs. Secondary data are used for the assessment, collected from LCA databases, public statistics, scientific literature, and industrial reports. The main LCA databases used for the study are Agri-footprint 4.0 (Durlinger et al., 2017), and Ecoinvent 3.6 (Wernet et al., 2016).

2.2.1.1. Declared units

Two declared units (DUs) are considered for the study. First, a unit (DU_1) based on mass (i.e., 100 g of ingested product) is used to quantify and compare the potential impact of the four main different types of meat consumed in Italy (beef, pork, processed pork, and poultry). Then, a declared unit corresponding to the daily consumption of meat by the omnivorous Italian population for one year (2018) is used to evaluate the annual potential environmental impacts. The daily amount of meat corresponds to the average consumption of meat by the Italian meat-eaters (i.e., 127.7 g/d per capita as reported in Table 1), minus the fraction of "*Other*" meat (4.7 g/d) since no information on its potential environmental and health impacts was available. The composition of the second declared unit (DU_2) is presented in Table 2.

Table 2. Daily Italian meat consumption by omnivorous population. The actual consumption, divided per meat source and processing, is used as declared unit in the study (DU_2).

Meat		**Actual consumption**		
		kt/y	$g/(d*pc_o)$	%
Beef	Fresh	563.9	27.5	21.6
	Processed	25.8	1.3	0.98
Pork	Fresh	331.7	16.2	12.7
	Processed	920.1	44.9	35.1
Poultry	Fresh	680	33.1	25.9
Total		***2.620***	***123.0***	***100***

2.2.1.2. System boundaries

The life cycle of meat is investigated from the production of the materials and energy used in the farm, through the final distribution of the packaged product, to its final consumption. Treatment of human excretion after meat ingestion is excluded from the assessment. A scheme representing the system boundaries of the study is presented in Figure 1. Even though some differences exist in the life cycle of the four types of meat examined (e.g., farming activities, feed production), five common macro unit processes (UPs) are identified: farming activities (UP1), slaughtering and processing (UP2), packaging (UP3), distribution (UP4), and consumption (UP5). For the consumption stage (UP5), the health impacts associated with meat ingestion are also included in the assessment (see Section 2.3).

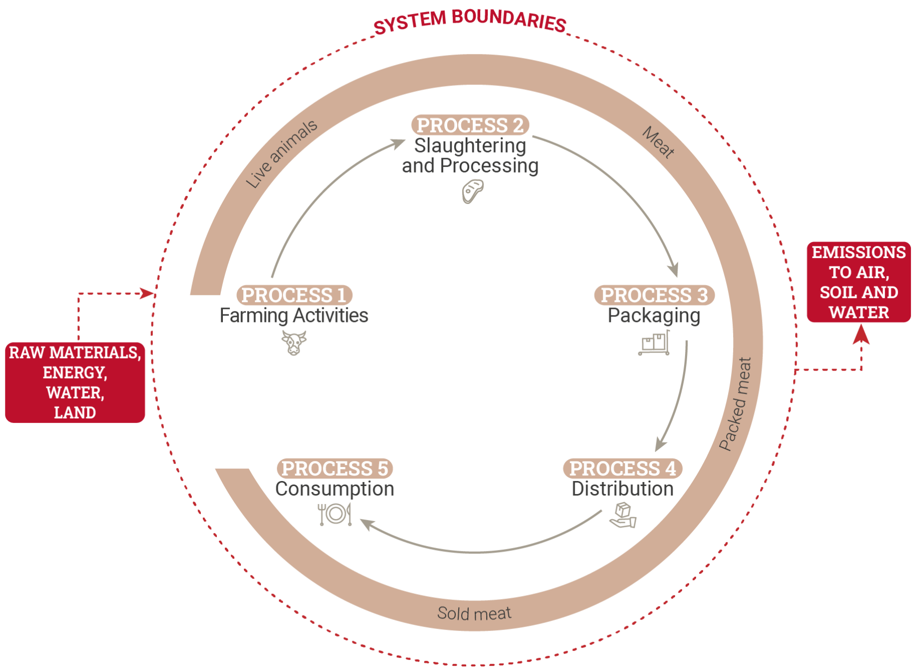

Figure 1. Processes of the meat life cycle included in the assessment (see Figure S.1 of supplementary materials for details)

2.2.1.3. Allocation procedure

The way multifunctionality is addressed affects significantly the results of LCA studies related to the agri-food sector (Notarnicola et al., 2017a). No consensus has been reached yet on how to allocate the impacts between meat and the co-products, such as milk and skin (Wilfart et al., 2021). In this study, an economic allocation procedure is chosen, with the prices for the different products taken from the Agri-footprint database (Durlinger et al., 2017). The only exception regards the allocation procedure in dairy farming. In this case, in- and out-flows are partitioned between co-products (i.e., milk and meat) based on a bio-physical allocation in line with the PEF working group recommendations' (IDF, 2015): almost 86% of the flows are allocated to milk, 12% to meat and the remaining 2% to calves.

2.2.1.4. Impact assessment

Inputs and outputs of the system are converted into potential environmental impact through the ReCiPe impact assessment method (Huijbregts et al., 2017). The life cycle impact assessment is performed with the 9.1 version of the SimaPro software (Pré Consultants, 2020). The following fourteen impact categories are investigated: climate change (over 100 years), ozone depletion, terrestrial acidification, marine eutrophication, freshwater eutrophication, human toxicity, photochemical ozone formation, particulate matter formation, terrestrial eco-toxicity, marine eco-toxicity, freshwater eco-toxicity, ionising radiation, land use, water use. The most relevant characterization factors considered in the ReCiPe method for the climate change impact over 100 years are 30.5 kg CO_2eq per kg of fossil methane, 27.75 kg CO_2eq per kg of biogenic methane, and 265 kg CO_2eq per kg of nitrous oxide. The assessment of the health impact is based on epidemiological studies, as presented in section 2.3.

2.2.2. Life cycle inventory

The following paragraphs present the inventories for the five unit processes: farming activities (2.2.2.1), slaughtering and processing (2.2.2.2), packaging (2.2.2.3), distribution (2.2.2.4), and consumption (2.2.2.5).***Farming activities (UP1)***

Due to lack of primary data regarding Italian farming activities, farms are modelled from datasets representative of European farms available on the Agri-footprint database: i.e., an Irish beef farm, and Dutch dairy, pork, and poultry farms. The main inputs to UP1 are feed (transported to the farm), water, and energy, whereas the outputs are the live animals and potential secondary products (e.g., milk). Datasets have been adjusted to better represent the Italian scenario. To simplify, the same farming datasets were used for imported meat too. The edits applied to the original Agri-footprint datasets are briefly summarized here and presented more in detail in Section S1.1 of the supplementary material. Amount and type of feed considered in the original datasets are left unchanged, whereas feed sources are modified to reflect the actual origins. The only exception are beef and dairy-beef farms, where grazing is entirely substituted with Italian maize silage. Beef meat is assumed to come mainly from beef herds (79%), and the remaining from dairy-beef farms (Basile, 2019). Cereal and legume origins are modelled based on FAOSTAT data on Italian production and imports. Transportation of feed to the farm is included in this unit process (see Section S1.1.1 in the supplementary material for the details on transportation modelling). When available, the main greenhouse gas emissions (i.e., CH_4, N_2O) generated in-farm are modified from the original dataset in order to reflect Italian data reported in the annual greenhouse gas inventory of the European Union (European Environmental Agency, 2020). Finally, the Italian electric mix from the ELCD database is used to model energetic consumption both for in-farm activities and for ancillary processes (e.g., feed mixing).

2.2.2.2. Slaughtering and processing (UP2)

The datasets available on the Agri-footprint database are used for the slaughtering process. The main inputs in this stage are water, electricity, and thermal energy. Even though bovines do not require a scalding phase, electric consumption for their slaughter (i.e., 79.8 kJ per 100 g of slaughtered meat) is higher than the one for pork and chickens. The reason can be ascribed to the lower yields for beef slaughtering in terms of kg of meat per kg of live animal. Pork meat, instead, requires more thermal energy. The Italian electricity mix is considered for electric consumption, whereas a natural gas boiler has been assumed to provide the thermal energy needs. Transportation of the live animals from the farm to the slaughterhouse are included in this unit process, while no transportation from the slaughterhouse to the processing plant is considered.

Meat is processed in many ways in Italy, including various types of sausages and cold cuts. To simplify, the meat types consumed in Italy are grouped into three categories: i) fresh meat with no need for further processing, ii) dry-cured ham, and iii) baked ham. The correspondence between each type of meat consumed in Italy and the meat category is reported in Table S.16. To give a couple of examples, *salame* is modelled as dry-cured ham, whereas canned meat as baked ham. For the aging phase of dry-cured ham, 6.25 g of sodium chloride (Toldra, 2004) and 0.38 kWh (Kvalsvik, 2017) are considered to be used per 100 g of ham. As for baked ham, 0.0056 Nm^3 CH_4 and 30 g of brine are considered to be used per 100 g of finished product (Bonou and Birkved, 2016). The brine composition considered for the study is reported in Table S.15. Food losses (5%) and their treatment as organic waste are considered for both fresh and processed meat. Moreover, wastewater treatment is also considered for the slaughtering phase.

2.2.2.3. Packaging (UP3)

A single use packaging made of polystyrene tray (3.3 g per 100 g of meat) and polyethylene film (0.4 g per 100 g of meat) were considered for all types of meat (Notarnicola et al., 2017b). Average European datasets were used to model the production of the packaging. It was assumed that meat is packaged in the same place where the animals are slaughtered and processed.

2.2.2.4. Distribution (UP4)

The distribution stage refers to the transportation of packaged meat from the processing plant to an average retailer. Food waste along the distribution chain (4%) and its final treatment are also included in the unit process. Average distances to retailers are considered for meat produced and consumed in Italy. The distances are quantified based on regional meat production (Macrì, 2017), assuming that retailers buy meat within the same region. If a region consumes more meat than it produces, retailers are assumed to buy the extra meat from another region. An average distance of 100 km is considered for meat transported within the same region, whereas 500 km are considered for inter-regional transportation. Imported meat is assumed to be shipped to Italy via sea for extra-European countries, and via truck for transportation within

Europe. Trucks are chosen rather than rail since 95% of European food is transported by road (Dionori et al., 2015). Truck and sea distances from the capital city of the supplying country to Rome are estimated via Google Maps (Google, 2019) and Sea Routes (SeaRoutes, 2019), respectively. Both truck and ship transportation are modelled considering refrigerating means. Average transportation distances included in the LCA for the Italian meat supply are shown in Table S.17. Finally, 0.105 MJ of electric consumption from the national grid is assumed to keep 100 g of meat refrigerated at the retailer (Heller and Keoleian, 2018).

2.2.2.5. Consumption (UP5)

The last unit process considered in the study includes: i) transportation of the packaged meat from the retailer to the place of consumption, ii) meal preparation, iii) meal consumption, and iv) waste treatment. No domestic refrigeration nor human excretion are included. Transportation is modelled assuming that consumers buy on average thirty items when they shop for groceries, and that a portion of meat (i.e., 100 g) is one of those items. In other words, meat is considered to be responsible for one thirtieth of the impacts generated in a 4-km two-ways journey to a retailer (Notarnicola et al., 2017b). Cured meat is assumed to be consumed without any further preparation, whereas 0.85 MJ of natural gas are considered to be used to cook 100 g of fresh meat (Notarnicola et al., 2017b). Eleven percent of meat is assumed to be wasted in the consumption phase (FAO, 2011) and treated as organic waste.

2.3. Health impact from meat ingestion

In the assessment, only the health impacts for which a robust scientific literature (i.e., systematic reviews of epidemiological studies) was available were included. These include the relationship between eating red and processed meat and contracting four diseases: colorectal cancer (Schwingshackl et al., 2018), type 2 diabetes mellitus (Schwingshackl et al., 2017), stroke (Bechthold et al., 2019), and coronary heart disease (Bechthold et al., 2019). In line with the existing literature, no risk change for these diseases was attributed to poultry meat (Springmann et al., 2020). Other health consequences potentially linked to meat consumption were excluded from the assessment due to lack of extensive data, such as higher risk for antibiotic resistance (EFSA and ECDC, 2019), obesity (Rouhani et al., 2014), zoonosis (Espinosa et al., 2020), and food poisoning (Hennekinne et al., 2015), or lower risk for nutritional deficiencies in infants (Leroy and Cofnas, 2020).

The disease risk for an Italian omnivore is estimated from the dose-response curves drawn in the systematic reviews, assuming the average daily intake of red and processed meat presented in section 2.1. Considering red meat and processed meat as two independent risk factors (Springmann et al., 2018), the proportion of the diseases contracted in Italy attributable to meat consumption (i.e., population attributable fraction, PAF) can be estimated. Given that no information was available on the number and age of people who contracted these diseases in Italy (and on the amount of meat consumed daily by the different age groups), the PAF proportion was assumed to be valid also for the share of disability-adjusted life years (DALYs) lost (or gained) in Italy for each of the diseases. Steady state conditions were assumed for the intake of meat by the Italian population and the DALY lost. The total DALYs lost in Italy due to the four diseases are from the 2017 Global Burden of Disease study (Monasta et al., 2019). The DALYs indicate the sum of years of potential life lost due to premature mortality and the years of productive life lost due to disability. Considering an Italian population (P) of 60.5 million people in 2018, divided into 56.2 million meat eaters (O) and 4.3 million non-meat eaters (V), the fraction of health losses seen in the Italian omnivore population attributed to disease **i** (i.e., PAF_{O_i}), is calculated through equation 1:

$$PAF_{O_i} = \frac{\sum_j P_o \times \Delta R_{O_{i,j}}}{\sum_j (P_o \times \Delta R_{O_{i,j}}) + 1} \qquad 1$$

Where P_o is the fraction of Italian omnivores, and $\Delta R_{O_{i,j}}$ is the risk variation of losing/gaining DALYs with respect to the baseline risk factor of disease **i** due to the risk factor **j** (i.e., the consumption of red or processed meat). This value is derived from the relative risk curves produced from cohort studies which starts from a null consumption of meat (Bechthold et al., 2019; Schwingshackl et al., 2018, 2017). For each disease **i**, the $PAF_{O_{i,j}}$ is assessed for each risk factor **j**. Finally, the $DALY_{O_{i,j}}$ lost by the omnivorous population due to the different risk factors **j** are calculated multiplying the $PAF_{O_{i,j}}$ times the total amount of DALYs lost in Italy in 2018 due to the disease **i** reported in the Global Burden of Disease. All the steps to assess the DALYs are reported in detail in the spreadsheet in the supplementary material. To estimate the DALYs linked to type 2 diabetes mellitus, it is considered that 90% of Italian diabetes cases are type 2 diabetes (ISTAT, 2017).

2.4. Monetization phase

The potential environmental impacts have been monetized to quantify potential costs for society. Monetization is considered a weighting method in LCA, since it allows to rank the impacts and to aggregate them (Amadei et al., 2021; Pizzol et al., 2015). Here, the impact assessment results are converted into a single score (i.e., a monetary value) using the environmental prices recommended by CE Delft (Bruyn et al., 2018). The environmental prices are representative for Europe (EU28), and they are based on the impact pathway approach developed in the EU project NEEDS (2008). The prices indicate the loss of welfare due to one additional kg of pollutant emitted to the environment in an average European location (Bruyn et al., 2018). Different approaches were adopted to obtain a price for the environmental impacts: for instance, the cost for GHG emissions (57 € per t of CO_2eq) was considered based on both the damage cost of climate change and the abatement cost to reach a 40% GHG emission reduction in 2030 compared to 1990. On the other hand, the price for the impact on ecosystems and human health (e.g., respiratory diseases caused by the formation of particulate matter) is based on stated preference studies and budget constraints (i.e., willingness to pay). The prices for each environmental impact category are presented in Table S.19, and we refer the reader to the original report for all the details on the modelling assumptions. Since the method does not provide a price for water use, this category was excluded from the quantification of the total monetary burden. The prices proposed by CE Delft are used here because: i) they are developed from the same characterization model (ReCiPe) used for the impact assessment, and ii) they have been previously used by the European Commission (2019).

For the monetization of the health implications of meat ingestion, the amount of DALYs lost or gained are multiplied by 55,000 €/DALY. This value is assumed to represent the willingness to pay for an additional year of healthy life for an average European citizen (Bruyn et al., 2018).

2.5. Interpretation

2.5.1. Comparison with plant-based alternatives

The external costs of meat are preliminarily compared with two plant-based alternatives: peas and soybeans. Costs are compared until the slaughtering phase of meat production since the available inventory for the plant-based alternatives (Agri-footprint) is referred only to their production. European productions are considered for the legumes: Italian for soybeans, and an average between French and German productions for peas. Italian and European productions are considered since the majority of legumes consumed in Italy are cultivated there (FAO, 2021; IDH and IUCN NL, 2017). The impacts are compared both on a mass basis (DU_1) and in terms of proteins (i.e., 100 g of proteins produced). A protein content of 20 g, 16 g, and 17.5 g, are considered for 100 g of beef, pork, and poultry meat, respectively (Poore and Nemecek, 2018); whereas a protein content of 21.5 g is considered for 100 g of dried peas (Poore and Nemecek, 2018), and 36 g for 100 g soy beans (U.S. Department of Agriculture, 2019).

2.5.2. Sensitivity analyses

Sensitivity analyses are performed on the uncertain parameters considered in the study: i) the prices used to translate the potential environmental impacts into monetary costs (3.1.2), ii) the risk variation ($\Delta R_{O_{i,j}}$) of contracting the four diseases (3.2), and iii) the monetary value of DALYs. The baseline results (S_0) are compared to a “minimum” cost scenario and a “maximum” one. The minimum cost scenario (S_{min}) is obtained from the lower bound of the environmental price range proposed by CE Delft, the lower bound of the disease relative risks drawn in the reviews of the cohort studies, and a DALY value of 55,000 €. On the other extreme, the maximum cost scenario (S_{max}) is obtained using the upper bound of the environmental price range, the upper bound of the disease relative risks, and a DALY value of 110,000 €, i.e., the highest value associated to a life year lost due to disability reported by Bruyn et al. (2018).

3. RESULTS

The following sections present the potential pre-ingestion impacts -linked to the life cycle of meat before ingestion- and their external costs (3.1), the potential health impact from meat ingestion and its cost (3.2), and the total potential yearly cost for society from meat consumption (3.3).

3.1. External pre-ingestion costs

3.1.1. Life cycle impact assessment results

The impact assessment results per 100 g of consumed meat (DU_1) are presented in Figure 2. Only the six impact categories with a higher influence on the external costs are shown, while the remaining impact categories are presented in Table S20. Although water consumption is not included in the monetized result, the impact is shown in Figure 2 for its relevance to society.

Beef meat presents the highest impact in all categories but terrestrial ecotoxicity, where poultry meat shows the worst performance. Regarding the impact on climate change, feed production, farming activities, and slaughtering are responsible from 65% (processed pork) to 77% (beef) of the total impact. The processing phase is responsible for 5% of the climate impact for unprocessed meat, mainly due to food loss, and 15% for processed meat. In the case of pork meat processing, dry cured ham generates around five times the global warming impact of baked ham (330 vs 65 g CO_2eq/100 g meat), mainly due to the energy demand for curing. The role of packaging production is negligible for all types of meat, whereas the distribution phase contributes to 5% of the total climate impact for beef meat and around 15% for the other types of meat. Food loss is a relevant source of GHG emissions, and its impact increases moving down the supply chain since the loss is linked to a higher number of activities. In total, beef meat generates 3.26 kg CO_2eq/DU_1, whereas pork, processed pork, and poultry meat generate 1.15, 1.21, and 0.94 kg CO_2eq/DU_1, respectively (see Table S20). The impacts before the slaughtering phase are presented in Table S21. Before slaughtering, pork and poultry meat generate around 30% of the beef impact (2.52 kg CO_2eq/100 g of slaughtered meat). This is mainly due to enteric fermentation, which accounts for approximately 35% of the climate impact of slaughtered beef, and to the lower feed-to-meat conversion ratio for beef. Feed production generates around 1 kg CO_2eq per 100 g of slaughtered beef, mainly due to maize production (60%) and manure management (18%). Feed production is the major responsible for the climate impact of pork, accounting for 64% of the impact until slaughtering. Soybean meal is responsible for approximately 30% of the impact even though it accounts for less than 10% of the feed mass. Most of the impact is linked to land use change in South America, since soybean meal used in Italian farms is typically imported from Argentina and Brazil (IDH and IUCN NL, 2017). Feed production -in particular soybean meal and palm oil- is the main responsible for the global warming potential of poultry meat too, generating 87% of the impact until slaughtering.

Processes until slaughtering account from 74% to 80% of the impacts on terrestrial acidification too, mainly due to ammonia emissions. In the case of beef, 60% of the acidification impact is linked to manure management, and 33% to direct field emissions from fertilization. Manure management and emissions from fertilizers are the main culprits for the acidification impact of pork production too, but the impact per 100 g of meat is 75% lower than beef. Direct ammonia emissions from manure management generate 65% of the acidification impact of poultry meat, whereas the production of feed (i.e., direct ammonia emissions to air from field fertilization) is responsible for 30%. Beef impact on marine eutrophication is five and eight times the one of pork and poultry meat, respectively. For all meat types, 80% of the eutrophication impact is linked to processes until slaughtering. The main contributors to the impact are nitrate emissions to water, and ammonia emissions to air. The remaining 20% of the impact is linked to meat that is produced and, later, wasted. Pre-processing phases are responsible for most of particulate matter formation as well (from 70% to 80%). Ammonia emissions to the atmosphere from manure management and fertilization are the main sources of impact, followed by nitrogen oxide emissions from agricultural field machines, transportation, and energy production. Beef meat has a higher impact for land use too, mainly linked with its low food conversion ratio, and with the larger land requirements to cultivate the feed. As previously mentioned, poultry meat has the worst environmental performance in the terrestrial ecotoxicity category, with an impact 30% higher than pork and 40% higher than beef. The impacts are mainly linked to the use of pesticides for growing the animal feed: in the case of poultry, 70% of the impact comes from soymeal production and 27% from palm oil. Finally, beef requires 70 L of water per 100 g of meat, approximately six and eight times the amount of water consumed by poultry (around 11 L/DU_1) and pork (around 9 L/DU_1). Differences in water consumption for the different meat types depend mainly on the amount and type of feed.

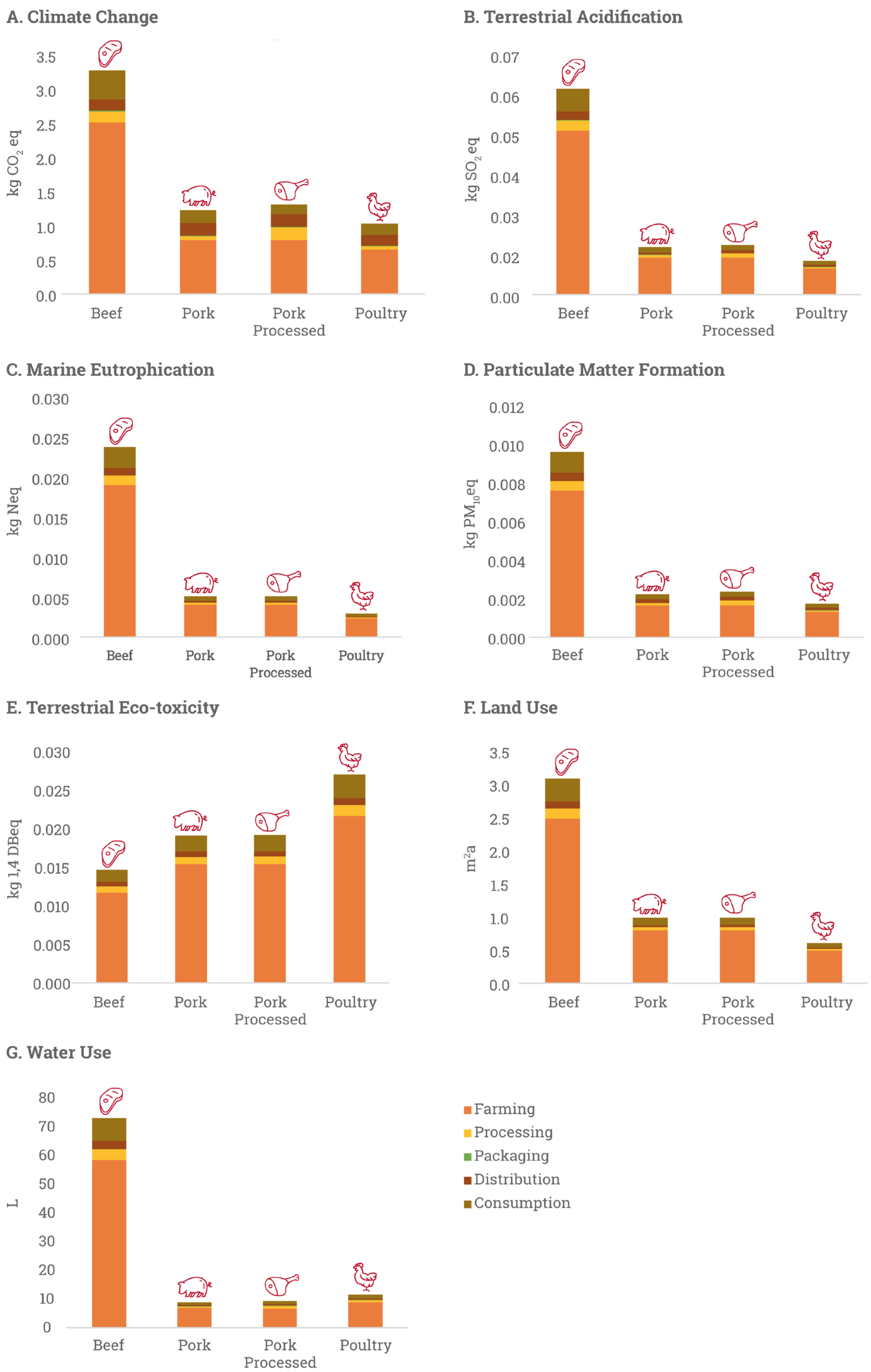

Figure 2. Comparison of the life cycle impact assessment results (DU_1) for the different life cycle stages of the four types of meat: a) climate change; b) terrestrial acidification; c) marine eutrophication; d) particulate matter formation; e) terrestrial eco-toxicity; f) land use; g) water use.

3.1.2. Monetized results

Figure 3 shows the monetization results of the impacts pre-ingestion, while the relative data are reported in Table S22. In line with the midpoint results, beef meat generates the highest cost on society: 1.35 € per 100 g (DU_1). Lower external costs are associated with the consumption of pork, processed pork, and poultry meat: 0.50, 0.51 and 0.47 €/DU_1, respectively. Particulate matter formation is the main responsible (28%) for the external costs associated with beef meat, followed by acidification potential (22%), land use (19%), and global warming potential (14%). Particulate matter has a relevant role also in the life cycle costs of pork (18%) and poultry (15%) meat. However, the highest external costs from pork and poultry meat consumption (pre-ingestion) are linked to ecotoxicity: 0.17 €/100 g of pork meat (34% of total) and 0.24 €/100 g of poultry meat (i.e., 50% of total). The impacts related to land use, acidification, and climate change, account from 10% to 18% of the pre-ingestion external costs of pork and poultry meat.

Figure 3. Comparison of the pre-ingestion external costs ($euro_{2015}$) generated by the life cycle of 100 g (DU_1) of beef, pork, processed pork and poultry meat.

3.2. External post-ingestion costs

In this section are presented the main results from the assessment of the external costs generated by the ingestion of meat in Italy, while all the details can be found in the supplementary material (Section S5 and spreadsheet). Based on the reviews of the cohort studies, the average Italian daily consumption of red meat (43.8 g/d) increases the risk of contracting three of the four diseases considered (see Table S23 in the supplementary material): from a 3.5% increase for colorectal cancer, through a 5.4% increase for stroke, to an 8.6% increase for types 2 diabetes. At the same time, it reduces by 3% the risk for coronary heart disease; Bechthold et al. (2019) found in fact a reduction in the risk of coronary heart disease with a consumption of red meat up to 60 g per day. On the other hand, the average Italian daily consumption of processed meat generates a higher risk for all the diseases considered: from a 14% increase for coronary heart disease to a

30% increase for type 2 diabetes. The conversion of the risk variation in DALYs is presented in Table S24, and it shows that meat consumption (red plus processed meat) is responsible for approximately 15% of the total DALYs lost in Italy due to colorectal cancer, 26% of the DALYs lost due to type 2 diabetes, 17% of the DALYs lost due to stroke, and 9% of the DALYs lost due to coronary heart disease. Processed meat accounted for around 90% of the total health impacts linked to meat consumption. The average DALYs lost due to the ingestion of 100 g of meat (DU_1) result to be 5.5x10-6 for red meat (i.e., approximately 3 minutes) and 4.2x10-5 (i.e., approximately 22 minutes) for processed meat. It is worth highlighting that these health impacts per 100 g of meat do not reflect the impact caused by the intake of 100 g of meat *una-tantum*, but they represent the total costs on society generated by the annual consumption of red and processed meat in Italy (896 kt and 946 kt, respectively) normalized on a 100 g portion. The conversion of DALYs into external costs is presented in Figure 4. The average external cost per 100 g of red meat results to be 0.30 € (in an interval spanning from an actual benefit of 0.74 € to a cost of 1.04 €), and 2.33 € for processed meat (from 0.78 € to 3.26 €). The annual DALYs lost to meat consumption range from a minimum of 13,300 (corresponding to a monetary value of 0.73 bn €), when the lower bounds of the relative risk variation are considered, to a maximum of 731,000 (i.e., 40.2 bn €) when the upper bounds are considered.

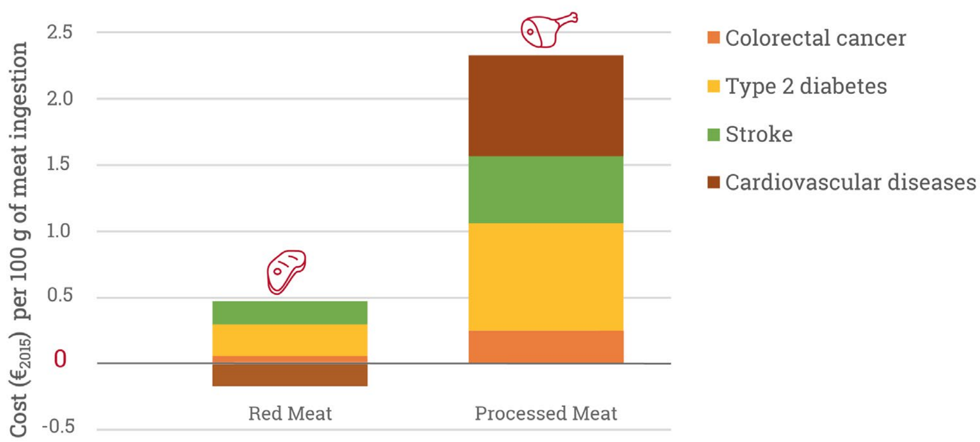

Figure 4. Health costs ($€_{2015}$) linked to the ingestion of 100 g of red and processed meat.

The impact of meat consumption on cardio-vascular diseases showed extremely high uncertainties, going from actual DALY benefits to the highest DALY losses among the diseases considered. To reduce uncertainty, the impact on cardio-vascular diseases was excluded from the analysis. The external costs of meat ingestion excluding cardio-vascular disease result to be 0.47 € (from 0.17 to 0.75 €) and 1.56 € (from 1.19 to 1.88 €)

per 100 g of red and processed meat, respectively. This is reflected in an annual cost for society ranging from 12.7 bn € to 24.5 bn €, with an average value of 19.1 bn € (corresponding to around 315 € per capita).

3.3. Total external costs

The total external costs from meat consumption are reported in Table 3. Excluding the costs from cardio-vascular diseases, processed pork results to be the type of meat generating the highest cost on society, with an external cost of 2.1 €/100 g. Beef meat follows with 1.9 €/100 g, whereas the consumption of 100 g of fresh pork and poultry meat cost to society approximately 1 € and 0.5 €, respectively. In the case of processed pork meat, 76% of the external cost is linked to the potential disease burden. The opposite is true for beef meat, with 74% of the external cost linked to the emissions arising to produce, process, and supply the meat. In the case of fresh pork meat, the external costs are almost equally distributed between costs pre-ingestion and post-ingestion.

The annual external cost of Italian meat consumption results to be 36.5 bn €, corresponding to approximately 600 € per Italian resident (assuming all the costs were borne by the Italian population). Pork meat accounts for 61% of the total cost, mainly due to the health impact associated with the ingestion of processed meat. Beef and poultry meat have a lower but still significant cost on society, with a total damage quantified in 11 bn € and 3.2 bn €, respectively.

*Table 3. External costs referred to 100 g of meat (DU_1) and annual 2018 Italian consumption (DU_2). *Weighted average costs for fresh beef (96%) and processed beef meat (4%).*

	Costs		Beef*	Pork (fresh)	Pork (processed)	Poultry	Total
DU_1 [100 g]	Pre-ingestion	€	1.35	0.5	0.51	0.47	Not applicable
	Post-ingestion	€	0.52	0.47	1.56	0	Not applicable
	Total	€	1.88	0.97	2.07	0.47	Not applicable
DU_2 [annual]	Pre-ingestion	bn €	7.98	1.65	4.69	3.21	17.5
	Post-ingestion	bn €	3.08	1.57	14.4	0	19.1
	Total	bn €	11.1	3.22	19.1	3.21	36.6

4. INTERPRETATION

4.1. Comparison with plant-based alternatives

The comparison of the life cycle impact assessment results for legumes and the four types of meat is shown in Table S25 and S26. In line with previous studies (Clune et al., 2017; Poore and Nemecek, 2018; Saget et al., 2021), legumes generate lower environmental impacts in all impact categories, both on a mass and protein basis. The only exception is the higher water consumption to produce 100 g of soybeans compared to 100 g of pork and poultry meats. However, when the food is compared in terms of proteins, soybeans require a lower amount of water (38 L/100 g protein) than all meat types (from 43 L/100 g protein of pork meat to 290

L/100 g protein for beef meat). As for climate change, meat production generates from 12 to 46 times the GHG emissions of legumes on a mass basis. The gap further increases when the comparison is done on a protein basis: the meat generating the lowest impact (i.e., poultry meat with 3.7 kg CO_2eq/100 g protein) is responsible for approximately 17 times the average emissions caused by legumes (i.e., 0.2 kg CO_2eq/100 g protein). Same ratios were found for terrestrial acidification, marine eutrophication, particulate matter formation, and terrestrial ecotoxicity, while a reduction in the impact ratio was noticed for land use, with meat using from 3 to 12 times the agricultural soil used for growing legumes.

The external cost of legumes' production phase is presented in Table S27 and Table S28. In terms of mass, legumes' production generates a cost on society (less than 0.05 € per 100 g) from 4 to 13% the one of meat. As for the potential health damage from the ingestion of legumes, cohort studies did not find any correlation between the consumption of legumes and the four diseases here considered (Bechthold et al., 2019; Schwingshackl et al., 2018, 2017). Notwithstanding the potential health benefits of consuming more legumes, the overall cost for society of consuming 100 g of legumes is from 8 to 40 times lower than the one of meat. In terms of proteins, 100 g of plant-based proteins cost around 0.17 € to society, compared to 2 - 12 € for 100 g of meat proteins.

4.2. Sensitivity analyses

To test the robustness of the results, minimum and maximum cost scenarios are modelled. The main results are summarized in Figure 5, where S_{min} and S_{max} indicate the two extreme scenarios. The type of meat with the highest degree of uncertainty appears to be fresh pork, with a maximum cost resulting to be 8 times the minimum cost. On the other hand, the lowest variation is observed for processed pork (i.e., S_{max} is 3.7 times S_{min}). The annual external cost due to meat consumption in Italy varies from 92.3 bn€ in the worst scenario (i.e., around 1,500 € per capita) to 19.1 bn€ in the best scenario (i.e., around 300 € per capita).

Beef meat shows the lowest variation in the pre-ingestion costs (from 0.56 to 3.61 €/DU_1), whereas pork meat costs per DU_1 range from 0.16 € to 1.22 €. In the high-cost scenario (S_{max}), around 60% of the pre-ingestion costs are related to the impacts on land use, due to the high economic value associated with ecosystem services and loss of biodiversity in this scenario. The contribution of climate change spans from 11 to 14% of the overall cost for the different types of meat, reaching a maximum of 0.3 € per 100 g of beef meat. In the low-cost scenario (S_{min}), almost half of the costs are linked to the formation of particulate matter in the atmosphere. Excluding the ingestion costs, the meat supply chain generates a cost on society from 6.3 bn € (i.e., around 100 € year^{-1} pc^{-1}) to 43.2 bn€ (i.e., 700 € year^{-1} pc^{-1}).

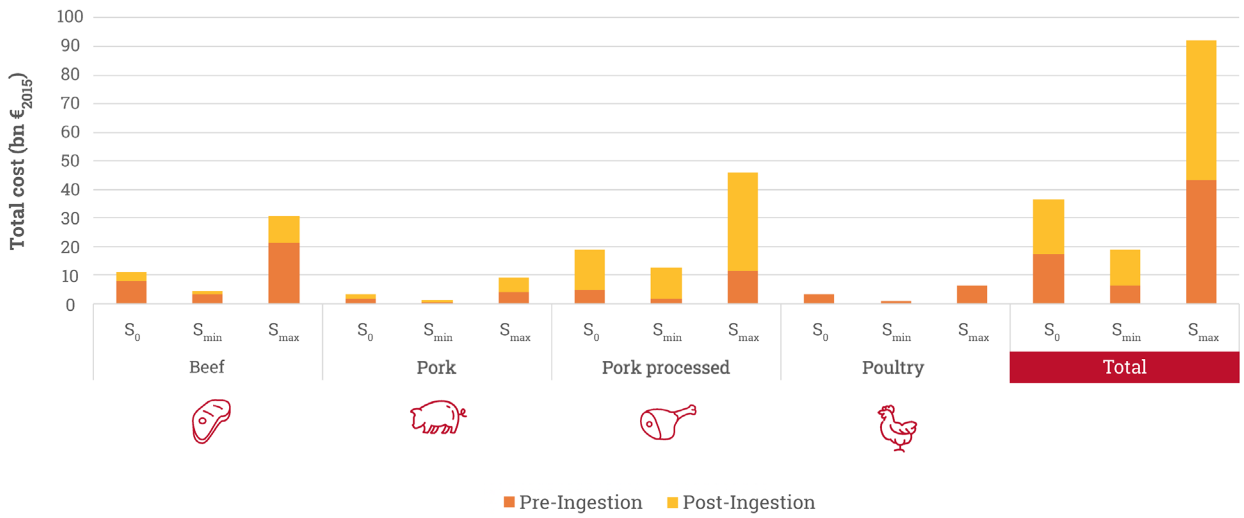

Figure 5. Total external cost linked to meat consumption in Italy in one year (2018) considering the three different scenarios of the sensitivity analysis: S_0 (baseline), S_{min} (low costs), S_{max} (high costs).

5. LIMITATIONS

The main limitations of the study concern the lack of primary inventory data for meat production, the estimation of health risks, and the uncertainty related to the monetization process.

The use of recognized LCA databases increased the quality of results in terms of transparency and reproducibility, but it lacked representativeness for the specific case study. Italian meat production emissions were based on Agri-footprint datasets, which have been previously used to calculate average environmental impacts linked to food production and consumption in Europe (Notarnicola et al., 2017b; Sala and Castellani, 2019). Although we partially edited these datasets to better represent the Italian scenario, they do not encompass the whole spectrum of Italian farms (e.g., no data is available for extensive farming systems in hills or mountains (Zucali et al., 2017)) nor farms from where meat is imported. Costs from pork and poultry meat resulted to be higher in our case with respect to using the original Agri-footprint datasets mainly because of the larger consumption of soymeal from South America. On the other hand, beef meat resulted to be less costly in our case thanks to lower ammonia emissions considered for feed production. Greenhouse gas emissions from beef meat production are in line with a previous study that assessed the climate impact of ten beef farms in the north of Italy: 14.5 kg CO2-eq per kg of beef live weight vs. an average of 15 kg CO2-eq estimated by Bonnin et al. (2021). Overall, edits did not lead to significant variations in the results: if the original datasets were used, the overall costs for society would be 1.4% lower. Despite the apparent low sensitivity of the results to the edits, primary data on food losses and on the farms where meat consumed in Italy is actually produced would significantly improve the accuracy of the impact assessment. For instance, a recent study found via material flow analysis a larger consumption of meat in Italy compared to the present study (Ferronato et al., 2021), suggesting a potential underestimation of the total external costs assessed here. The impact from transportation might be underestimated too: in our study, distances were calculated from maps assuming that products were traveling on the shortest path between two locations (without any additional stop), and secondary data were used for the emissions. Results showed a limited contribution of transportation to the overall cost. Although our results are in line with previous assessments (Poore and Nemecek, 2018; Weber and Matthews, 2008), recent studies showed how shipping could play a larger role in the emissions from the supply chain of food (Li et al., 2022) and how LCA databases could underestimate the emissions from ships (Istrate et al., 2022).

As for monetization, although the prices adopted here provide results that are easy to understand and to compare, potential external costs arising from site-specific impacts should be explored to increase the accuracy of the results. Moreover, part of the impact of food supply chains occur typically beyond national and European boundaries: using European prices for such impacts results therefore critical (Arendt et al., 2020; Bruyn et al., 2018). External costs and benefits that were not accounted here for lack of data should be explored in the future: from the impact on additional environmental categories, such as freshwater depletion, indirect land-use change, and resource depletion (Ligthart and van Harmelen, 2019), through additional impacts related to human health damage, such as medical and administrative costs (Wijnen and Stipdonk, 2016), to other social impacts, such as animal welfare (Fernandes et al., 2021), occupational health, job-creation, and cultural and hedonistic values.

As for the post-ingestion assessment, more research on the health consequences of consuming meat in Italy is needed to: i) validate the modelling assumption, ii) account for the specificity of the Italian context (e.g., diet) in terms of health risks and meat nutritional properties (Morze et al., 2021), and iii) include the costs or benefits of other health consequences potentially linked to meat consumption currently excluded from the assessment due to lack of robust scientific evidence (e.g., antibiotic resistance, obesity, nutritional deficiencies). As regards pathogenic hazards (e.g., Salmonella) due to meat ingestion, a recent study showed that the impact on human health from foodborne illnesses due to beef consumption in the U.S. is of the same magnitude with the environmental impacts and the occupational hazards arising at the slaughterhouse (Li et al., 2019). Since the slaughtering stage represents a small fraction of the life-cycle environmental impact of meat in our case study, the inclusion of food poisoning and occupational hazard in the assessment would not affect the results in a significant way. In fact, foodborne illnesses due to pathogenic hazards from beef consumption and occupational risk at the slaughtering plant were calculated to reduce the healthy life in the U.S. of a few minutes per year per capita (Li et al., 2019), while the increasing risk of colorectal cancer, stroke, and types 2 diabetes due to red and processed meat consumption, was estimated in our study to reduce the healthy life of Italian meat-eaters of approximately 54 hours per year.

6. DISCUSSION and CONCLUSION

The goal of this study was to quantify the external cost generated from Italian meat consumption, due to the impacts on the environment and on human health. Such cost remains otherwise hidden as it is not accounted for in the price of food products. Results showed that the external cost of 100 g of meat pre-ingestion ranges from 0.5 € in the case of poultry and pork meat, to 1.3 € in the case of beef. The main emissions responsible for the external cost are the ones contributing to the formation of particulate matter, acidification, climate change, and eco-toxicity. Considering climate change, our results are lower than previous assessments (e.g., 1.8 € per kg of beef meat compared to 2.5 € in Springmann et al. (2017) and 4.5 € in Pieper et al. (2020)), due to different monetization factors and inventory data. As for the external costs after ingestion, around 350,000 DALYs are estimated to be lost every year in Italy because of red and processed meat consumption (excluding the potential effect on cardiovascular diseases, which showed a high degree of uncertainty). Assuming a value of 55,000 € per DALY lost, 100 g of red meat cost to society 0.5 €, while 100 g of processed meat cost 1.6 €. It should be pointed out that this cost was normalized based on the average daily meat consumption in Italy in 2018; if consumption reduced in the future, the health risk would reduce as well, and, as a consequence, the cost on society per 100 g of meat consumed. Coupling environmental and health costs, the consumption of 100 g of meat in Italy has a hidden cost of around 0.5 € for poultry, 1 € for pork, and 2 € for beef and processed pork. Extending the results to the entire meat consumption in Italy, the total cost was around 36.6 bn € in 2018 (ranging from 19.1 to 92.3 bn €). This cost, which does not include any benefit to society linked to the meat supply chain (e.g., employment, cultural heritage), is almost equally shared between pre-ingestion (48%) and post-ingestion (52%) impacts. The preliminary comparison with the production phase of plant-based alternatives showed that legumes generate a much lower cost on society, both on a mass basis (around 0.05 € per 100 g of legume) and on a protein basis. The legume cost refers only to the life cycle emissions, since no (or reduced) health risks are associated with their ingestion. To remain within the planetary boundaries of safe operating space for humanity, the EAT-LANCET commission recommends a daily consumption of 7 g (from 0 to 14 g) of beef and/or pork meat, and 29 g (from 0 to 58 g) of poultry meat (Willett et al., 2019). If the Italian meat-eaters adopted this diet (assuming that red meat was half fresh and half processed), the external cost of meat consumption would amount to around 30% of the current diet cost (see Table S30 and the spreadsheet in the supplementary material for more information). This is in line with the significant GHG emission and health savings showed by Stylianou et al. (2021) by substituting meat consumption with plant-based alternatives. Nevertheless, our results show that the burden on society would remain significant with a EAT-LANCET diet too (approximately 10 bn € annually). A consequential assessment including the potential implications of a national dietary change is however needed to confirm this result.

Our investigation is one of the first attempts to couple, through monetization, the life cycle impacts on multiple environmental categories with the health impacts linked to meat ingestion. The methodology adopted could help LCA practitioners to better understand potential advantages and disadvantages of using monetization in the LCA of food products. On the one hand, monetization can support and simplify the comparison between different types of meat by providing a final single score. On the other hand, the uncertainties of the prices recommend a prudent use of the results. The testing of more than one monetization method and the conversion of monetary units to the year of quantification represent promising path towards more robust results (Arendt et al., 2020). Further assessments are recommended to validate the results and to produce a robust background to support policy makers, civil society, and other stakeholders in understanding the implications of their choices. Integrating the ingestion phase in the LCA of other food products would be useful to draw a complete assessment of their social burden: the same methodology adopted here could be used for instance for products high in sugar content and alcohol (McLaren et al., 2021).

In the end, who pays for the external cost generated by meat production and consumption? While some costs are already borne by the meat-eaters (e.g., carbon taxation or trading scheme linked to some carbon emissions along the supply chain (Gren et al., 2019)), most costs are borne indiscriminately (and likely unknowingly) by the entire society (Pieper et al., 2020). For instance, the Italian society is already bearing the health costs associated with particulate matter emissions from Italian farms or the higher prices for food due to lower yields caused by acidification. Some costs are also borne by people living outside of Italy, affected for instance by adverse climate events indirectly caused by the meat consumed in Italy, or by impacts directly happening outside of Italy (e.g., emissions from fields where feed for Italian animals is produced). Internalizing the external costs would make the people generating the impact bearing its costs (i.e., polluter-pays principle): ideally, a person consuming meat would pay a higher price, and the extra money would be used to compensate the damaged population. However, it is important to stress that internalizing the cost would not prevent the damage to happen. Even if polluters paid a higher price, human and environmental health remain priceless. Despite discussing a monetization of environmental impacts, the authors have approached this study with a strong sustainability mind-set: natural capital should not be considered as replaceable with human-made capital, as no price could be paid for most ecosystem services (Ekins et al., 2003). This study aimed at shedding light on costs currently invisible to the society and at trying to help the general public, as well as most policy makers, to better grasp their actual extent. The authors' hope is that this new awareness can lead not only to a fairer distribution of the costs, but also to the diffusion of more sustainable practices that would prevent the damage in the first place. This should be considered only as the first step to generating a new understanding of issues related to the sustainability of the food system, of our public health and of the protection of our environment.

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