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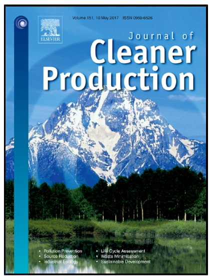

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The impact of greenhouse gas emissions in the EU food chain: a quantitative and economic assessment using an environmentally extended input-output approach

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Abstract

In order to provide a valuable knowledge basis for future global warming mitigation strategies and policy implementation, this study carries out an integrated assessment of greenhouse gas (GHG) emissions throughout the EU-25 food supply chain, considering the highest available level of product disaggregation. Based on an environmentally extended input-output (EE-IO) approach, we estimate the environmental impacts resulting from the 'food and non-alcoholic beverages' supply chain from production to waste management, by 44 food products, grouped in 11 categories. Further, we perform a Structural Path Analysis to identify the hotspots along the supply chain with the highest emissions. Finally, we carry out an assessment of the economic impact of GHG emissions on each product category, considering both the related environmental pressure intensity and the cost of environmental damage (social cost). The results offer new insights on the amount, composition and origin of GHG emissions in the food supply chain. More precisely, detailed evidence is provided in support of the findings of previous studies that have shown that the contribution of farm-level activities on overall GHG emissions is mostly related to N_2O and CH_4 emissions. Moreover, we highlight the large environmental impact associated with CO_2 emissions, even if they are scattered among a very high number of activities, with a limited contribution each. Hence, we infer that multiple hotspots for CO_2 exist along the whole supply chain and that many of them occur in downstream stages, e.g. transportation, processing, packaging, waste disposal, as well as in the cold chain activities. As for the economic assessment of emissions, the highest costs are attributed to the highest emitting product categories, but the share of social costs of these emissions as compared to the overall production value, affect each product differently. Hence, the impact of a hypothetical price control measure, introduced to internalize the social cost of emissions, would vary significantly from one product category to another. Overall, our

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findings suggest that, in order to achieve effective and efficient GHG mitigation in the food system, an integrated approach is required, including both concrete technological and managerial measures at various stages of the food supply chain and for specific product categories, as well as appropriate economic incentive-based mechanisms accounting for the social cost of damage (e.g. a 'carbon tax'), that can prompt polluters to reduce their emissions along the whole supply chain.

Keywords

Greenhouse Gas emission, EU food supply chain, EE-IO approach, E3IOT model, environmental impact, social cost.

Highlights

- GHG emissions assessed in EU food supply chains with a high level of product detail
- Impacts from both upstream and downstream activities are relevant
- The social cost of emissions varies from one product category to another
- An integrated GHG mitigation approach based on economic incentives is recommended

1 Introduction

In order to mitigate the adverse effects of global warming, both policy makers and private actors are setting targets to reduce greenhouse gas (GHG) emissions worldwide. As a result of the recent Paris negotiations of the United Nations Framework Convention on Climate Change (2015), more than a hundred countries agreed to undertake concerted efforts to combat global warming and to adapt to climate change effects.

As part of its climate action policy, the European Union (EU) has set out a roadmap for transitioning to a competitive low-carbon economy in 2050, implying action in all sectors responsible for emissions, including agriculture (European Commission, 2011). In fact, agriculture is one of the sectors with the highest shares of GHG emissions in the EU-28 (European Environment Agency, 2016a). More precisely, GHG emissions from agricultural activities have been estimated to be 436 $MtCO_2eq$. (around 10% of total emissions) in 2014. They mainly consist of methane (54.4%) and dinitrogen oxide (43.2%), resulting from manure, livestock, and fertilizers (European Environment Agency, 2016b; Westhoek et al., 2012). Thus, the long-term target is to reduce GHG emissions in agriculture by approximately 30% by 2050 compared to 2005 levels (European Commission, 2011). Up to now, EU actions have resulted in an overall decrease of GHG emissions of more than 24% with respect to 1990 and about 3% compared to 2005, progressively decoupled with the gross domestic product (increased by 47% with respect to 1990) (Dace and Blumberga, 2016; European Environment Agency, 2016a).

However, agriculture, cannot be considered the only relevant source of emissions in the food supply chain (Vermeulen et al., 2012). In fact, the food chain produces GHGs at all stages of its life cycle, from the farming process and its inputs, through manufacture, distribution, refrigeration, retailing, food preparation at home, and waste disposal (Garnett, 2011).

Indeed, according to an increasing number of studies, climate change mitigation options should be more appropriately addressed by means of integrated approaches, addressing the whole food chain rather than only agriculture. Examples of such integrated approaches are provided in the recent literature (see for instance European Environment Agency, 2013). However, results usually refer to highly aggregated economic sectors. Furthermore, the environmental impacts are expressed only in physical terms, with scarce consideration of their economic impacts.

On the contrary, an interesting option consists in the identification and provision of economic incentives prompting producers and consumers to internalize the social costs of pollution (Unnevehr and Jensen, 1999). This is the basis of the price control approach, in which policy makers impose a tax on emissions (e.g. a 'carbon tax'), inducing economic actors to reduce environmentally damaging activities (Luckow et al., 2015). In fact, since a price control approach applies to final commodities, it covers the entire supply chain, rather than single production phases separately, in order to properly assess the overall environmental impact. Specifically concerning the agri-food sector, this results in the need to include, along with agricultural activities, upstream and downstream phases in an integrated assessment (Coderoni et al., 2015).

This study presents an integrated and detailed assessment of GHG emissions throughout the EU-25 food supply chain, considering the highest available level of product disaggregation in order to offer a practical basis for future mitigation strategies and sectorial policy implementation.

Specifically, the study provides:
(i) a quantification of the magnitude of GHG emissions induced by each product category;
(ii) the assessment of the supply chain stages responsible for the release of the largest share of GHG emissions for each product category;
(iii) the measurement of the economic impact of GHG emissions on the entire food supply chain and on each product category, considering both the related environmental pressure intensity and the cost of environmental damage (social cost).

2 Methodology

2.1 The EE-IO approach and the E3IOT model

Based on the literature reviewed, we chose to perform an Environmentally Extended Input-Output Analysis (EE-IOA) that is an example of top-down approach. The EE-IOA is based on the Input-Output Analysis methodology, using monetary transactions between economic sectors to represent the interrelationships between production processes of goods and services and the related environmental emissions.

In brief, the EE-IOA methodology can be described as follows[1]. Under the crucial assumption of linear technology, an m×m matrix $\boldsymbol{A}$ ('technology matrix') is defined such that each column of $\boldsymbol{A}$ shows the domestic intermediate industry output (in monetary terms) that is required to produce one unit of output of the sector. Then, defining $\mathbf{y}$ as the vector of final consumption (m×1) by households and governments and $\boldsymbol{x}$ as the vector of total industry

[1] A detailed illustration can be found in Huppes et al. (2008).

output (m×1), in a situation of market balance the amount produced ($\boldsymbol{x}$) corresponds exactly to the amount consumed by industries ($\boldsymbol{Ax}$) plus the amount for final consumption ($\boldsymbol{y}$):

$$\boldsymbol{x} = \boldsymbol{Ax} + \boldsymbol{y} \tag{1}$$

Hence, the total domestic industry output required to satisfy final consumption is calculated as follows:

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} = \boldsymbol{Ly} \tag{2}$$

being $\boldsymbol{I}$ the identity matrix (m×m) and $\boldsymbol{L}$ the so-called Leontief inverse matrix.

Then, the EE-IO model assumes that the amount of environmental intervention generated by an industry is proportional to the amount of its produced output, and the nature of the environmental interventions and the ratios between them are fixed (Tukker et al., 2006). For this purpose, a q×m 'intervention matrix' $\boldsymbol{B}$ is defined, showing the amount of pollutants emitted and natural resources consumed to produce one unit monetary output of each industry. Consequently, the vector of total direct and indirect environmental impact driven by domestic industries implied in satisfying a certain amount of final consumption is $\boldsymbol{m}$ (q×1), given by:

$$\boldsymbol{m} = \boldsymbol{Bx} = \boldsymbol{BLy} \tag{3}$$

The advantage of the top-down approach is that it offers a complete and consistent framework for allocating the environmental impacts caused by products used in a specific region. There is no need, as in the case of bottom-up approaches, to make cut-offs of the processes (and consequently, of the environmental impacts); they are all accounted for systematically (Huppes et al., 2008). Hence, EE-IOA is best suited for comparing aggregated groups of products (Lave et al., 1995).

A further advantage of the Input-Output approach is that it enables the implementation of a Structural Path Analysis (SPA) to point out the hotspots along the whole supply chain, through a Taylor expansion of the Leontief inverse matrix. For instance, Minx et al. (2008) found that a large number of small processes together contribute to a significant fraction of emissions in the meat product supply chain, that would likely be neglected by cut-offs in an LCA study.

In this study, we implement the IO approach using the E3IOT model and the related CMLCA software (Huppes et al., 2008; Tukker et al., 2011, 2006). Drawing from a number of different data sources2, E3IOT represents the EU economy with a level of detail that no other database can provide (Huppes et al., 2008; Tukker et al., 2011). We use the latest release of the database that refers to 2003 and the EU-25 economy, covering 478 commodities and services and considering the environmental emissions during production, consumption, and waste management phases (Huppes et al., 2008). Each phase is described by a specific 'technology matrix' (i.e. $\boldsymbol{A}_{11}$ and $\boldsymbol{A}_{22}$ are the 478×478 'production' and 'consumption' technology matrices, $\boldsymbol{A}_{33}$ is the 9×9 'use of wastes between disposal activities technology matrix'). $\boldsymbol{B}_1$, $\boldsymbol{B}_2$, and $\boldsymbol{B}_3$ are the 'intervention matrices', respectively specific for production, consumption and

[2] They include: OECD input–output tables at country level, Eurostat final expenditure studies, LCA EcoInvent database, and the CEDA 3.0 Environmental Input–Output database and technology matrix

disposal activities. To sum up, the full mathematical structure of E3IOT is the following:

$$\boldsymbol{m} = (\boldsymbol{B_1 B_2 B_3})\left(\boldsymbol{I} - \begin{pmatrix} \boldsymbol{A_{11}} & \boldsymbol{A_{12}} & \boldsymbol{A_{13}} \\ \boldsymbol{A_{21}} & \boldsymbol{A_{22}} & \boldsymbol{A_{23}} \\ \boldsymbol{A_{31}} & \boldsymbol{A_{32}} & \boldsymbol{A_{33}} \end{pmatrix}\right)^{-1} \begin{pmatrix} \boldsymbol{y_1} \\ \boldsymbol{y_2} \\ \boldsymbol{y_3} \end{pmatrix} \tag{4}$$

2.2 GHG emissions quantitative assessment

As a first step of the analysis, we employ the E3IOT model for a quantitative assessment of the environmental impacts resulting from the 'food and non-alcoholic beverages' supply chain allocating them to final consumed products. More precisely, we focus on the 'global warming' impact category, that includes 24 emissions (Table 1).

The targeted product categories correspond to those included in the COICOP classification under the code 01 (44 products in 11 categories), as reported in Table 2.

Table 1 - GHGs contributing to Global Warming in E3IOT

#	Gas	#	Gas
1	1,1,1-trichloroethane	**13**	HCFC-123
2	Carbon dioxide	**14**	HCFC-124
3	CFC-11	**15**	HCFC-141b
4	CFC-113	**16**	HCFC-142b
5	CFC-114	**17**	HCFC-22
6	CFC-115	**18**	HCFC-225ca
7	CFC-12	**19**	HCFC-225cb
8	CFC-13	**20**	Methane
9	Dichloromethane	**21**	Methyl Chloride
10	Dinitrogen oxide	**22**	Methylbromide
11	HALON-1211	**23**	Tetrachloromethane
12	HALON-1301	**24**	Trichloromethane

Further insights on the activities that induce the highest emissions in the various nodes of the final products upstream in the supply chain are then identified using a Structural Path Analysis (SPA). The SPA highlights individual nodes contributing to the total GHG emissions throughout the supply chain. It is carried out for those emissions with stronger impact on global warming, namely methane, dinitrogen oxide and carbon dioxide, accounting for about 90% of total GHG emissions (see Table 2). Structural paths are analysed for each emission with a maximum length of three paths and without any contribution cut-off (0%). The absence of a minimum cut-off may make the analysis lose in accuracy; however, this study aims at highlighting where the impacts are mainly located, rather than to define their precise volume.

2.3 GHG emissions economic assessment

As a second step of the analysis, we perform a critical review of existing CO_2 pricing methods and related studies, and identify the most appropriate price estimates to account for the economic impact (i.e. social costs) associated with the GHG emissions of each product category.

Currently, the only available market price of carbon dioxide is provided within the European Trading System (EU-ETS, introduced by DIR. 2003/87/EC). The EU-ETS represents the most prominent EU-wide policy to reduce GHG emissions (Parag and Fawcett, 2014) but it covers only 45% of total emissions and does not apply to many sectors, including agriculture, food industry, and transport (European Commission, 2016). Moreover, due to its market-based nature, the ETS defines CO_2 prices in a highly variable system, with changes that often depend on market conditions (e.g. limited industrial production due to recent economic recession), rather than actual greening measures.

In the absence of an established price for GHG emissions that could be used as a benchmark for the food supply chain, their economic value can be assessed utilizing two different conceptual perspectives: the 'cost of prevention' and the 'cost of damage' approaches.

According to the 'cost of prevention' approach, an economic quantification of emissions may be determined by the amount of money that is needed to prevent GHG emissions via efficiency-increasing or energy-saving activities (Hunkeler et al., 2008). However, the 'cost of prevention' is not applicable for our purpose because it requires the achievement of reduction targets within a defined time span. In addition, this approach does not take into consideration relevant differences in both production processes and regional factors (e.g. natural resources, maturity of local markets, etc.) that in turn affect costs and mitigation options significantly (Dickie et al., 2014).

Following a 'cost of damage' approach, the price for GHG emissions can be defined as the monetary value of the damage done by emitting one additional tonne of carbon at some point in time (Pearce, 2003), and it represents the societal cost of current and future damages related to climate change (Luckow et al., 2015). Various estimates have been provided over the years (European Commission, 2005; IAWG, 2013). Prices obtained in the former study vary from a minimum of approximately 4 €/tonCO_2eq., up to 139 €/tonCO_2eq. In the latter study, several possible scenarios and different years of reference have been identified, entailing multiple results. Estimated prices range from 33 \$/tonCO_2eq., up to 71 \$/ton for 2050. The same study also reports the possible extreme values (95° percentile) that may be reached, with a maximum cost of carbon of 221 \$/tonCO_2eq. Further studies conducted by Springmann et al. (2016) and Wirsenius et al. (2011) assume an intermediate price between 50 and 60 €/tonCO_2eq. It is evident that all these values are strongly affected by uncertainties and vary according to several conditions (e.g. time span considered, depreciation rates, population density, etc.) (Hunkeler et al., 2008).

However, for the purpose of this study, we choose the 'cost of damage' approach as the best-suited pricing method for our objectives, and assume a benchmark value of 50 €/tonCO_2eq.

Based on these factors, we calculate the social costs and their impact on the total value of final consumption of each product category.

3 Results

3.1 Results of the quantitative assessment of GHG emissions by product category

As a first result of our elaborations, we calculate the amount of GHG emissions for each product category considering the upstream impacts from final consumption all the way back-up the supply chain (Table 2).

The overall GHG emissions from the whole food supply chain amounts to 1,209 $MtCO_2$eq. The highest contributions derive from the consumption of products of animal origin, namely 'meat' and 'milk, cheese, and eggs' (459.7 and 209.5 $MtCO_2$eq., respectively), accounting for more than 55% of total emissions. Specifically, the consumption of products coming from 'meat packing plants', 'poultry slaughtering and processing' and 'sausages and other prepared meat products' brings the burden of more than 35% of the overall food-related GHG impact. The third most emitting product category is 'bread and cereals', with an absolute impact of around 140 $MtCO_2$eq. (11.4% of total GHG emissions). Product categories more strictly related to primary activities, such as 'fruit' and 'vegetables', are responsible for a lower impact, with a contribution of about 7 and 5% of total GHGs each. Finally, the emission contributes of the remaining product categories (i.e. 'oils and fats', 'fish and seafood', 'sugar', 'mineral waters and soft drinks', and 'coffee, tea, and cocoa') are much smaller - between 2.9% and 4.6%.

As a second result, we estimate the impact associated with each product category in relation to the modelled GHGs, namely 'CH_4', 'N_2O', 'CO_2'and 'other GHGs'. The most impacting gas in the whole food chain is by far CO_2 (49%), followed by N_2O (24.8%) and CH_4 (17.7%). Other GHGs account for 8.5% of total emissions. In fact, CO_2 is the most emitted GHG in percentage for almost each product category, with values ranging from around 25% ('vegetables') up to even 90% ('commercial fishing') of their impact. Interestingly, the consumption of processed products (e.g. 'poultry slaughtering and processing', 'natural, processed and imitation cheese', 'bread, cake and related products', etc.) always carries the weight of a high share of CO_2 emissions (values often higher than 40%, with peaks greater than 60%).

Further, we observe that highest shares of CH_4 are usually associated with the consumption of products of animal origin (e.g. 32.7% for 'meat', 13.7% for 'milk and eggs') and highest shares of N_2O are mostly related to the consumption of tree and crop products (e.g. 53.8% for 'fruits'). Finally, results report a non-negligible contribution of 'other GHGs' for many product categories, such as 'frozen bakery products', 'ice cream and frozen desserts', 'bottled and canned soft drinks', etc.).

Table 2 - Total emissions in the food and non-alcoholic beverages supply chain by product category* (CO_2 equivalents)

Product category	Total emissions		Share of main GHGs			
			CH_4	N_2O	CO_2	Other GHGs
	(Mt)	(%)	(%)	(%)	(%)	(%)
Meat	***459,7***	***38,0%***	***32,7%***	***19,1%***	***41,3%***	***7,0%***
C_meat packing plants	209,0	17,3%	36,2%	21,3%	36,8%	5,7%
C_poultry slaughtering and processing	146,0	12,1%	28,6%	16,0%	46,6%	8,8%
C_sausages and other prepared meat products	89,5	7,4%	31,3%	18,6%	43,1%	7,0%
C_miscellaneous livestock	15,2	1,3%	31,9%	21,9%	39,7%	6,5%
Milk, cheese and eggs	***209,5***	***17,3%***	***13,7%***	***26,6%***	***50,5%***	***9,2%***
C_fluid milk	87,9	7,3%	11,6%	28,1%	50,6%	9,6%
C_natural, processed and imitation cheese	73,0	6,0%	11,7%	27,7%	51,9%	8,8%
C_poultry and eggs	22,2	1,8%	32,2%	18,5%	41,0%	8,3%
C_dry, condensed and evaporated dairy products	20,4	1,7%	10,6%	25,3%	54,4%	9,7%

C_creamery butter	5,2	0,4%	11,0%	25,1%	54,2%	9,6%
C_dairy farm products	0,8	0,1%	13,4%	35,9%	44,6%	6,1%
Bread and cereals	***138,2***	***11,4%***	***8,0%***	***21,9%***	***58,3%***	***11,8%***
C_bread, cake and related products	38,8	3,2%	8,4%	18,5%	61,4%	11,7%
C_potato chips and similar snacks	24,8	2,1%	6,2%	22,8%	57,1%	13,9%
C_cereal breakfast foods	22,5	1,9%	8,5%	25,6%	56,1%	9,8%
C_prepared flour mixes and doughs	18,3	1,5%	8,9%	29,0%	53,7%	8,5%
C_cookies and crackers	17,2	1,4%	7,6%	16,6%	63,0%	12,8%
C_frozen bakery products, except bread	9,4	0,8%	8,0%	16,1%	58,0%	17,9%
C_flour and other grain mill products	4,2	0,3%	9,6%	37,4%	47,7%	5,4%
C_macaroni, spaghetti, vermicelli and noodles	3,0	0,2%	8,0%	15,7%	62,8%	13,5%
Fruit	***81,8***	***6,8%***	***4,6%***	***39,9%***	***48,7%***	***6,7%***
C_fruits	36,7	3,0%	3,6%	53,8%	38,2%	4,4%
C_frozen fruits, fruit juices and vegetables	36,0	3,0%	5,5%	27,8%	58,2%	8,6%
C_dehydraed fruits, vegetables and soups	5,7	0,5%	6,7%	17,7%	63,6%	12,0%
C_tree nuts	3,4	0,3%	3,5%	55,9%	37,1%	3,5%
Vegetables	***59,0***	***4,9%***	***3,7%***	***61,5%***	***30,6%***	***4,1%***
C_vegetables	52,5	4,3%	3,1%	68,9%	24,2%	3,8%
C_greenhouse and nursery products	6,5	0,5%	9,0%	1,8%	82,5%	6,7%
Oils and fats	***56,1***	***4,6%***	***6,5%***	***35,5%***	***48,9%***	***9,0%***
C_edible fats and oils, n.e.c.	55,6	4,6%	6,6%	35,3%	49,1%	9,1%
C_oil bearing crops	0,5	0,0%	3,4%	63,5%	28,0%	5,1%
Sugar, jam, honey, etc.	***51,3***	***4,2%***	***6,8%***	***22,1%***	***59,7%***	***11,4%***
C_candy and other confectionery products	21,1	1,7%	6,4%	20,2%	58,9%	14,5%
C_canned fruits, vegetables, preserves, jams and jellies	16,7	1,4%	7,1%	22,1%	61,8%	9,0%
C_sugar	6,4	0,5%	4,8%	30,4%	59,9%	4,9%
C_ice cream and frozen desserts	5,7	0,5%	9,3%	19,1%	56,7%	14,8%
C_chocolate and cocoa products	1,4	0,1%	6,3%	25,0%	58,4%	10,4%
Fish and seafood	***47,4***	***3,9%***	***8,2%***	***4,0%***	***81,9%***	***5,9%***
C_prepared fresh or frozen fish and seafoods	23,6	2,0%	10,6%	5,6%	77,8%	6,1%
C_canned and cured fish and seafoods	15,3	1,3%	6,8%	3,5%	83,3%	6,3%
C_commercial fishing	8,5	0,7%	4,1%	0,5%	90,9%	4,6%
Mineral waters, soft drinks, etc.	***40,9***	***3,4%***	***6,5%***	***9,8%***	***65,3%***	***18,5%***
C_bottled and canned soft drinks	37,0	3,1%	6,5%	9,0%	66,2%	18,4%
C_flavoring extracts and flavoring syrups, n.e.c.	3,9	0,3%	6,3%	17,3%	57,1%	19,2%
Coffee, tea and cocoa	***35,3***	***2,9%***	***4,4%***	***38,0%***	***51,3%***	***6,3%***
C_roasted coffee	35,3	2,9%	4,4%	38,0%	51,3%	6,3%
Food products n.e.c.	***30,1***	***2,5%***	***9,9%***	***21,7%***	***56,6%***	***11,8%***
C_food preparations, n.e.c.	11,6	1,0%	7,4%	22,5%	56,7%	13,4%
C_frozen specialities, n.e.c.	9,4	0,8%	14,8%	18,9%	55,9%	10,4%
C_canned specialities	3,5	0,3%	11,5%	15,0%	61,6%	11,8%
C_pickles, sauces and salad dressings	3,2	0,3%	7,3%	20,8%	59,4%	12,4%
C_salted and roasted nuts and seeds	2,2	0,2%	4,3%	42,9%	44,5%	8,3%
C_manufactured ice	0,2	0,0%	6,8%	1,3%	79,9%	12,1%
C_miscellaneous crops	0,0	0,0%	4,0%	62,4%	29,7%	4,0%
Total	**1209,3**	**100,0%**	**17,7%**	**24,8%**	**49,0%**	**8,5%**

* Product categories in bold refer to COICOP classification (code 01), other items refer to E3IOT nomenclature where "C_" stands for final consumption

3.2 Results of the Structural Path Analysis

Since the full results of the SPA conducted are cumbersome, below we report only data concerning the 10 most impacting food-related paths for each considered gas[3].

With respect to methane (Table 3), the 10 most impacting paths account for 19.68% of the whole EU-25 methane emissions, corresponding to 95.16 $MtCO_2eq$. The main contribution comes from the consumption of products of animal origin and, specifically, from the related breeding activities upstream in the supply chain (namely 'meat animals', 'poultry and eggs' and 'miscellaneous livestock'), confirming previous findings. For instance, the rearing activity of 'meat animals', is primarily responsible for the methane impact associated with products coming from 'meat packing plants' (2.04 $MtCH_4$ or 46.92 $MtCO_2eq.$), with a share of 9.7% of the total CH_4 emissions in the EU-25.

Table 3 - SPA: methane (CH_4) emissions in the food supply chain*

Volume ($MtCH_4$)	Volume ($MtCO_2eq.$)	Share (%)	Path (1)	Path (2)	Path (3)
2.04	46.92	9.70%	C_meat packing plants	Meat packing plants	Meat animals
1.08	24.84	5.14%	C_poultry slaughtering and processing	Poultry slaughtering and processing	Poultry and eggs
0.26	6.07	1.26%	C_poultry and eggs	Poultry and eggs	
0.22	5.08	1.05%	C_fluid milk	Fluid milk	Dairy farm products
0.15	3.47	0.72%	C_sausages and other prepared meat products	Sausages and other prepared meat products	Meat animals
0.15	3.40	0.70%	C_miscellaneous livestock	Miscellaneous livestock	
0.13	2.92	0.60%	C_natural, processed and imitation cheese	Natural, processed, and imitation cheese	Dairy farm products
0.04	1.00	0.21%	C_prepared fresh or frozen fish and seafoods	Prepared fresh or frozen fish and seafoods	Miscellaneous livestock
0.03	0.73	0.15%	C_dry, condensed and evaporated dairy products	Dry, condensed. and evaporated dairy products	Dairy farm products
0.03	0.71	0.15%	C_meat packing plants	Sanitary services, steam supply and irrigation systems	
4.14	**95.16**	**19.68%**			

* 10 most impacting paths; maximum number of paths = 3; cut-off at 0%
"C_" stands for consumption

As far as dinitrogen oxide is concerned (Table 4), the first 10 food-related paths account for 22.58% of the whole N_2O impact in the EU-25. The two highest emitting paths are related to the consumption of vegetables and fruits, with an overall contribution of more than 13% of the whole N_2O emissions. Generally, it is confirmed that dinitrogen oxide emissions mainly arise from primary activities, namely the production of 'vegetables', 'fruits', 'oil bearing crops', etc.

Table 4 - SPA: dinitrogen oxide (N_2O) emissions in the food supply chain*

Volume (MtN_2O)	Volume ($MtCO_2eq.$)	Share (%)	Path (1)	Path (2)	Path (3)
0.12	34.93	8.80%	C_vegetables	Vegetables	
0.07	19.36	4.88%	C_fruits	Fruits	

[3] Full tables (115,213 rows for each modelled GHG) are available on request in electronic format.

0.04	12.91	3.25%	C_roasted coffee	Roasted coffee	Fruits
0.02	4.91	1.24%	C_edible fats and oils, n.e.c.	Edible fats and oils, n.e.c.	Oil bearing crops
0.02	4.53	1.14%	C_frozen fruits, fruit juices, and vegetables	Frozen fruits, fruit juices, and vegetables	Vegetables
0.01	3.43	0.86%	C_frozen fruits, fruit juices, and vegetables	Frozen fruits, fruit juices, and vegetables	Fruits
0.01	3.08	0.78%	C_cereal breakfast foods	Cereal breakfast foods	Food grains
0.01	2.55	0.64%	C_potato chips and similar snacks	Potato chips and similar snacks	Vegetables
0.01	2.10	0.53%	C_prepared flour mixes and doughs	Prepared flour mixes and doughs	Food grains
0.01	1.85	0.47%	C_tree nuts	Tree nuts	
0.30	**89.64**	**22.58%**			

* 10 most impacting paths; maximum number of paths = 3; cut-off at 0%
"C_" stands for consumption

Finally, Table 5 displays the results of the SPA concerning carbon dioxide. The reported food-related products have low-contribute paths for CO_2, with single values much lower than 1% and with an aggregate contribute of less than 2%. Furthermore, the first food-related path for carbon dioxide is the 17th most impacting one in the whole SPA list and its impact comes from primary production of fruits. Generally, the CO_2 emitting paths of the food system are related to both agricultural and processing activities.

Table 5 - SPA: carbon dioxide (CO_2) emissions in the food supply chain*

Volume ($MtCO_2$)	Share (%)	Path (1)	Path (2)	Path (3)
7.93	0.22%	C_fruits	Fruits	
6.96	0.20%	C_prepared fresh or frozen fish and seafoods	Prepared fresh or frozen fish and seafoods	Commercial fishing
5.43	0.15%	C_commercial fishing	Commercial fishing	
5.29	0.15%	C_roasted coffee	Roasted coffee	Fruits
5.22	0.15%	C_meat packing plants	Meat packing plants	Meat animals
5.22	0.15%	C_canned and cured fish and seafoods	Canned and cured fish and seafoods	Commercial fishing
5.08	0.14%	C_frozen fruits, fruit juices, and vegetables	Frozen fruits, fruit juices, and vegetables	
4.99	0.14%	C_meat packing plants	Meat packing plants	
4.30	0.12%	C_vegetables	Vegetables	
4.11	0.12%	C_edible fats and oils, n.e.c.	Edible fats and oils, n.e.c.	
54.53	**1.54%**			

* 10 most impacting paths; maximum number of paths = 3; cut-off at 0%
"C_" stands for consumption

3.3 Results of the economic assessment of GHG emissions by product categories

Based on E3IOT results, we compared the economic value of final consumption of each food product categories with the social cost related to their GHG emissions (Table 6).

To do that, we performed the following calculations (Table 6):

a) the value of final consumption, as provided by E3IOT;
b) the 'Environmental Pressure Intensity' (EPI), i.e. the amount of GHG emissions per

economic value of final consumption (European Environment Agency, 2013);

c) the "Economic Impact' (EI) of GHG emissions, given by the volume of GHG emissions multiplied by the reference price of 50 €/tonCO_2eq.;
d) the 'Relative Economic Impact' (REI), i.e. the amount of the social costs associated to the GHG emitted as a share of final consumption value of final consumption.

Overall, we observe that product categories with highest value of final consumption generally are those with highest emissions. This is particularly the case of the 'meat', 'bread and cereals' and 'milk, cheese and eggs'. However, while 'meat' and 'milk' categories account for 38.0% and 17.3% of total GHG emissions, their share of economic value is lower - 27.7% and 16.0%, respectively. On the contrary, the environmental impact of 'bread and cereals' (11.4%) is significantly lower than the related economic value (17.3%).

As for the Environmental Pressure Intensity, we observe different patterns among the product considered. In fact, while the EPI of the whole 'food and non-alcoholic beverages' supply chain is equal to 2.7 kgCO_2eq. per euro of product consumed, the EPI associated with the consumption of 'meat', 'oils and fats' and 'fruit' are the highest, with values of 4.0, 3.4 and 3.2 kgCO_2eq./€ respectively. Conversely, 'bread and cereals', 'vegetables' and 'mineral waters and soft drinks' register a much lower environmental pressure intensity, 1.9 kgCO_2eq./€ each.

The Relative Economic Impact calculated for the overall food chain is 14.5%. The product categories with highest REIs are 'meat' (19.9%), 'oils and fats' (17.0%), 'fruit' (16.1%), 'coffee, tea and cocoa' (15.8%) and 'milk, cheese and eggs' (15.7%), 'mineral waters', 'bread and cereals' and 'vegetables' show economic impacts (9.5%, 9.6%, and 9.7% respectively) lower than the average.

Table 6 - Economic impact of GHG emissions by product category within the food supply chain

Product category	**Total value of final consumption [a]**		**Environmental Pressure Intensity [b]**	**GHG Economic Impact [c]**	**Relative Economic Impact [d=c/a]**
	(M€)	**(%)**	**(kgCO_2eq./€)**	**(M€)**	**(%)**
Meat	115,590	27.7%	4.0	22,985	19.9%
Bread and cereals	72,270	17.3%	1.9	6,910	9.6%
Milk, cheese and eggs	66,689	16.0%	3.1	10,475	15.7%
Vegetables	30,300	7.3%	1.9	2,950	9.7%
Fruit	25,361	6.1%	3.2	4,090	16.1%
Sugar, jam, honey, etc.	22,414	5.4%	2.3	2,565	11.4%
Fish and seafood	21,970	5.3%	2.2	2,370	10.8%
Mineral waters, soft drinks, etc.	21,430	5.1%	1.9	2,045	9.5%
Oils and fats	16,465	3.9%	3.4	2,805	17.0%
Food products n.e.c.	13,668	3.3%	2.2	1,505	11.0%
Coffee, tea and cocoa	11,200	2.7%	3.2	1,765	15.8%
Total / Average	**417,357**	100.0%	**2.7**	**60,465**	**14.5%**

4 Discussion

The results of this study, compared with those of existing literature, provide interesting insights on the amount and composition of GHG emissions in the food supply chain. In fact, previous research has concentrated on environmental impacts ensuing from agricultural activity, but very little attention has been paid to subsequent stages and to final consumption.

As a first consideration, we notice that our estimate of total environmental impact calculated for the whole food supply chain (1,209.3 MtCO_2eq.) is considerably greater than those reported in the literature for the sole agriculture (Dickie et al., 2014; European Environment Agency, 2016b; Eurostat, 2016). Specifically, referring to EU-25 countries and to the year 2003 to compare the figures on a consistent basis, GHG emissions from agriculture are estimated at 420 MtCO_2eq. (Eurostat, 2016), that is nearly 800 MtCO_2eq. less. Besides discrepancies due to different measurement methods adopted and recent developments in total emissions, we believe that such a wide difference provides evidence of significant environmental impacts occurring in downstream stages in the chain, i.e. food processing and distribution. In fact, since most of agricultural final products are used as intermediate inputs by processing industries, the environmental impacts of services has taken an important role in the EU food system (European Environment Agency, 2014; Marin et al., 2012).

Additional insights attain the nature and origin of the environmental impact assessed and the identification of the individual nodes contributing to the total GHG emissions at various stages of the supply chain.

Based on SPA results, we observe that significant environmental impacts in terms of N_2O and CH_4 emissions are associated with farm-level activities. The former ones are mostly due to the abundant use of fertilizers on croplands and manure management (Dickie et al., 2014; European Environment Agency, 2016b), while the latter ensue from the enteric fermentation of ruminants and manure management activity (European Environment Agency, 2016b).

These results are consistent with existing literature reporting that the sole agricultural activities mostly emit methane and dinitrogen oxide gases, with a very limited share of impact from carbon dioxide, often lower than 3% (Dickie et al., 2014; European Environment Agency, 2016b; Vermeulen et al., 2012).

However, in line with the results of previous studies (Carlsson-Kanyama and González, 2009; Minx et al., 2008; Vermeulen et al., 2012), our calculations show that N_2O and CH_4 contribute to total emissions are rather low (24.8% and 17.7% respectively), while the largest impact is by far due to CO_2, with 49% of total emissions.

Unfortunately, the SPA results show that CO_2 emissions are scattered among a very high number of activities at various stages of the supply chain, with a limited contribution each, so that it is not possible to trace back CO_2 emissions to any specific stage or activity. However we can argue that multiple hotspots for CO_2 exist along the whole supply chain and that many of them occur in downstream stages, e.g. transportation, processing, packaging, waste disposal, etc.

Further, we observe that a non-negligible share of 'other GHGs' (primarily composed of refrigerant gases) contributes to the total environmental impact, that are likely to be originated by cold chain activities, as pointed out by Vermeulen et al. (2012).

Additional interesting results of the study relate to the different contribution of each product category to the total environmental impact. In this respect our findings are in line with those of Reynolds et al. (2015) who highlight the large contribution of products of animal origin. Besides, the E3IOT model implemented provides information with a high level of detail, showing that 'meat' and 'milk, cheese, and eggs', product categories contribute to more than half of total emissions.

These considerations point out that either technical and managerial options, either policy intervention are needed to improve the environmental sustainability of the food system taking into account the different features of the various product categories and related production activities.

4.1 Technical and managerial mitigation options

Technical and managerial mitigation options could effectively target primary activities, aiming at reducing methane and dinitrogen oxide impacts. Dickie et al. (2014) and Yue et al. (2017), for instance, recommend improved production and management of N-based fertilizers (e.g. lower and optimized use, use of organic ones) and to contain methane emissions by means of better feeding practices (e.g. use of forages with a lower protein content) and improved rice straw management. Improving irrigation efficiency and adjusting the crops to their prior cropping regions would also help to reduce the impacts from primary activities (Huang et al., 2016). Other innovative solutions consider carbon sequestration in agricultural practices (e.g. reforestation) (Kämpf et al., 2016; Li et al., 2017; Vermeulen et al., 2012) and efficient manure management, such as composting or anaerobic digestion to obtain a stable source of carbon and, possibly, natural gas (Dickie et al., 2014).

On the pre- and post-production side, innovation should be targeted at making a more efficient use of technologies for refrigeration, processing and transport, as well as the switching to clean fuels and energy efficient household appliances. Furthermore, improved management of food reserves along with reductions in overconsumption of food and consumer waste, as well as reduced reliance on cold chain and higher consumption of seasonal produce (Vermeulen et al., 2012) would help in the mitigation of GHG impact by the whole food system.

4.2 Policy mitigation options

As far as policy intervention is concerned, two main approaches can be adopted to change consumption and production habits in society: traditional regulatory approaches (sometimes referred to as command-and-control approaches), or market-based policies that rely on economic incentives to correct producer and consumer behaviour.

Following a regulatory approach, various environmental measures have been framed into the CAP, during the last 15 years. These include cross-compliance and rural development (introduced by the Fischler reform in 2003), and more recently, the 'greening practices' of the 2013 reform, promoting resource efficiency and supporting the shift toward a low-carbon economy in the food sector (European Parliament, 2017). However, recent studies argue that many of these practices, namely the maintenance of permanent grassland and of an ‘ecological focus area’, as well as crop diversification, cannot be considered very effective in terms of land-use change and impact minimization (European Parliament, 2016; Solazzo et al., 2016). Furthermore, many authors question the cost-effectiveness of the CAP regulatory approach and its ability to reduce GHG emissions (Cropper and Oates, 1992; Erjavec et al., 2015; Kirchner et al., 2016; Solazzo et al., 2016; Swinnen, 2015).

Following a market-based approach, the hypothesised implementation of a ‘carbon tax’ is one of the most frequently proposed cost-effective policy option in the literature (Briggs et al., 2016; Springmann et al., 2016; Wirsenius et al., 2011). A carbon tax imposes additional costs on emission-intensive activities so as to reduce their environmental impacts. Hence, prices of products with higher emissions will increase, and consequently their demand may be driven to a lower level by the market, along with GHG emissions. Consumption changes in response to price depend on price elasticity values, varying from one product to another. Consequently, the introduction of a ‘carbon tax’ would have diverse effects on the various food product categories and, in turn, on the production activities involved in their provision to final consumers.

The economic quantification of the environmental impact shows significant differences among the various food product categories, with values ranging from 1.9 to 4.0 kg of emitted CO_2eq. per euro of product consumed, consistently with the findings of previous studies (European Environment Agency, 2013). In line with the results of Springmann et al. (2016), the highest relative impact is registered for the ‘meat’ product category, followed by ‘oils and fats’ and ‘milk, cheese and eggs’, being the product categories with the highest environmental burdens as a share of their final consumption value.

Meat and dairy products are among those with highest prices and elasticity values (Andreyeva et al., 2010; Wirsenius et al., 2011), given the possibility to change the protein intake source shifting from red to white meat or even from meat to legumes, while cereals and vegetables, for instance, have lower prices and elasticity values. Hence, the two categories would experience, respectively, high and low consumption reductions, as concluded also by Springmann et al. (2016).

Furthermore, the application of a ‘carbon tax’ on food commodities and the consequent shifting from animal-based to plant-based diets, a part from the related environmental benefits (Tukker et al., 2011; Wirsenius et al., 2011), would also positively affect the consumer health, as envisaged by Springmann et al. (2016) and Joyce et al. (2014).

4.3 Limitations of the study

The findings of this study are subject to limitations, mostly ensuing from the features of the model implemented. First, we acknowledge that E3IOT was developed based on US sector data, since no detailed input-output tables are available for EU economy. However, this does not seem to be a crucial limitation for the present study, given that US and EU economies have a similar level of development (Huppes et al., 2008). As a second and more relevant issue, the database has not been updated for many years now, so that most probably, the structure of the economy assessed has changed and technologies have improved meanwhile. Specifically, an overall decreasing trend is observed for GHG emissions during the last ten years (Eurostat, 2016). In the same period, the overall environmental impact arising from the whole food chain resulting from our study may have changed as well.

We were not able to overcome this problem, but we still believe that the study provides useful information on the nature and the origin of the GHG emissions along the food chain. In fact, rather than offering updated absolute results, the study aims at providing a general assessment of the impacts arising in the food system within the EU economy in relative terms. Actually, absolute emissions and economic values of final consumption change within years according to several factors (technology improvement, economic recession, adoption of new regulations, etc.), while relationships between food sectors are more likely to remain consistent.

5 Conclusions

This study assesses the environmental and economic impacts of GHG emissions ensuing from the consumption of food and non-alcoholic beverages in the in the EU-25 supply chain. The results offer new insights on the amount, composition and origin of GHG emissions in the food supply chain. More precisely, detailed evidence is provided in support of the findings of previous studies that have shown that the contribution of farm-level activities on overall GHG emissions is mostly related to N_2O and CH_4 emissions. Moreover, we highlight the large environmental impact associated with CO_2 emissions, even if they are scattered among a very high number of activities, with a limited contribution each. Hence, we infer that multiple hotspots for CO_2 exist along the whole supply chain and that many of them occur in downstream stages, e.g. transportation, processing, packaging, waste disposal, as well as in the cold chain activities.

In conclusion, our findings suggest that in order to achieve effective and efficient GHG mitigation in the food sector, an integrated supply chain approach is required. Such an integrated approach should include both: a) concrete technological and managerial measures for GHG mitigation at various stages of the food supply chain and for specific product categories (rather than only for agricultural activities) and b) appropriate economic incentive-based mechanisms (e.g. a 'carbon tax') that can prompt polluters to reduce their emissions along the whole supply chain, taking into account the social cost of damage.

Finally, we observe that the introduction of a 'carbon tax' would have diverse effects on the various food product categories and, in turn, on the production activities involved in their provision to final consumers.

In light of the results obtained and of the limitations of the present study, future research is needed in several directions. On one hand, specific studies are required aimed at further developing improved and updated input-output tables that could better represent the EU economy and the associated environmental burdens. On the other hand, the opportunities and limits of various economic incentives should be further explored, considering both the potential impacts on consumption patterns ensuing from the introduction of a 'carbon tax' and the opportunity to support virtuous vertical coordination initiatives (e.g. Green Supply chain Management) within the EU food chain.

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