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Evaluation of the environmental sustainability of the inshore great scallop (*Pecten maximus*) fishery in Galicia

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Abstract:

Great scallop (*Pecten maximus*) is a bivalve species belonging to the Pectinidae family that is deeply linked to the Way of Saint James, becoming a gourmet product of the Galician cuisine. The goal of this study was to fill the gaps that currently exist in a specific inventory dedicated to the capture and processing of great scallop, as well as to assess the environmental burdens derived from this system. The construction of a comprehensive life cycle inventory was one of the fundamental stages, gathering primary information from questionnaires filled out by 14 skippers and the manager of the evisceration plant in the port of Cambados. Diesel consumption of the fishing boats was identified as the major contributor to the environmental burdens. Furthermore, electricity consumption on the evisceration plant also stood out as a determinant element in the environmental profile of the product. The integrated GHG emission/protein content correlation placed the scallop in the quadrant of high protein content (the highest of the fisheries), but also high environmental impact (mainly due to the high FUI and low edible yield). It is important to highlight that to date and according to our knowledge, this is the first study that aims to analyse the environmental impacts of the great scallop fishery.

1. Introduction

Within the different aquatic species, bivalves have traditionally been considered a source of healthy animal protein and high levels of essential fatty acids, which has led to a significant increase in consumer demand. In fact, it is estimated that around 25% of the seafood consumed in Spain in 2018 is canned, fresh or frozen molluscs, of which a significant percentage correspond to bivalve species (MAPA 2021). Due to their excellent organoleptic qualities, the consumption of bivalves has traditionally been associated with products of high commercial value, representing a gourmet product, as is the case of oysters, scallops and clams.

Great scallop (*Pecten maximus*) is a bivalve species that belongs to the *Pectinidae* family, commonly referred as "scallop". Great scallop is essentially a coastal species that lives on clean firm sand, fine or sandy gravel bottoms (Brand 2006a), which feeds mainly on phytoplankton, algae and organic particles in suspension. This species is characterised by its wide geographical distribution along the European Atlantic coastline from Spain to Norway (Brand 2006b). Scallops have been commercially landed in Europe for over 100 years, but modern dredge fisheries really began to develop in the 1950s and 1960s around the coasts of the British Isles and France (Duncan et al. 2016). Since then, landings of *P. maximus* have remained constant, accounting for about 67% of total European scallop landings in 2013 (European Commission 2020). Given that this species is not well managed in much of its fishing area, and coupled with the significant increase in fishing effort, there is growing concern about the long-term environmental sustainability of this fishery. In fact, *P. maximus* fisheries in Europe are now almost all fully exploited or overexploited, becoming dependent on fishing catch limits. With the natural variability of scallop catches, this has led to instability of supplies for this fishery (Duncan et al. 2016).

If European landing data are compared with the Spanish scenario, significant divergences are observed. In 2018, 116 tonnes of great scallops were caught (MAPA 2020a), which were entirely captured in the Galician "rias" (**Figure 1**). The Galician rias are complex ecosystems with a unique biodiversity, quality and abundance of marine resources, as demonstrated by the fishing and shellfish farming tradition in the region (Picado et al. 2016). The reason behind the low catches lies in the strict control that is followed in Galicia to respect closed seasons and catch per boat ratios. In fact, for the scallop fishery the following regulations apply to ensure a continuous supply over the years and avoid the depletion of scallop stocks: (i) The gears, tackle, tools, implements, equipment and techniques permitted for the professional extraction of live marine resources are regulated by the ORRDER 15/2011, of January 28; (ii) The minimum size of various fishery products in the Autonomous Community of Galicia, including scallops are regulated by the ORDER of July 27, 2012; and (iii) The closed season is established every year in the general plan of shellfish exploitation, published by the Regional Government. The corresponding plan for this article is the ORDER of December 20, 2018.

Thus, the scarcity of fresh scallops in Spanish markets, together with the nutritional quality of all bivalve species, makes the Galician great scallop highly appreciated, becoming a gastronomic reference of the Galician cuisine that can be considered a gourmet product. In fact, the market Price of a Galician great scallop can reach around 5-6 euros per unit in an average Spanish market (typically sold including the shell), depending on the size of the product.

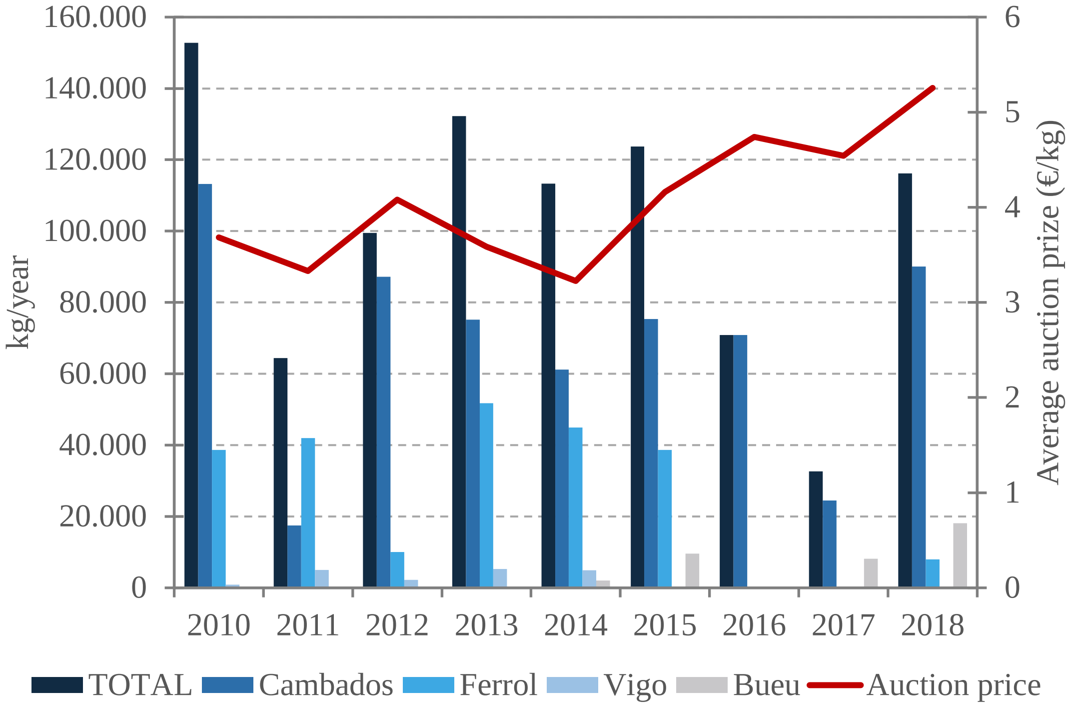

Figure 1. Catches of Atlantic scallop during the years 2010-2018 in different Galician ports. The red line represents the average auction price.

Taking into account the growing global demand for fishery products, both from catches and aquaculture (FAO 2020), as well as the high environmental costs of fishing, it is increasingly essential to assess the environmental burdens of the fisheries and aquaculture sectors. The Life Cycle Assessment (LCA) methodology (ISO 14040, 14044) can be used to support decision-making in fisheries by identifying critical points to reduce their environmental impacts or by comparing several alternative systems (Ruiz-Salmón et al. 2021). The application of LCA methodology to determine the environmental impacts of fish catch, farming and processing started at mid-2000. A long list of LCA seafood studies on diverse pelagic (Vázquez-Rowe et al. 2010; Villanueva-Rey et al. 2018; Laso et al. 2018) or demersal (Vázquez-Rowe et al. 2011; Avadí et al. 2018; Ziegler et al. 2013; Svanes et al. 2011) finfish has been reported; but also crustacean species (Farmery et al. 2015; Driscoll et al. 2015; Vázquez-Rowe et al. 2013a; Ziegler et al. 2011). Concerning the different commercially exploited bivalve species, there are some relevant studies on the environmental assessment of bivalves culture, both mussels (Iribarren et al. 2010; Tamburini et al. 2020; Lourguioui et al. 2017; Aubin et al. 2018) and oysters (Tamburini et al. 2019). Some information on fuel use and greenhouse gas emissions related to bivalve extraction can be obtained from some studies at different scales, from small fleets to a global scale (Greer et al. 2019; Parker et al. 2018; Parker and Tyedmers 2015; Kitts et al. 2008). It is important also to highlight that not only fishing activities and catches have been traditionally evaluated, but also the production of processed seafood products (Vázquez-Rowe et al. 2013b; Almeida et al. 2015), fishmeal and fish oil (Fréon et al. 2017) and the certification for eco-labelling (Vázquez-Rowe et al. 2016).

This study aims to analyse the environmental impacts related to the capture, landing and processing of scallops by the Galician fleet in the "Ría de Arousa" through the LCA methodology. Beyond this objective, it is necessary to continue to raise awareness among stakeholders and consumers about the environmental impact of different products and services.

It is especially interesting to know the environmental implications of this gourmet product, which is not only a reference of tasty delicacy, but also a symbol in the traditional popularity of the Way of Saint James. Preserving the traditional values associated with Galician gastronomic culture is in itself a long-term objective, and the fact that this work sets out to understand the environmental profile associated with the capture, landing and processing of scallops may demonstrate the potency of the Galician fishing sector. Finally, a comparison of the environmental and nutritional quality in terms of greenhouse gas emissions and protein content with respect to other widely consumed foods is provided.

2. Materials and methods

2.1. Definition of goal and scope. Functional Unit

Due to the lack of a specific inventory dedicated to the capture and processing of Galician great scallops, the objective of this LCA study is to fill those gaps, providing valuable information to assess the environmental burdens associated with capture and processing operations related to the extraction of great scallops in Galician waters. The scope of the study focuses on all stages required for the extraction and processing of great scallops. Waste treatment operations were taken into account within the system boundaries, corresponding to a cradle-to-gate analysis (Guinée et al. 2001)

The Functional Unit (FU) chosen to analyse the capture and processing of the great scallop is based on a product-oriented approach (1 raw eviscerated frozen scallop that left the processing plant ready for the market). This FU contains 139.5 g of great scallop, 3.3 g of plastic film and 5 g of plastic label. Due to the waste generated during the processing stage, 139.5 g of final eviscerated scallop correspond to 155 g of landed scallop. The edible meat of the scallop is 20.5 g, which corresponds to 13.2% of the gross weight of the scallop. This value is in line with Tyedmers (2004), where it is stated that the abductor muscle in scallops generally represents around 10-12% of the live weight of the animal. It is important to note the reason for selecting this FU. During the months of December to March, while the fishing season is open, scallops are sold fresh, while the rest of the year, scallops caught during these months are sold frozen.

Since most of the Galician scallops are sold frozen, it was decided to analyse this case because it is more representative.

2.2. Description of fishing and post-harvesting operations

The ideal season for scallop fishing is mainly during the winter months and therefore, the scallop season in Galician waters runs from December to February/March. Twenty-one trawlers with a scallop fishing license operate in the port of Cambados, which in 2018 reached a total of 90,029 kg of great scallop. Hence, the fishing and processing system evaluated consists of two subsystems which are SS1 – Vessel operations and SS2 – Post-harvesting operations. **Figure 2** shows the subsystems and process steps included within the system boundaries.

The vessel operations subsystem includes all activities that are carried out until the boat arrives at the port of Cambados, where all the catches of the day are landed. The assessed fleet operates in waters within the Ria de Arousa between 5-9 miles operating at a speed of 2-2.5 knots. The fleet is composed entirely of small-scale boats with an average size of 10,7 metres in length, 3-4 metres in beam and an average gross tonnage of 7.9. It is important to note that once the scallop season is over, vessels may engage in other traditional fisheries, being the following the main gears and in brackets the target species: “Xeito” (pilchard), “Miños” (spider crab), “Vetas” (mackerel, pout), “Bou de vara” (queen scallop, Velvet swim crab, spider crab) and “Bou de man” (cuttlefish, octopus).

In order to start the fishing period, the Fishermen´s Association must submit a catch and processing plan together with an authorized company (in charge of the evisceration processes) to the Regional Government for approval. The Cambados Fishermen´s Association has a plan in place to ensure the sustainability of the fishery and the commercial value of the product based on two pillars: (1) a minimum size of 115 mm, (2) a maximum daily catch for the entire fleet of 3,000 kg, a quota that is shared proportionally among all fishermen in the fleet.

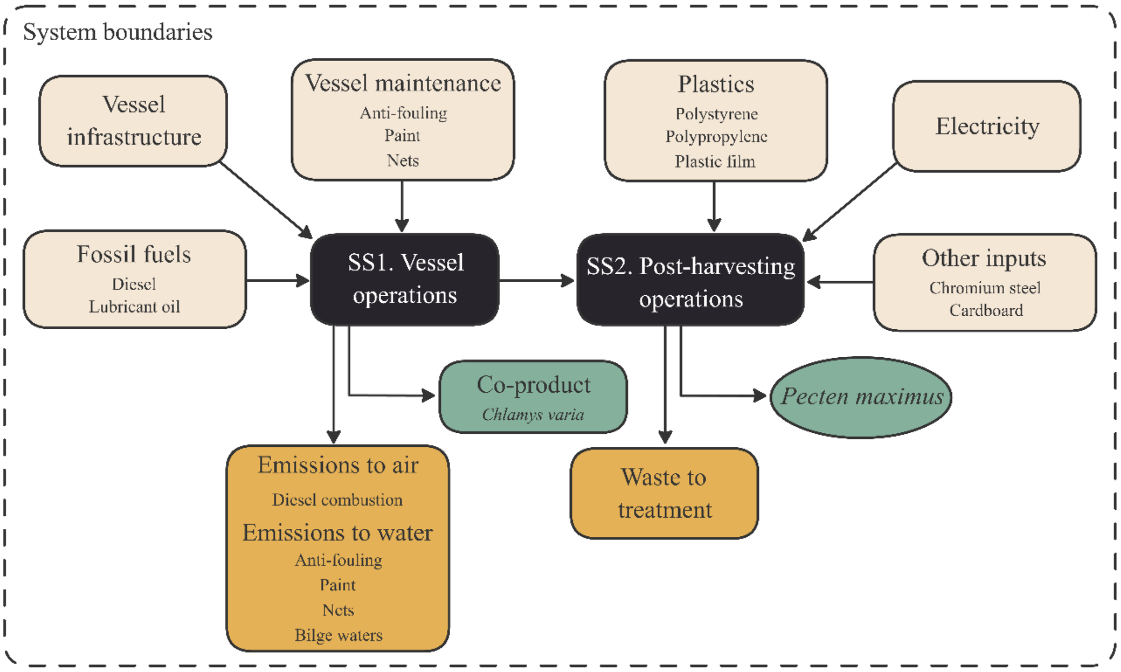

Figure 2. Flow chart of scallop fishing and processing. Legend: Black: Subsystems; Cream: Inputs; Yellow: Emissions and waste generated; Green: Products and co-products.

This fishing activity is the only bottom trawling gear allowed in the Galician small-scale fisheries, restricted to in-shore water of the Ria de Arousa and is not allowed in the other Galician rias (Outeiro et al. 2020). Great scallop fishery is carried out using a dredge (**Figure 3**), which is made of steel and the net is made of polyethylene with a mesh width of about 100 mm and a total weight of 2 kg. Other characteristics of the fleet are two days of rest per week and a maximum power set at 500 hp. Although it is well documented the impact that some types of toothed dredges can cause on other species living in or on the seabed due to the effect of their long teeth (Hinz et al. 2012; Stewart and Howarth 2016), it is important to note that this particular fishing gear does not dredge the ground, but slides parallel to the bottom, remaining open up to 4-5 cm thanks to the speed of the vessel, reducing the impact caused on the seabed. The “sweep chain” is made up of a series of metal teeth inclined inwards, which allows the dredge to pass obstacles without dragging them.

It is documented that scallop fisheries in general are relatively target-species specific (Duncan et al. 2016). In fact, a study conducted on the queen scallop trawl fishery (Duncan 2009), indicated a relatively low level (3.4%) of by-catch while Boyle and Thompson (2012) reported similar general trends (7.4%), but highlighting the species variability in queen scallop trawl by-catch (Duncan et al. 2016). It is noteworthy that the majority of by-catch is discarded damaged, dying, or dead (Jenkins and Brand 2001; Aldous et al. 2013; Stewart and Howarth 2016). In the present study, the conclusion on the high selectivity of the fishery has been based on three elements: (1) the unanimous opinion of the fishermen on the cleanliness of this fishing gear, including those who did not belong to that fleet; (2) the follow-up on landings in port; (3) the port authorities verify that the fishing gear does nor discharge other species by-catch, which is punishable by an administrative sanction. With all this information, and due to the lack of official data or statistics, discards were not quantified. It is relevant to mention that variegated scallops (*Chlamys varia*) are also caught, representing around 10% of the total catch, which is considered as a co-product.

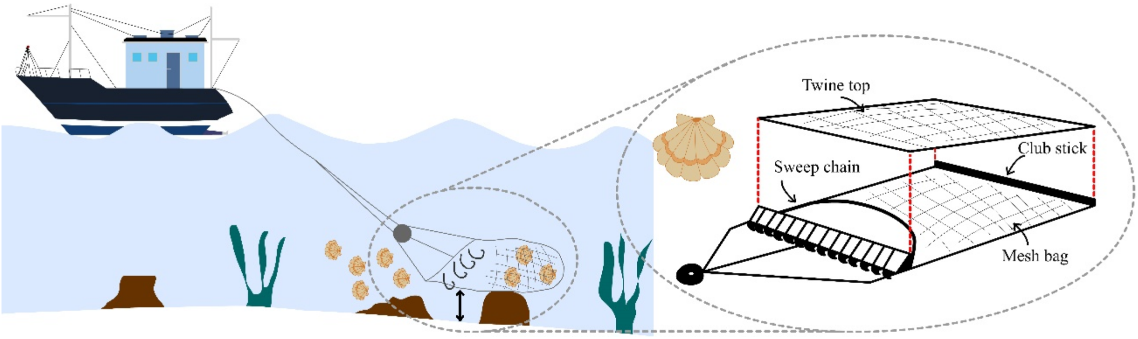

Figure 3. Simplified diagram of scallop fishery operations. On the right, the dredge used is shown in detail.

Subsystem 2 – Post-harvesting operations starts once the boats arrive at the port and the great scallops are taken to the processing plant of the Association of fishermen of the Port of Cambados, where they are kept for a full day in propylene drums with clean seawater for filtration. Once filtered, great scallops are taken to the evisceration area, where the workers in charge remove the hepatopancreas and soft tissues, maintaining the abductor muscle and gonads. Each scallop is then individually wrapped in plastic film, labelled and stored in cardboard boxes for year-round frozen distribution. It is important to note that scallops are vacuum packed in their original shell, since traditionally the scallop is baked in its shell.

The evisceration process is carried out by hand with a knife, highlighting the non-consumption of chemicals, additives or other elements, only the consumption of electricity and cleaning and protection materials for workers (knives, gloves, etc.) are noteworthy.

2.3. Data collection

Data acquisition is the most relevant step in an LCA study since the quality of the life cycle inventory data directly influences the quality and representativeness of the environmental results. In this study, a considerable effort was made to acquire data from primary sources to obtain reliable results. The data used for the Subsystem 1. Vessel operations were obtained from a set of 14 artisanal boats registered in the Port of Cambados, representing 67% of the 21 boats that make up the entire fleet in this town.

A series of questionnaires fulfilled by fishermen provided the primary information of the life cycle inventory. These questionnaires included the most relevant operational parameters necessary to carry out the environmental analysis, such as the distance to the fishing area, trips made per day and months dedicated to the maintenance of the boat, as well as the direct material consumption in the boat (diesel, anti-fouling, paint, lubricant oil, nets, etc.). An example of these questionnaires is included in the **Table S1.1** of supporting information. Different aspects directly related to the boat construction (weight and material of the boat, dimensions, lifetime, etc.) were also considered to build the life cycle inventory. Although this study used primary information to determine the consumption of materials related to fishing, it was necessary to use secondary data from scientific studies and the database for the background system. In this way, the Ecoinvent database v3.5 (Moreno Ruiz et al. 2018) was used as the main source of secondary data for the background system.

The questionnaires showed that the boats are sending to the docks for maintenance for 1-2 months per year, so paint and anti-fouling were considered important inputs in vessel operations as in previous research (Vázquez-Rowe et al. 2011; Villanueva-Rey et al. 2018). Data regarding the composition of the main paints and anti-fouling agents were taken from Vázquez-Rowe et al. (2010). Regarding the nets, as in Vázquez-Rowe et al. (2010), the composition based on nylon and lead was taken into account, although the dimensions and weight provided by the questionnaires were considered. The annual consumption of nets was increased by 25% to take into account the potential replacement due to net losses at sea. This value was estimated as the maximum replacement ratio due to net losses during fishing according to the information provided by fishermen and net menders. Finally, the release of lead into the sea due to net use was also estimated.

With respect to the boat construction, to establish the consumption of materials, the lifetime and the total weight of the boat were considered. In this way the "consumption" of the boat per year was estimated, using the Ecoinvent database to consider the necessary materials for the construction of an average small-size boat. These materials include wood (71%), steel (26%), plastics (2%), lead (0.3%), other metals (0.3%), epoxy resin (0.02%) and other elements.

It is important to note that the time dedicated to the scallop campaign has been considered, as this type of small-scale vessel operates all year in different small-scale fisheries. In some cases, the questionnaires collected data directly related to the scallop fishery, but in other cases, the data obtained were related to annual consumption, so a temporal disambiguation was necessary. The direct gaseous emissions from diesel combustion were taken from Ecoinvent, considering the EEA (2013) emission factors. Finally, bilge water was also included within the system boundaries.

Data acquisition to develop the life cycle inventory of the post-harvesting operations (Subsystem 2) was obtained mainly through primary sources. The information was provided by the manager of the processing plant located in the Port of Cambados. The information included a wide set of operational and capital goods aspects related to the different stages described in section 2.2, which included the main material and energy consumption of the plant. Secondary data taken from the Ecoinvent database was used for the background processes involved in the production of operational inputs such as electricity, plastics, or packaging material. The consumption of materials includes the months of plant activity (mainly from December to

March), while the electricity consumption refers to the whole year, since the scallops are stored throughout the year in the cold room before they are marketed.

2.4. Co-product allocation strategies

The recommendations of the ISO standards give priority to the division of the unit process into sub-processes or the extension of the system boundaries to include additional co-product functions as opposed to the application of allocation factors. The scallop fishery includes the capture of a small amount of variegated scallop, which is also highly valued by Galician gastronomy, with a good market niche, so the allocation of environmental loads between the two products is required. When accounting the total catch ratios, 90.0% mass allocation is considered for great scallop, while if the wholesale prices are considered, an economic allocation factor of 87.9% is achieved, as detailed in **Table S1.2** of supporting information. Therefore, because of the small difference in whether one method or the other is used, mass allocation was considered the most appropriate approach for this case study. This selection was based on the fact that the use of mass allocation enables reducing the uncertainty caused by fish prices volatility (Vázquez-Rowe et al. 2011).

2.5. Life cycle impact assessment: methodology

A wide range of environmental indicators have been used in this study to establish the environmental impact of great scallop fishing and processing. In this sense, the life cycle impact assessment step was carried out using the ReCiPe 2016 v1.1 methodology in a hierarchist perspective at midpoint level (Huijbregts et al. 2016) in terms of the following impact categories: Global Warming (GW) and Stratospheric Ozone Depletion (SOD) to establish the impacts on the atmosphere and the ozone layer related to gaseous emissions; Freshwater Eutrophication (FE), Marine Eutrophication (ME), Freshwater Ecotoxicity (FET) and Marine Ecotoxicity (MET) to quantify the impacts on fresh and marine water since the Galician rías correspond to fluvial-marine transition ecosystems; and Fuel Resource Scarcity (FRS) to establish a link with fuel consumption in the boats, as it is proven as one main hotspots in fishing. SimaPro v9.0 (PRé Consultants 2017) was the software used to lead the computational implementation of the life cycle inventories.

2.6. Uncertainty analysis: Monte Carlo simulation

When managing multiple life cycle inventories, the common procedure is based on the definition of an average inventory data. The use of these average values involves the handling of standard deviations and, consequently, data quality problems. The different types of uncertainty include those related to the choice of scenarios (e.g., choice of functional unit or allocation methods), those related to the LCA model (e.g., uncertainties of characterization factors), and uncertainty related to parameters (e.g., measurement inaccuracies or variability resulting from horizontal averaging) (Huijbregts 2002). In the present study, the focus has been mainly on data uncertainty due to variability caused by using an average life cycle inventory from several boats. To assess the uncertainty of the average inventory data, the Monte Carlo method was used. For simplicity, the normal distribution was assumed to be the probability distribution of the life cycle inventory, so it was necessary to characterize all the inputs data with their mean and standard deviation. The Monte Carlo analysis was performed using the Monte Carlo module of the SimaPro v9.0 software on background data (processes from the Ecoinvent database v3.5). The number of iterations was set to 1000 at a 95% significance level (Longo et al. 2017).

2.7. GHG emission/protein content correlation

In order to place the environmental and nutritional aspects of great scallops in the context of an average diet, the environmental performance of this product in terms of its carbon footprint and the protein content has been compared with that of other widely consumed food (seafood, meat, dairy products and fruits and vegetables).

The carbon footprint was chosen as environmental indicator because it is a widespread element that enjoys high consumer recognition (Laurent et al. 2012). It is important to point out that the ready-to-eat product was considered for the analysis, i.e. eviscerated great scallops, harvested fruit or seafood landed at the port and all products are considered in a cradle-to-gate approach, excluding the production of packaging, retail, transport and consumption stages. The carbon footprint values were reported for 1 kg of edible weight for all the foodstuffs assessed. For this purpose, the values given per unit of live weight were translated into the edible yield using different species-factors for edible yield from different sources: (i) FAO (1989) for fish; (ii) Ruiz-Torralba et al (2018) for fruits; (iii) Clune et al (2017) for meat; and (iv) for cases where specific values were not available, generic data collected in Hartikainen et al (2018) were used. At this point, it is important to note that a 100% edible part was considered for dairy products.

To introduce nutritional quality, the protein content in grams per 100 g of edible product was considered, obtained from the Spanish Agency of Food Security and Nutrition (AESAN 2018). Protein content was chosen as an indicator of nutritional quality since many nutrient density models indicate that protein should be encouraged; furthermore it is demonstrated that protein has the strongest positive correlation with the level of GHG emissions linked to the 19 main macronutrients (van Dooren et al. 2017).

3. Results and discussion

3.1. Quantitative analysis of inputs and outputs

The life cycle inventory of the fishing stage encompassed all the necessary elements for vessel operation, including an average fuel consumption of 123 mL or 772.7 mg of net per scallop. These values indicate that the nets, although they need constant repairs and renovations, represent a very low consumption throughout the year compared to main elements such as diesel. Based on the average weight of each boat (7.9 tonnes) and the average lifespan (38 years), given that on average, boats dedicated 3 months per year on scallop fishery and taking into account the total scallop captures in the season and the mass allocation factors, the “consumption” of infrastructure was calculated as 1.84 g of vessel per scallop meanwhile consumption of 132.1, 337.1 and 891.5 mg of anti-fouling, paint, and lubricant oil, respectively, were calculated for maintenance operations.

As for the inventory of the processing subsystem, the low consumption of materials stands out. Only the consumption of plastic film is noteworthy, since each scallop is individually packed with 8.3 g of plastic film. It is also important to highlight the consumption of electricity, which was around 90,000 kWh in 2018 for the operation of the freezers where the scallops are stored. The life cycle inventories calculated for the two considered subsystems are summarized in **Table 1**.

Table 1. Inventory data for the subsystems considered in the study per FU

Subsystem 1. Vessel operations					
Inputs from the Technosphere			**Outputs to the Ocean**		
Materials	**Unit**	**Value**	**Emissions**	**Unit**	**Value**
Diesel	mL	111.8	Lead	mg	37.5
Nets	mg	772.7	Xylene	mg	17.9
Anti-fouling	mg	132.1	Cobalt	µg	348
Boat Paint	mg	337.1	COD	g	1.69
Lubricant oil	mg	891.5	Copper	mg	28.7
Infrastructure	g	1.84	**Outputs to the Atmosphere**		
			Emissions	**Unit**	**Value**
			CO_2	g	355
			SO_2	g	3.3
			NMVOC	mg	361
			NO_X	g	7.7
			CO	mg	806
			Outputs to the Technosphere		
			Products	**Unit**	**Value**
			Pecten maximus	g	155
			Co-products	**Unit**	**Value**
			Chlamys varia	g	17.2
Subsystem 2. Post-harvesting operations					
Inputs from the Technosphere			**Outputs to the Technosphere**		
Materials	**Unit**	**Value**	**Products**	**Unit**	**Value**
Pecten maximus from SS1	g	155	Frozen scallop	g	139.5
Plastic film	g	10.7	Packaging	g	8.3
Corrugated board	g	2.6	**Waste to treatment**	**Unit**	**Value**
Chromium Steel	mg	2.9	Biowaste	g	15.5
Polypropylene	mg	13.6	Mixed plastics to landfill	mg	60.5
Polyethylene	mg	138.2	Steel to recycling	mg	2.9

Energy	**Unit**	**Value**	Polypropylene to recycling	mg	13.6
Electricity	MJ	0.56			

Life cycle inventory analysis has shown that direct consumption of materials on the boat is a key element in understanding the environmental profile of the final frozen scallop. Fuel consumption is the most important component of the inventory, reaching 111.8 mL of diesel per scallop and a fuel use intensity (FUI) of 721.2 L/tonne.

This value is higher than those reported by other authors, i.e. Kitts et al. (2008) and Tyedmers (2004) reported 364 and 350 L/tonne respectively. These values represent less than 50% of those obtained in this study, however, these values should be taken with caution, as they refer to fisheries in the late 1990s in North America. Another more recent study reported the FUI of general mollusc fisheries using dredges in North America at 295 L/tonne with a minimum value of 71 L/tonne and a maximum of 361 L/tonne (Parker and Tyedmers 2015). This same study, however, reported the average for mollusc dredge fisheries in Europe at 525 L/tonne, which is much closer to that reported in the present study. Finally, in Parker et al. (2018), which is a study on fuel consumption in different fisheries around the world, an average value of 523 L/tonne is reported for all types of demersal molluscs

In general, the fuel consumption obtained in the present study is higher than others reported in previous work on scallop or mollusc fisheries with dredges. This may be representative of the low performance of a fishery with very strict fishing quotas, which makes the combined fuel consumption during the vessel travel to the catch area and the fishing activities inefficient. However, maintaining these fishing quotas is essential to ensure the long-term sustainability of this fishery, so improvement actions should focus on reducing fishing effort (Farmery et al. 2014) i.e. improving fuel efficiency by targeting high-density scallop aggregations. For this purpose, technologies such as multi-beam echosounders or video survey techniques have proved to be a fast and accurate way to map the location of scallop beds (Duncan et al. 2016).

3.2. Environmental characterization of great scallop fishing and processing

The relative distribution of the environmental impacts in the processing stage is shown in **Figure 4**. The final results per FU for the different allocation approaches (mass and economic); as well as a complete breakdown of the results, including the relative contribution to the impact of each item of the life cycle inventory in each impact category can be found in the supporting information S2.

Looking at the full set of environmental results, the fishing stage can be designed as the most burdensome subsystem, as it accounted for most of the impact in MET (98.5%), GW (83.5%), FRS (82.0%), SOD (72.9%), and ME (52.0%). It should be noted that, in the categories related to freshwater, the production of electricity for the operation of the evisceration plant is the main contributor to environmental impact. This is due to the Spanish electricity mix in the Ecoinvent database, which shows a significant percentage of electricity production from coal. The treatment of waste from coal and lignite mining is responsible for the high impact in these impact categories.

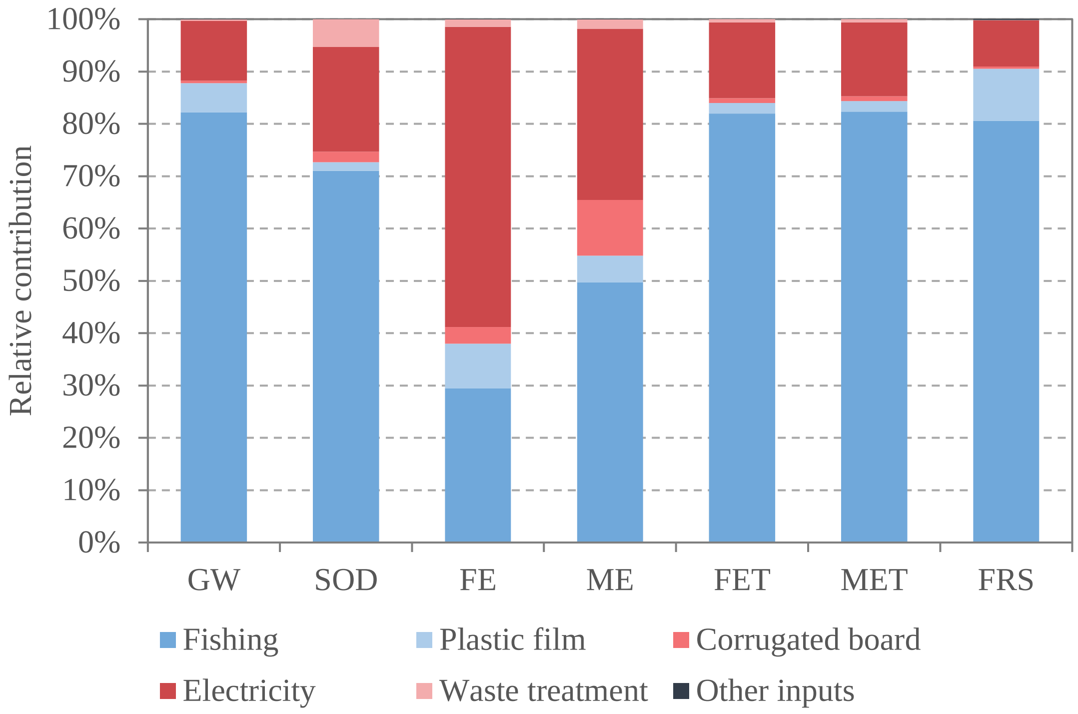

Figure 4. Relative contribution of environmental impacts per process involved in the fishing and processing of scallops

Plastic film production presented a considerably uniform distribution of environmental impacts across almost all categories, with contributions between 5% and 10%, except for SOD and MET categories, where it showed no relevant impact (<2%). Corrugated board production achieved a significant impact on ME (ca. 10%), although in the other categories it was not very relevant, reaching even less than 0.5% in GW, MET and FRS. The treatment of the waste generated during the processing is not relevant, except in the SOD category (ca. 5%) and, finally, the influence of other consumables on the environmental profile is irrelevant, below 0.2% in all impact categories. The consumption of electricity in the plant is the only element of the post-harvesting operations subsystem that is relevant to the environmental profile. In fact, this makes sense since great scallops must be stored in freezers for their distribution during the rest of the year. This fact leaves open the option of future improvement actions leading to lower electricity consumption or the search for cleaner production systems to ensure an even lower impact of electricity consumption on the environmental profile.

In order to highlight the process with the greatest environmental impact in the life cycle of the system, the individual contributions of the fishing stage were broken down in **Figure 5**. According to the results, there are three main activities that produce most of the environmental impacts. In the first place, diesel production and combustion accounted for most of the impact in GW (97.7%), SOD (92.2%), FRS (98.0%) and FE (55.5%). The great influence of this element in the profile can be explained from the perspective that Diesel production presented a high impact on fossil resource scarcity category, while the emission of GHG and other gaseous pollutants to the atmosphere during diesel combustion is behind the high values in GW and SOD, respectively. In the other categories, diesel relative contribution is reduced by the presence of other elements more relevant.

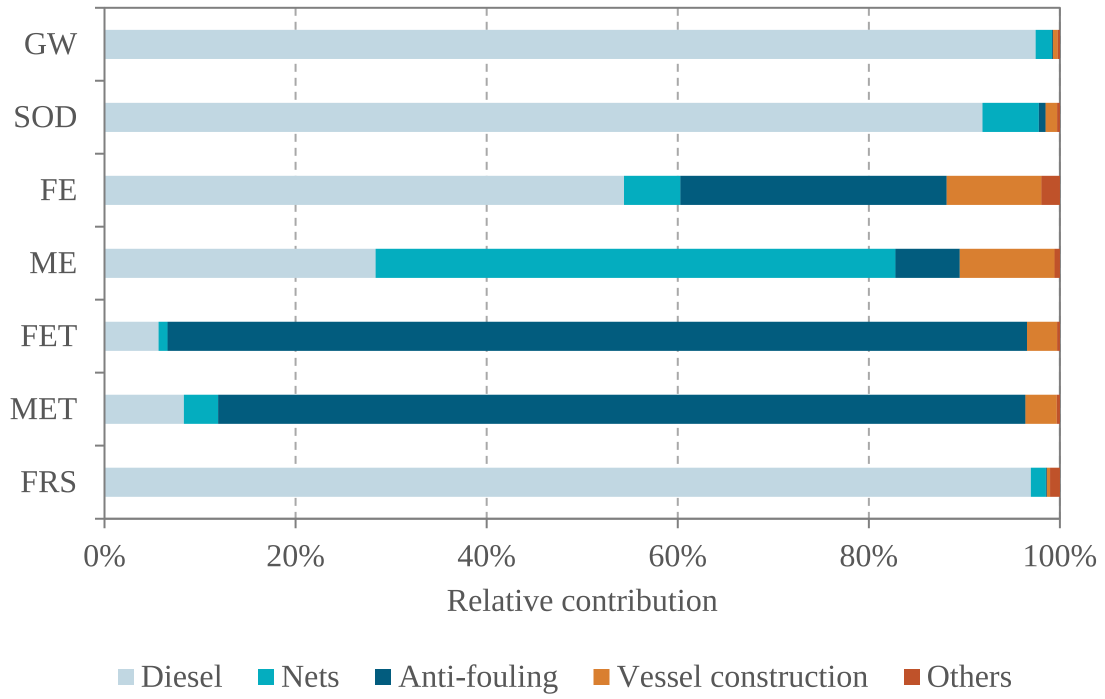

Figure 5. Relative contributions (in %) by component in the environmental profile of scallop fishing.

The production and consumption of anti-fouling presented a relevant impact on the ecotoxicity categories (98.9% and 40.5% in MET and FET categories, respectively). The high impact of this element is mainly due to the emission of Cu- and Sn-based emissions into the sea during vessel operation. As for the ME category, the element with the greatest environmental impact is the manufacture and use of nets, which represents 54.7% of the impact in this category, while in the others it is always less than 6%. Regarding vessel construction, as in previous research (Hospido and Tyedmers 2005; Vázquez-Rowe et al. 2011; Laso et al. 2018), it has been shown not to have a major relevance on the environmental profile due to the long lifetime of this type of vessel. The environmental impact of boat construction is only noteworthy in the categories of FET (19.3%), FE (10.1%) and ME (10.0%) due to the treatment of the waste generated during the production of the raw materials. The element “others”, which includes the production and use of boat paint and lubricant oil and the treatment of bilge water, presented a relatively constant contribution around 1-2% in all impact categories.

3.3. Uncertainty analysis

As mentioned above, the LCI for the fishing stage was constructed using average data from 14 fishing boats and the background data was taken from the Ecoinvent database. An uncertainty analysis was performed to assess the extent to which the uncertainties of the background data and the deviation from the primary data can influence the environmental results.

The mean values of the impact categories have been represented in a bar chart and the uncertainty margins express the 95% confidence interval (Fantin et al. 2015). **Figure 6** shows the impact assessment profile per FU with 95% confidence interval.

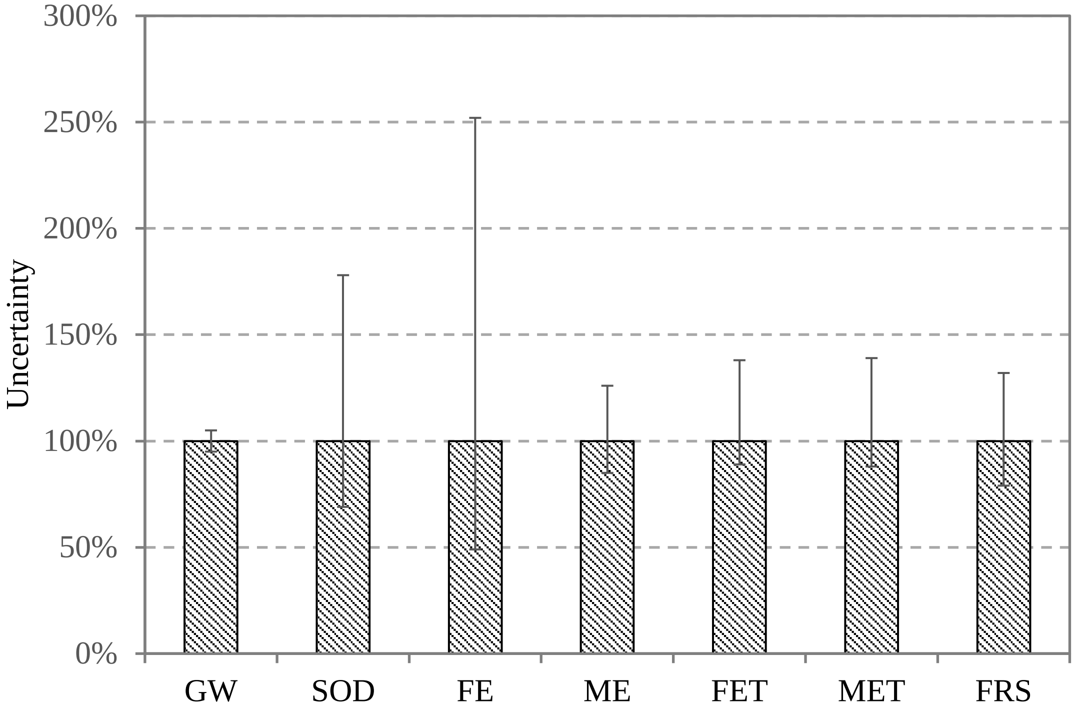

Figure 6. Bar-chart of Monte Carlo simulation results for each impact category per FU. The error bars represent the 95% confidence interval. Legend: GW-Global Warming, SOD-Stratospheric Ozone Depletion, FE-Freshwater Eutrophication, ME-Marine Eutrophication, FET-Freshwater Ecotoxicity, MET-marine Ecotoxicity, FRS-Fossil Resources Scarcity.

According to these results, FE and FET showed the highest data variability, while GW and ME showed the lowest. This uncertainty probably comes mainly from the uncertainty values in some Ecoinvent background data that were propagated to the final results, since the variability of the data handled from fishing boats is quite low as they have similar sizes and characteristics. These results are in line with other uncertainty analyses performed on life cycle inventories based on Ecoinvent data (Fantin et al. 2015; Longo et al. 2017; Lijó et al. 2017), which showed that the highest uncertainty was associated with the categories of Freshwater Eutrophication and Ozone Depletion categories while the lowest uncertainty was associated with Global Warming, Acidification and Marine Eutrophication. The numerical results of the Monte Carlo calculation in terms of statistical characteristics related to probability distribution of each impact category: mean, median, standard deviation, coefficient of variation, standard error of the mean can be found in the supporting information S2.

3.4. GHG emission and protein content in different foodstuffs

Figure 7 shows the comparative analysis between the protein content and GHG emissions of different food products. The results were represented according to the average value obtained for the sample, so that the elements with better or worse results can be easily identified. It is important to note that the size of the bubble represents the consumption in Spain in 2018, obtained from the Ministry of Agriculture, Fisheries and Food (MAPA 2020b).

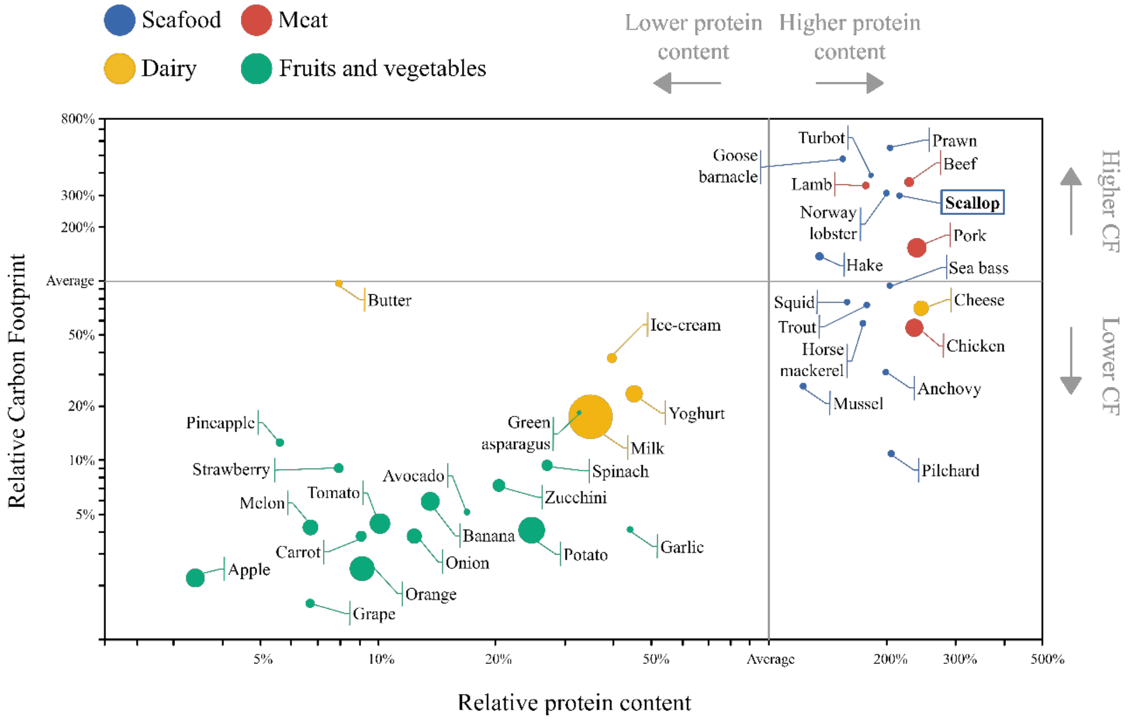

Figure 7. Protein content and carbon footprint of different foodstuffs. Log transformed data scaled around average of all the products analysed. The colour of the bubbles represents the different groups.

According to the obtained results, the analysed food categories can be classified into 3 groups: 1) fruits and vegetables and most dairy products are located in the low-protein and low-CF sector. 2) meat products are placed in the high-protein and high-GHG sector, which makes sense given the high environmental costs linked to meat products. Although chicken is the exception, as it is below the average carbon footprint. 3) seafood is entirely located in the high protein sector but is almost equally divided between high and low emissions. The seafood species with high emissions are mainly molluscs and crustaceans (with low catch ratios) and turbot (farmed in aquaculture facilities), while the low-emissions species include finfish with high catch ratios by purse seine and similar fishing gears (horse mackerel, anchovy, pilchard…) but also mussels farmed in rafts with a very low impact and scallops.

In general, the results obtained match the expected correlation between protein content and the associated GHG emissions (van Dooren et al. 2017; González et al. 2011). Great scallops are in the quadrant of high protein content (the highest of the fisheries and just below meat), but also high environmental impact in terms of carbon footprint. It is important to consider the edible content of great scallop, which is particularly low around 13.2% compared to finfish species, where edible muscle usually constitutes 50-60% of the total weight (Tyedmers 2004). Therefore, taking these data, the results obtained are in line with those reported by Hallström et al. (2019), where it is reported that crustaceans, flatfishes, scallops and oysters had the highest climate impact among the different fisheries due to a combination of resource-intensive production and/or low edible yield. The Galician great scallop fishery assessed in this study has both circumstances: high FUI and low edible yield.

4. Conclusions

In this study, an important part of the great scallop trawling fleet from the Port of Cambados has been inventoried, representing 77.5% of the total Galician landings in 2018. As far as the authors are aware, this is the first comprehensive life cycle assessment performed on the Galician great scallop fishing fleet. The results showed that the main critical points of the process are the fishing stage and the consumption of electricity in the processing facilities. More specifically, diesel consumption in fishing boats stands out as the critical point.

It has been shown that, in the combination of environmental and nutritional aspects, great scallop presented one of the best profiles within the category of seafood. The protein content of the scallop is one of the highest in the category of seafood, at the level of some meats such as beef or chicken, while the environmental profile in terms of carbon footprint is, as expected given its low edible yield, on a par with other molluscs and crustaceans such as goose barnacle, prawn and Norway lobster.

This work represents an important step forward in the search for sustainability of the Galician fishing sector, which has a great influence on the productive fabric of this region. This study has shed light on the determination of material and energy flows of the fishing and processing of great scallop, filling the existing gaps in the inventory data of this species. Finally, future perspectives on the environmental assessment of different scallop fisheries in Europe should aim at providing the environmental burdens of a wide range of fleets, for which this study can be used as the first iteration for following studies in the coming years.

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Figures Legends

Figure 1. Catches of Atlantic scallop during the years 2010-2018 in different Galician ports. The red line represents the average auction price (Xunta de Galicia, 2020a).

Figure 2. Flow chart of scallop fishing and processing. Legend: Black: Subsystems; Cream: Inputs; Yellow: Emissions and waste generated; Green: Products and co-products.

Figure 3. Simplified diagram of scallop fishery operations. On the right, the dredge used is shown in detail.

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