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Environmental impacts of animal-based food supply chains with market characteristics

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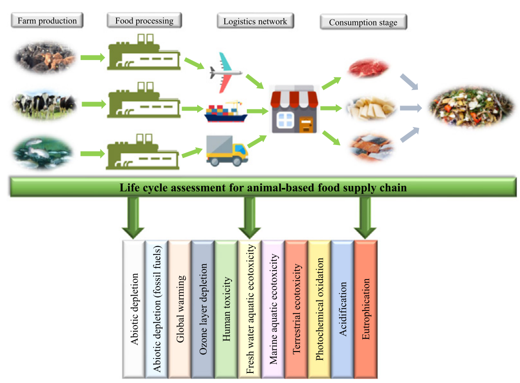
HIGHLIGHTS

- Environmental impacts of animal-based food supply chains with were evaluated.
- Attention should be paid to product market when calculating food impact.
- The type of food products and logistics determine the hotspot in food supply chain.
- Novel feed, sustainable aviation fuel & food waste reduction offer impact reduction.
- Novel interventions could reduce climate impact by 15% to 82%.

GRAPHICAL ABSTRACT



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ABSTRACT

Animal-based food supply chains lead to significant environmental impacts, which can be influenced by production systems, distribution networks and consumption patterns. To develop strategy aimed at reducing the environmental impact of animal-based food supply chains, the common environmental hotspots among different types of food, the role of transport logistics and the consequence of end market need to be better understood. Life cycle assessment was adopted to model three types of animal-based food chains (beef, butter and salmon), with specific technologies, high spatial-resolution logistics and typical consumption patterns for three markets: local, regional (intra-European) and international. The results confirmed that the farm production stage usually had the greatest environmental impact, except when air transport was used for distribution. Potentially, the role of end market also can significantly influence the environmental impacts. To understand more, three improvement options were examined in detail with regard to hotspots for climate change: novel feed ingredients (farm production stage), sustainable aviation fuel (transport and logistics stage) and reduction of wasted food (consumption and end of life stage). Significant reduction was achieved in the salmon system by sustainable aviation fuel (64%) and novel feed (15%). Minimizing food waste drove the greatest reduction in the beef supply chain (23%) and the international butter supply chain can reduce 50% of GHG mission by adopting sustainable aviation fuel. Combined interventions could reduce GHG emission of animal-based food supply chains by 15% to 82%, depending on market, transport and food waste behaviour. The results show that eco-

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efficiency information of animal-based foods should include the full supply chain. The effective mitigation strategy to achieve the greatest reduction should not only consider the impacts on-farm, but also detail of the downstream impacts, such as food distribution network and consumption patterns.

Nomenclature

GHG	Greenhouse gas
FSC	Food supply chains
ABFSC	Animal-based food supply chains
SAF	Sustainable aviation fuel
LCA	Life cycle assessment
BSF	Black soldier fly

1. Introduction

Food supply chains (FSC) have a critical role in supporting modern human society (Dokić et al., 2020). However, they also lead to environmental issues at regional level (e.g. land resource (Fenu and Malloci, 2020), water resource (Guiamel and Lee, 2020; Kansoh et al., 2020; Oo et al., 2020) and biodiversity (Tansey, 2012)) and global level (e.g. species extinction (Phalan et al., 2011), climate change (Garnett, 2011)). Due to increasing food demand (Springmann et al., 2018a), the negative impacts of FSC could be exacerbated. Animal-based food supply chains (ABFSC) have greater negative impacts than plant-based systems (Springmann et al., 2018b), which has encouraged the adoption of plant-based diets both from perspective of health and sustainability (Willett et al., 2019). However, the global consumption of animal-based food is still increasing (Churchward-Venne et al., 2017), which is putting a growing pressure on ecosystems and non-renewable resources. Previous studies have evaluated the environmental impacts of different stages in the food system (e.g. farm, processor, logistics, retail and consumer) (Finnegan et al., 2017; Poore and Nemecek, 2018; Scholz et al., 2015; Yan et al., 2013), from a sector perspective (e.g. dairy, beefs, cereals) (Fallahpour et al., 2012; Foley et al., 2011; Yan et al., 2011), and at country or region level (Notarnicola et al., 2017). There are few studies that have investigated the general characteristics of different FSC, especially for ABFSC considering the detail of distribution network and end market. It is important to understand the environmental impacts of ABFSC, and to identify the characteristics of these systems that identify opportunities for impact reduction. In addition, it is also not clear whether some abatement strategies (Avadí and Fréon, 2013; Yan et al., 2013) are transferable to other systems and the effectiveness of potential measures in different types of ABFSC.

Feed production has been identified as common hotspot in both livestock systems (Foley et al., 2011) and aquaculture systems (Pelletier et al., 2009). Replacing conventional feed supplements with more environmental friendly ingredients could help to reduce the impacts of the farm stage. Novel protein sources, such as microalgae, cyanobacteria and insects have been tested in livestock and aquaculture systems (Smetana et al., 2017; van Huis and Oonincx, 2017; Yaakob et al., 2014). *Spirulina* and *Chlorella* are the two most commercialized cyanobacteria and microalgae for feed supplements. Due to the high protein content and digestibility, they can be used in livestock (Yaakob et al., 2014) and Atlantic salmon (Burr et al., 2011) systems. These novel feeds may ease some environmental issues, such as land use. However, they may increase the greenhouse gas (GHG) emission, due to higher consumption of energy and organic inputs (Smetana et al., 2017; Taelman et al., 2013). Evaluation of novel feed across different FSC has not been reported. Since the variation of feed ingredients in different farming systems (e.g., beef vs salmon) could be significant, it is worth investigating the effect of novel feed in different FSC.

There are studies that focus on food processing (Yan and Holden, 2018), but these have been independent of upstream and downstream components of the system. Such studies are typically of interest to the processing industry, but are seen as being of little importance for full supply chain management, because they are believed to represent a small proportion of the impacts of FSC. A few studies have considered the full FSC, but these assume a single end market (Flysjö, 2011) or a single region (Notarnicola et al., 2017), which cannot reflect different characteristics of the end-market, such as consumption pattern and food distribution network. Most ABFSC are for perishable goods. Compared to marine transport, air transport can effectively reduce food loss in logistics by greatly reducing delivery time (Lemma et al., 2014). Due to an increasing demand of fresh food (Blackburn and Scudder, 2009), the market for air transport based FSC is growing. However, air transport could be responsible for a significant share of the environmental impacts of FSC (Ziegler et al., 2013). In terms of GHG emission, the main impact of air transport is from the production and usage of jet fuel. Sustainable aviation fuel (SAF) is the main approach to GHG reduction in aviation sector (Doliente et al., 2020). However, the effect of using SAF on the environmental impacts of FSC is unknown. The characteristics of the end-market and transported food may have a significant influence on impact reduction by introducing SAF in different ABFSC.

According to the UN Food and Agriculture Organization, one third of global food was wasted or lost in the FSC from farm to consumption (FAO, 2011). It has become a critical issue, which leads to significant waste of non-renewable resources (Lundie and Peters, 2005) and environmental impact, particularly climate change. Worldwide food waste accounts for 8% of global GHG emission (FAO, 2015). Reduction of wasted food provides an effective pathway to minimize environmental impacts (Chen et al., 2020), especially for animal-sourced FSC. However, compared to other abatement approaches, whether the effect of reducing wasted food is the most effective for ABFSC remains unknown. In addition, many life cycle assessment (LCA) studies treat 'waste' as having no inherent impacts (Djuric Ilic et al., 2018), which cannot reflect the accounting conventions used during the life cycle inventory stage. It is important to understand the impact of food waste in ABFSC from a life cycle perspective.

Due to the gap in understanding the general characteristics of ABFSC and the effect of market features, novel feed ingredients, logistics and wasted food on environmental performance, it is difficult for stakeholders to identify effective measures for improvement. Therefore, the objectives of this study were to identify the environmental commonality among ABFSC and quantify the reduction effect of novel interventions with detailed market characteristics. The study evaluated the most important environmental impacts for each FSC, such as GHG emission, eutrophication, acidification, resource depletion, as well as some that receive less attention such as, toxicity, photochemical oxidation and ozone layer depletion (Notarnicola et al., 2017). Dairy, meat and fish are the main categories of animal-based food. The consumption of these foodstuffs is increasing rapidly. Dairy is forecast to have 21% global growth by 2027 (OECD, 2016), meat is forecast to have a 16% increase in global production by 2025 (OECD, 2016) and fish consumption has doubled in the last 50 years (FAO, 2016). Butter, beef and salmon were selected as representative in each category. The paper was structured as follow: first, we justified the selection of FSC with detail market features, then we described the modelling framework and specific implementation for each FSC. Scenarios were tested with different end markets and interventions to reduce impacts with the results and discussion section focusing on the key findings.

2. Methods

The environmental impacts of FSC vary due to differences in animal species, production technologies (de Vries et al., 2015; Djekic et al., 2014; Pelletier et al., 2009), processing (Yan and Holden, 2018), logistics (Galli et al., 2015), retail consumption and waste (Göbel et al., 2015). In order to reflect the characteristics of current ABFSC, this study used recent production data and first-hand surveys to complete the life cycle inventory. The methodological steps were: (1) selection of representative FSCs for the dairy, meat and fish sector, in terms of data availability, market share and variety of consumption in the market; (2) selection of LCA methods and definition of key assumptions for the study; and (3) selection of environmental improvement scenarios for GHG emission reduction in the production, distribution and consumption stages. Each step was described below, and the results were then used for the calculation of the environmental impacts of ABFSC and analysis of the improvement opportunities.

2.1. The food supply chains

The selection of food chains was based on data availability and geography. All were produced and processed in Europe, where growing market demand and the identification of a simple, single function product from a complex food chain was possible. Irish butter (with solid content of 84.4%) was chosen to represent the dairy chain because it is ubiquitous, sold as a consumer product, rather than as an ingredient, is consumed in the local market and has significant export markets in Europe and beyond. Ireland is the third largest butter producer in Europe. It produced an order of magnitude more butter per capita than other large producers (e.g. France and Germany) (CLAL, 2019). Irish beef steak was chosen to represent the meat sector because it is a premium product, with little secondary processing and is sold as a consumer product in Ireland, Europe and beyond. Irish beef is popular in the international markets, which has driven ambitious sectoral growth (Chen and Holden, 2018a). Currently, Ireland is the 6th largest beef exporter in the world, with the greatest per capita production in Europe (Workman, 2020). Norwegian salmon fillet was chosen to represent fish products. Because Norway is the main producer in the global salmon market with significant exports (Marine Harvest, 2017). This study used production and processing data from Norway for salmon, and from Ireland for beef and dairy.

2.2. Life cycle assessment

2.2.1. Goal

The reason for the study was to gain greater understanding of the common environmental hotspots among different types of ABFSC, the role of transport logistics and the implications of end market. The application was to use the baseline data to identify the common environmental hotspots among different ABFSC and initiate policy thinking for effective approaches to reduce the environmental issues of greatest public concern. The study audience are stakeholders of all FSC. The results are not associated with a specific product and are not being used for direct comparison among products.

2.2.2. Scope

Each FSC was described with five stages: material extraction and supply, primary production (farm or aquaculture), food processing in factory, distribution and retail, and consumption (Supporting Information (SI) Figs. S1–S3). Country level average farm production models (dairy, beef, salmon) were adopted to model the 'cradle-to-farm gate' in the specific countries of interest (Ireland and Norway). The data on food processing were collected by site surveys conducted in selected processing factories representing the process technology in each sector. For food distribution, the transport networks from processing to retailer were modelled based on current supply chains to a local, regional and international market. The logistics of the entire FSC consisted of material transport to the farm for production, products from farm to processing facilitates, and food distribution from processing facilitates to retailers. It was assumed that each food could be transported by three types of distribution networks, which were characterized by the dominance of truck, ship or airplane depending on which was most representative of the market data. Accordingly, three end markets were identified for each distribution network: domestic market in the country of origin (truck), European market (truck and or coastal shipping) and international market outside of Europe (airplane because the product was sold a fresh). Market share and food waste data were collated for each product and end market. It is important to distinguish food waste and residues, since different management approaches and interventions should be adopted for wasted food (Oldfield et al., 2016) and agriculture residues (Chen et al., 2020). For this research, food waste in the consumption stage is the food that is disposed of by the consumer that could have been eaten. The 'food loss' in production, processing and distribution has been accounted as part of food output in upstream. This resulted in three food products and nine end market models, with appropriate logistics (SI Table S1). The detailed distribution networks from food processing facilities to retailers were defined by consulting with stakeholders in each sector (SI Figs. S4–S6). Wasted food in supermarkets was estimated for fish waste to be 5% (Xue et al., 2017), 0.5% for butter and 2.5% for beef (Scholz et al., 2015). The national values for wasted food for each product were estimated for each end-consumer market (SI Table S1).

The functional unit for each FSC was 1 kg of food delivered to the consumer. The impact method CML2001 was adopted and all eleven impact indicators (Dreyer et al., 2003) were evaluated in this study. The elementary flows were classified and characterized to express impact using standard units. For example, all the potential toxicities were grouped into human, fresh water, marine and terrestrial and total impact was expressed in kg 1,4-DB (1,4-Dichlorobenzene)-equivalent units. The FSC systems are multifunctional, with both farm and processing stages creating multiple products. Appropriate allocation methods were adopted for each FSC stage (SI Table S2).

2.2.3. Life cycle inventory

The life cycle inventory for farm production (SI Table S4) and food processing (SI Table S5) were collated from national reports, industry data and by using surveys. The detail of data source and quality for each stage of ABFSC was shown in SI Table S3. The background LCA data for farm production and processing was derived from Agri-footprint and Eco-invent databases. The inventories of food distribution networks consist of road, sea and air transport. The emissions per unit product transportation were from the Eco-invent database. The energy used for refrigeration during transport was also included. The transport of food from retailer to consumer was not included, since the uncertainty is high and the contribution to total impacts is small (Notarnicola et al., 2017). The details of inventory for each ABFSC were as follow.

2.2.3.1. Salmon supply chain. The six main ingredients in salmon feed (SI Table S4) represent the average feed composition for the Norwegian salmon industry. The marine (31%) and vegetable (66%) ingredients were composed of anchoveta, pelagic trimming, capelin, soybean, rapeseed and wheat (SI Tables S7–S8). The energy (electricity and diesel), chemical (e.g., lice treatment, cleaning) and equipment (e.g., fish net and gear) for production were calculated. A waste management scenario (recycling) for fishing equipment was taken from the 'Nofir' project (https://nofir.no/lca/). The main emissions to atmosphere were from energy consumption for aquaculture activities, feed production and material transport (Ziegler et al., 2013). Most emissions to water were caused by nutrient waste. The emission factors for nitrogen and phosphorus to water were derived from Wang et al. (2012). Processing data were taken from plants in Norway. The main inputs were electricity (or thermal) energy for processing and cleaning, detergent and disinfectant for washing and packaging material. Alkylbenzene sulfonate was used as detergent. Sodium hypochlorite was assumed as the disinfectant. The remaining cleaning chemicals were assumed to be types of soap. Synthetic rubber was used as the main material for disposable caps and gloves. The materials for packaging were Expanded Polystyrene box, corrugated cardboard box and aluminium and plastic films. For salmon fillets the local market was Norway, the regional market was Denmark, and the international market was China.

2.2.3.2. Butter and beef supply chain. Irish cattle farming is dominated by grass grazing systems (Chen and Holden, 2018a) for the production of both dairy and beef animals. Animals graze in the field during spring, summer and autumn, and are fed mainly grass silage in the winter. Concentrates (SI Table S6) are fed when energy demand is high (dairy) or to achieve target live weight gain (beef). The ratios of grass, silage and concentrate feed in dairy and beef farm were taken from Chen and Holden (2018b) and Sharma et al. (2018). Fertilizer inputs for pasture were calculated from national recommendations (O'Donoghue et al., 2015). The inventory included water and energy (electricity and diesel), pesticides, packaging and cleaning agents for all farming activities was also included. For the cattle system, the main atmospheric emissions were from enteric fermentation, manure management (storage, spreading and excretion on field) and fertilizer application. The primary non-CO_2 emissions were methane, nitrous oxide (N_2O) and ammonia and nitrate (as indirect N_2O). An Intergovernmental Panel on Climate Change (IPCC) Tier 2 method (IPCC, 2006) was used to characterise emissions from enteric fermentation while Irish national average emission factors were used for stored manure (Duffy et al., 2014) and manure application in the field (Chadwick et al., 2000). The direct and indirect N_2O from fertilizer application, manure storage and spreading, and animal excretion were calculated with national level emission factors (Duffy et al., 2014; Hyde et al., 2003) (SI Table S9). The main water emissions were due to runoff and leaching. It was assumed that 30% of on-farm N from fertilizer and manure was lost through nitrate leaching (IPCC, 2006) and P surplus lost to waterways was estimated at 0.5 kg P/ha (Chen and Holden, 2018a). The GHG emission factor for the thermal energy generation in the processing plant was obtained from an emission report by the Sustainable Energy Authority of Ireland (SEAI, 2018). For butter the local market was Ireland, the regional market was Germany, and the international market was Japan. For beef steak, the local market was Ireland, the regional market was the United Kingdom, and the international market was the United States of America.

2.3. Impact reduction scenarios

Climate change is currently of most public concern at the global scale. Most of environmental interventions have data for GHG emission, while the information for other impacts is limited. Therefore, we chose climate change as the indicator for the impact reduction scenarios. In order to investigate the potential GHG reduction opportunities for the three FSC cases, three options were developed, one each for the production, distribution and consumption stages of the FSC. Each option has three scenarios S1, S2 and S3, which respectively represent the optimum, average and minimum GHG reduction effect. The value in S2 is the mid-value between S1 and S3 values. These scenarios reflect future trends and management of FSC (Agusdinata et al., 2011; Shields and Lupatsch, 2012; Xue et al., 2017). To evaluate potential for production impact reduction, an innovative insect protein feed scenario was selected (Smetana et al., 2016). Larval meals from *Hermetia illucens* (black soldier fly; BSF) is a promising insect protein supplement that can be used for cattle (Jayanegara et al., 2017) and salmon (Lock et al., 2016), offering a similar protein content to soybean meal (Salomone et al., 2017). According to Smetana et al. (2016), insect protein meal has environmental benefits, such as reducing land use, valorising waste and reducing resource depletion. However, the energy use in insect protein meal production may lead to greater GHG emissions (Salomone et al., 2017). In addition, due to the different composition of feed ingredients and feed demand in livestock and salmon systems, the effect of insect meal in the diet is unknown. In this study, the GHG intensity of BSF protein meal (1 kg of insect protein meal) was calculated from Salomone et al. (2017) (Table 1). Export logistics using aviation are a notable transport hotspot because of the small tonne-kilometres compared to ocean shipping (McKinnon, 2007). A scenario was tested where conventional jet fuel (kerosene) was replaced with SAF. Due to the variation of feedstock, the life cycle emissions of SAF are uncertain. Therefore, data were taken for the range of life cycle emissions for SAF published by the International Civil Aviation Organization (ICAO, 2019) (Table 1). Reducing wasted food in the consumption stage has great potential to reduce the impact of food SC, especially in medium/high-income countries (Xue et al., 2017). To quantify the benefits of wasted food reduction, three reduction ratios for all modelled for each food SCs (Table 1).

3. Results and discussion

3.1. Food supply chain analysis

The total environmental impacts of delivering 1 kg of food (salmon, beef or butter) (Table 2) varied by FSC, amount of wasted food and the market. The type of FSC defined the baseline impacts, the wasted food affected all environmental impacts, and transport mode had a significant influence on particular indicators: abiotic depletion (fossil fuels), global warming, ozone depletion and human toxicity. The contribution of the main life cycle stages for each FSC (Fig. 1) indicated the primary production (farm) stage had the greatest contribution to most of the impact categories, but this was only for supply to national and regional markets. This finding was consistent with previous LCA studies of the same kinds of food categories (de Vries et al., 2015; Flysjö, 2011; Notarnicola et al., 2017; Ziegler et al., 2013). It was worth noting that Fig. 1 showed the different contributions of farm production in different end markets, but the net environmental impacts of the production stage remained unchanged. The main change was adding the impacts of food transport and waste.

For the domestic and European salmon FSC, the aquaculture stage accounted for 75% to 88% of the total impacts over all environmental categories. However, the picture changed when considering the international market served by air freight. The contribution of aquaculture farming varied greatly among impact categories, with the least contribution to abiotic depletion (fossil fuels) and climate change, and greatest contribution to terrestrial ecotoxicity and eutrophication. Similar trends were seen for the dairy and beef farming. The total impacts of farm production in this study were within the range of impact values in previous studies (Foley et al., 2011; O'Brien et al., 2012; Ziegler et al., 2013). The impact contribution of the farm production stage (Fig. 2) was influenced by productivity and consumption of material and

Table 1
Scenarios for improvement options in production, distribution and consumption.

	Unit	S1	S2	S3
CF[a] of BSF[b] protein meal	kg CO2 eq./kg	1.01	1.19	1.36
CF of aviation fuel	g CO2 eq./MJ	5.2	35.5	65.7
Food waste reduction	%	100	50	25

[a] CF = carbon footprint.
[b] BSF = black soldier fly.

Table 2
Characterisation results of beef, butter and salmon FSC in different end markets.

Impact category	Unit	Beef SCs			Butter SCs			Salmon SCs		
		USA	UK	Ireland	Japan	Germany	Ireland	China	Denmark	Norway
Abiotic depletion	kg Sb eq.	3.66E−05	3.37E−05	3.35E−05	1.33E−05	1.37E−05	1.34E−05	1.03E−05	8.62E−06	9.11E−06
Abiotic depletion (fossil fuels)	MJ	1.64E+02	6.25E+01	6.16E+01	1.95E+02	3.36E+01	3.19E+01	2.17E+02	4.39E+01	4.57E+01
Global warming (GWP100a)	kg CO2 eq.	2.75E+01	1.96E+01	1.96E+01	2.03E+01	1.03E+01	1.04E+01	1.64E+01	5.02E+00	5.15E+00
Ozone layer depletion (ODP)	kg CFC-11 eq.	1.76E−06	5.58E−07	5.45E−07	2.23E−06	2.98E−07	2.71E−07	4.67E−06	2.59E−06	2.62E−06
Human toxicity	kg 1,4-DB eq.	7.14E+00	2.08E+00	2.06E+00	9.27E+00	1.08E+00	1.06E+00	1.87E+01	1.01E+01	1.01E+01
Fresh water aquatic ecotoxicity	kg 1,4-DB eq.	1.51E+00	1.27E+00	1.26E+00	1.25E+00	1.08E+00	1.07E+00	1.35E+00	1.03E+00	1.06E+00
Marine aquatic ecotoxicity	kg 1,4-DB eq.	5.49E+03	4.54E+03	4.51E+03	3.08E+03	2.22E+03	2.19E+03	4.86E+03	3.69E+03	3.74E+03
Terrestrial ecotoxicity	kg 1,4-DB eq.	1.07E−01	9.71E−02	9.71E−02	1.67E−01	1.77E−01	1.80E−01	1.79E−01	1.75E−01	1.76E−01
Photochemical oxidation	kg C2H4 eq.	5.09E−03	3.78E−03	3.76E−03	3.54E−03	1.97E−03	1.98E−03	3.42E−03	1.61E−03	1.62E−03
Acidification	kg SO2 eq.	1.56E−01	1.23E−01	1.22E−01	8.46E−02	4.80E−02	4.82E−02	7.08E−02	2.87E−02	2.86E−02
Eutrophication	kg PO4 eq.	1.19E−01	1.06E−01	1.06E−01	6.06E−02	5.72E−02	5.84E−02	1.09E−01	1.01E−01	1.01E−01

energy, which varied by types of FSC. For global warming, the contribution of dairy (44%) and beef (64%) farms was much higher than the salmon farm (26%). This was due to the high farm emissions associated with enteric fermentation and terrestrial manure management. Improving farm management will reduce environmental impacts of ABFSC, and the benefit will be more significant in livestock based FSC.

For salmon farming, feed production was the main contributor to most of the environmental impacts, except marine aquatic ecotoxicity and eutrophication. Vegetable feed ingredients caused a significant share of many environmental impacts. For example, the vegetable protein and oil accounted for more than 64% of GHG emission on farm. Some of vegetable ingredients (e.g., soy protein) lead to significant environmental impacts. Replacing them with low impact ingredients could potentially reduce the environmental impacts of salmon production (Rustad, 2016). The on-farm emissions including nitrogen, phosphorous and other organic waste dominated the impact of marine aquatic ecotoxicity and eutrophication. The smolt production contributed to abiotic depletion (9.3%) and photochemical oxidation (6.3%). The energy and transport processes during the farming stage made very little contribution to all impacts.

Dairy and beef farming were similar, because both systems operate in Ireland using grazed grass. Compared to salmon farming, feed production for the livestock systems had a smaller contribution to most of environmental impacts, except marine aquatic ecotoxicity and eutrophication. This was caused by greater feed demand of vegetable ingredients. To achieve necessary rates of liveweight gain, the beef farm stage required more imported feed than the dairy. Therefore, feed for the beef farm stage was responsible for a greater share of eutrophication. Considering the contribution of feed in all FSC (Fig. 2), there is scope to examine the use of alternative feed to reduce the impact of the primary production stage. In addition to feed, the manure management on the dairy and beef farms made a significant contribution to acidification (56% to 63%), eutrophication (34% to 44%) and global warming (13% to 18%). The emissions responsible for these impacts included ammonia and nitrate leaching from manure storage and field excretion. Similar findings were identified in previous studies (Chen and Holden, 2018a; O'Brien et al., 2012; Yan et al., 2013). The nitrate and ammonia not only contribute to global warming, but also lead to resource depletion (Cui et al., 2016). Using bioprocessing technology could mitigate GHG emission through biomass utilisation and waste valorisation (Sepehri and Sarrafzadeh, 2018; Sepehri et al., 2020). The climate change by both dairy and beef farming was mainly driven by enteric fermentation (48% for beef and 37% for dairy). This emission depends on the biological characteristics of cattle, so the room for improvement through farm management is limited (Chen and Holden, 2018b; de Vries et al., 2015). The impact from fertilizer use on farm stands out compared to aquaculture, because of the dominance of locally grown, grazed grass in the animal diet. Fertilizer production and use was important for both types of farm, but the impact contribution of fertilizer on the dairy farm was greater than the beef farm, because more fertilizer is used for grass management on dairy farms to meet the requirements of a compact calving, rotational grazing dairy production system (Fitzgerald et al., 2005).

Compared to the other ABFSC, the processing stage in the butter FSC accounted for relatively a high share of impacts. Because butter is a highly processed food (around 8 kg milk for 1 kg butter) that demands both energy and materials for the processing. In contrast, the salmon and beef products need little energy or material for processing, which leads to little scope for improvement in the processing stage for salmon and beef. There is perhaps some scope for butter producers or processing companies through improved process efficiency and reduction of energy and chemical inputs, though these improvements will be small in the context of the whole FSC. The most significant impacts of processing were abiotic depletion and aquatic ecotoxicity. These are important impacts for the local community as they are regional rather than global, even supplied to regional and the international market, processing represented 10% to 20% of freshwater and marine aquatic ecotoxicity. This impact was seen in Irish water quality reporting (Fanning et al., 2017) and should perhaps attract similar public interest as climate change.

For the international market, the distribution and retail stage were the largest contributor to abiotic depletion (fossil fuels), ozone layer depletion and human toxicity in all ABFSC. Farm production dominated the rest of the environmental impacts for the beef FSC. In contrast, international transport had a greater contribution than the farm to climate change, photochemical oxidation and acidification in the salmon and butter FSC. The greater impacts of salmon sold in the international market compared to national and regional markets reflected the impacts of air transport required to deliver fresh salmon between continents (Table 1), because there was no difference in rate of wasted food (SI Table S1). The impacts of air transport were mainly driven by the production and use of aviation kerosene. Therefore, replacing the conventional aviation kerosene with sustainable aviation fuel could be an option to reduce air transport impacts. Among the different ABFSC, the contribution of air transport to butter (10.8 kg CO_2 eq) and salmon (9.9 kg CO_2 eq.) was more significant than for beef (5.5 kg CO_2 eq.) (Fig. 1). The net GHG emission was determined by the transport distance. Due to the high GHG emission of beef production and short transport distance, the air transport in beef FSC only accounted for a small share of global warming. In contrast, for FSC with low environmental impacts and long transport distance, for example salmon FSC, the sustainable management should focus on optimizing the logistics through use of SAF and more efficient distribution networks. The environmental contribution of shipping was very small for regional markets. The impacts of salmon supply chains within Europe suggested truck-based distribution had greater impacts than marine transport distribution since the transport distances in the distribution networks were very similar (SI Fig. S4). It is worth noting that the butter FSC with air transport had the lowest terrestrial ecotoxicity, while the impact in the domestic

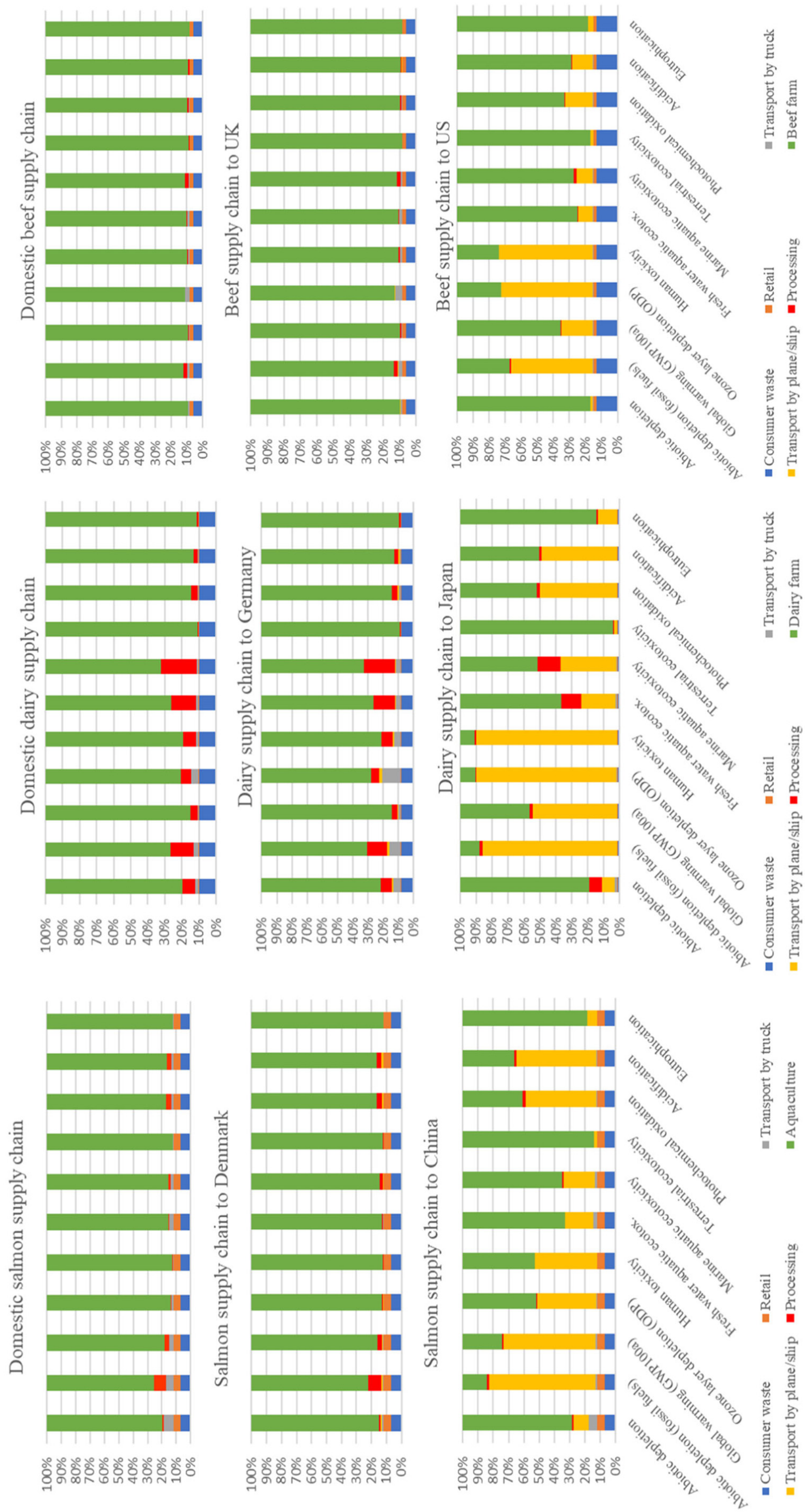

Fig. 1. The contribution of main life cycle phases to the environmental impacts in selected food supply chains.

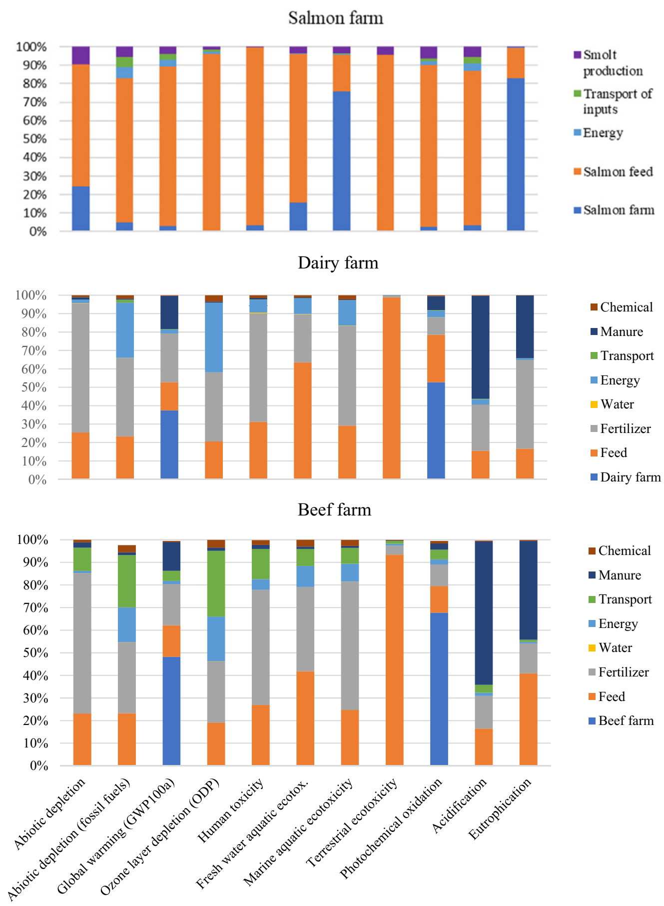

Fig. 2. Impact contribution on salmon, dairy and beef farm.

market was greatest (Table 2). This was influenced by different rates of wasted butter in Ireland (10%) and Japan (1%) (SI Table S1). A similar result was observed in the regional and domestic markets. Although the transport distances increased in the regional market (SI Table S1), the overall impacts for the two markets were almost the same, suggesting managing food waste offered a great opportunity to reduce the impacts of ABFSC, even offsetting the negative effect of air transport if the waste ratio was high. Comparing the international beef and butter FSC showed there was great opportunity to improve the environmental performance of the beef FSC, since the food waste was high (blue in Fig. 2), and considering the greater impacts associated with the beef FSC, the improvement effect of reduced wasted food should be significant (Table 2).

To summarize, alternative feed is an option to improve the environmental performance of all ABFSC and new feeding strategies should be formulated to reduce the impacts of production. Low emission SAF is an abatement measure for food processors or distributors to manage the environmental impacts of their food distribution networks, which demand freshness and short delivery times. Consumers can also have significant influence on the environmental impact of ABFSC through reducing wasted food. Therefore, better public education about impacts of wasting food waste should be conducted and effective packaging that can extend the expiration date should be developed by food processors. The policy makers influencing food production and distribution could developed supports for alternative feed and SAF. The policy makers in the end-market have greater influence on consumer behaviour through guiding consumption rather than compulsory measures. To respect the free market, current policies do not restrict the consumption of specific foods, due to the environmental issues, for example the high GHG emission associated with beef products, but they could influence wasted food.

3.2. Environmental improvement scenarios

The improvement scenario data (Table 3) were focused on climate change impact, as this is the environmental impact that dominates global interest, is universally relevant to all FSC stakeholders and is often correlated with other environmental impacts (Chiari and Zecca, 2011; Ontoria et al., 2019).

The novel feed scenario offered a greater range of GHG reduction for the salmon FSC than for butter or beef. It was because the farm GHG emissions for salmon were much less than for beef and butter. And the feed was the main GHG contributor for salmon production (Fig. 2). This is consistent with previous findings (Davidson et al., 2016; Ytrestøyl et al., 2015). According to Chen and Holden (2018b) and Foley et al. (2011), the GHG contribution of feed is less than 10% in most of livestock systems, so for butter and beef the environmental benefit of using low carbon footprint feed is more certain but the effect is small.

SAF offered the greatest GHG reduction effect for food supplied to international markets. The most significant effect was for salmon because air freighting was responsible for a large share of total GHG emission. Using SAF to replace conventional aviation fuel to supply salmon to the international market could offer a 64% reduction in total GHG emissions. Even the SAF with greatest carbon footprint could still reduce total GHG emissions by 18%. Since butter production needs a large amount of milk (Flysjö, 2011), the contribution of air freighting in the butter supply chain was smaller. The GHG reduction effect by SAF accounted for 14% to 50% of total GHG emission (Fig. 1). The GHG reduction using SAF for fresh beef transport to the international market was relatively small, partly because the market was closer than for butter and salmon. Considering the rapidly expanding global beef market (Smith et al., 2018), even the 6% to 21% reduction in GHG emissions made possible by SAF would be an important option for managing the carbon footprint of the global beef supply chain.

For the wasted food reduction scenario, reducing wasted beef could achieve the greatest GHG reduction effect. Compared to salmon and butter, the amount of waste beef and its carbon footprint were much greater. Managing waste beef would be critical to reduce the global burden of eating such red meat. Although many studies suggested minimizing food waste to reduce the GHG emission of food systems (Bernstad Saraiva Schott et al., 2016; Scholz et al., 2015), the results in this study implied minimizing wasted food was most effective for high impact food chains with a greater amounts of waste.

All the improvement options were beneficial for managing the GHG emission of ABFSC. A combined pessimistic scenario adopting all three

Table 3
The reduction (%) of GHG emission of food supply chains in each scenario.

	Feed scenario			Fuel scenario			Waste scenario			Combined	
	S3	S2	S1	S3	S2	S1	S3	S2	S1	Max	Min
Butter	0.63	0.76	0.88	13.74	31.55	49.90	1.25	1.49	1.98	51.75	15.45
Beef	2.31	2.43	2.55	5.80	13.21	20.91	15.50	18.00	23.01	40.77	21.14
Salmon	0.05	3.52	14.89	17.60	40.43	63.95	8.54	10.06	13.10	81.60	31.98

options over the production, transport and consumption phases could achieve between 15% and 32% GHG reduction for all ABFSC. The optimistic scenarios offered a 52% to 82% GHG reduction. At present, the full benefit of changing aviation fuel and reducing wasted food is perhaps lost in the food policy frameworks that are driven by national inventory and corporate reporting. The results suggested that if appropriate environmental management is applied, there is a significant improvement opportunity for ABFSC, especially when serving the international market. The strong relationship between climate impact and other impacts studies indicates that these interventions will be beneficial for a number of EU policies governed by legislation, particularly, reducing greenhouse gas emissions (European Climate Change Programme (Biermann and Geist, 2019)), freshwater eutrophication (Water and Nitrate Framework Directives (Kallis and Butler, 2001)) and acidification (Air Quality Directive, ammonia regulations (Denby et al., 2010)).

3.3. Future research

Although this research investigated important environmental impacts of beef, dairy and salmon FSC, due to lack of data, the environmental improvement scenarios only evaluated global warming. Further study should focus on the improvement scenarios for other environmental impacts and understanding whether trade-offs between impacts are universal for FSC or specific to particular sources. This is necessary to ensure joined up environmental policy and to have the correct granularity, i.e., should policy be devised for beef cows, dairy cows, sheep, pigs, salmon, trout, mussels and so on, or by products (fresh, minimal processing, highly processes, preserved) or can policies be defined that are equally functional for all ABFSC? In addition, this study did not include the effects of land use and land use change. Future research could settle on one or more methods currently available (Kløverpris et al., 2008; Scholz, 2007) or could adopt a multi-regional input-output approach for assessing the effect of land use change (Ermolieva et al., 2015; Golub and Hertel, 2012). Since this study only considered environmental aspects, the social and economic implications of improvement scenarios should also be determined as quantitatively as possible.

The characteristics of FSC keeps changing, for example, the marine ingredients in the salmon feed have decreased, whereas the terrestrial ingredients have increased (Davidson et al., 2016; Denby et al., 2010). In the future, the effort invested into driving impact reduction should be assessed considering the whole FSC and specific market scenarios, because this work demonstrated that the return on investment is market specific. There is potential to define groups of FSC that behave in a similar manner, even if they are based on different animals to ensure optimum policy interventions.

Based on this work, research and development of insect feed and SAF should be a focus of attention for the food industry in general, and ABFSC in particular. It is also clear that the actors in the FSC need to take some responsibility for enabling consumers to reduce wasted food, but ultimately the consumer has primary responsibility for the decisions they make when buying, preparing, eating and wasting food. Studies that only consider one type of product or FSC will not be enough to gain detailed insight into optimum policy and investment of effort for food system impact reduction.

4. Conclusions

The farm production stage is a common impact hotspot among all ABFSC, but its proportional contribution depends on the farm activities and downstream logistics. The important interaction between market and impact goes beyond mere food-miles, as the mode of transport is crucial, especially in air transport based FSC. For products with relatively low GHG emission in the production stage (e.g., salmon), the greatest emission reduction opportunity is in food distribution stage. However, for products with high GHG emission (e.g., beef), the mitigation strategy should focus on farm production. Wasted food behaviour in the end market also influences the environmental impact of ABFSC, especially for the ones with high food waste ratio. All three novel interventions identified, novel insect feed, using SAF in air transport and wasted food reduction, made significant contributions to reducing greenhouse gas emissions. Disconnection between producer, processor and market perhaps makes it difficult to create and implement effective impact reduction strategies. This study has provided insight for stakeholders of FSC that will help move towards to improve management of agricultural production, food processing, logistics and consumer policies for reducing the impacts of the food system. The findings of this study should be used as the basis for classifying all ABFSC in order to maximise the value of policy interventions without needing to target specific species or products.

CRediT authorship contribution statement

Wenhao Chen: Conceptualization, Methodology, Software, Writing – original draft, Visualization. **Sepideh Jafarzadeh:** Writing – review & editing. **Maitri Thakur:** Resources, Investigation. **Guðrún Ólafsdóttir:** Resources, Writing – review & editing. **Shraddha Mehta:** Resources, Investigation. **Sigurdur Bogason:** Resources. **Nicholas M. Holden:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary data

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