"There's nothing more Portuguese than bacalhau": The sustainability of bacalhau consumption in Portugal

Ayla T. Frost
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"THE SUSTAINABILITY OF BACALHAU CONSUMPTION IN PORTUGAL"

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NOVA School of Science and Technology

11th December 2022
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Lastly, I would like to thank Joana Dionisio for the words that inspired this work’s title:

“**There’s nothing more Portuguese than bacalhau**”
2. Abstract

*Bacalhau* is a typical Portuguese dish highly consumed by the population. *Bacalhau* is the Portuguese word for dried and salted cod, and is a key ingredient in so many iconic Portuguese dishes. Despite its elevated status in Portuguese food culture, *bacalhau* is fished in the cold Northern Atlantic waters far from the Portuguese coast. This study explores this tension between reionalities, and assesses the environmental impacts of Portuguese *bacalhau* importation and production. A life cycle assessment methodology is employed to assess an array of environmental impacts over the product’s lifetime. The results show that the curing stage of production is responsible for the vast majority of environmental impacts, followed by the capturing stage of production. This research recommends improving factory efficiency and adjusting fishing techniques to reduce the ecological impact of *bacalhau* production and ultimately cement its sustainability as an iconic Portuguese dish.

3. Introduction

Traditional cuisine is extremely powerful, both as a cultural and an ecological force. In Portugal, *bacalhau* is a dish that holds this sort of power. *Bacalhau* is the Portuguese term for cod, a dish consumed regularly in Portugal. As such, it is deeply intertwined with Portuguese cultural identity. Portugal is a country on the sea, and unsurprisingly, many of the most commonly consumed meals are fish and shellfish from nearby coastlines. Therefore, it may be surprising to hear that *bacalhau* is fished off the coastlines of Canada and Norway. This phenomenon raises questions about how a Norwegian fish can come to represent Portuguese national cuisine and identity. Furthermore, it raises interesting concerns about the sustainability of these processes, given the massive scale of *bacalhau* consumption and the routes of processing and shipping *bacalhau* from the cold Northern Atlantic waters to the Iberian peninsula.

3.1 Objectives and Research Question:

The overall aim of this work is to study the sustainability of *bacalhau* consumption in Portugal. In particular, this paper will trace each step of *bacalhau* production: from the day it is caught to its arrival in the grocery store. It will employ a technique called a life cycle assessment (LCA) to measure the sustainability of *bacalhau* production over its life cycle. The objectives of the study are to:

- Determine the environmental impacts of *bacalhau* production
- Identify critical processes and provide improvement recommendations
- Highlight the role of *bacalhau* in Portuguese culture

4. Literature Review

The Portuguese population has a long history of consuming *bacalhau*. Early records indicate European sailors were fishing for cod in the Saint Lawrence Estuary in Canada in the year 1000 BC (Pires, 2015). When the first chartered explorers reached the region, beginning with Giovanni Caboto in 1497, they famously recorded that the fish were so plentiful that they interfered with the progression of the ships (Sutton, 2011). Even as early as 1497, these explorers reported signs of systematic fishing, as well as drying and salting the cod, a technique originally developed by the Vikings to transport the fish to Europe in an edible condition (Sutton, 2011). The drying and salting technique that was originally employed to preserve the fish over this long journey is still utilized, dried and salted *bacalhau* being a staple of Portuguese grocery stores to this day.
Bacalhau was integrated quickly into the Portuguese diet for several reasons. One of the primary reasons is economic. During this time period, food was primarily seen as a way to stay alive, so fish were consumed regularly because they were an affordable and efficient way for early Europeans to consume necessary proteins and vitamins (Sutton, 2011). Bacalhau also became associated with Christianity, as it was frequently eaten on the 140 religious holidays per year during which meat consumption was forbidden (Madsen & Chkoniya, 2019; Pires, 2015). Bacalhau also was praised by the Church and the clergy for its association with humility and its ability to purify the body and soul (Madsen & Chkoniya, 2019).

Bacalhau also became associated with Christianity, as it was frequently eaten on the 140 religious holidays per year during which meat consumption was forbidden (Madsen & Chkoniya, 2019; Pires, 2015). Bacalhau also was praised by the Church and the clergy for its association with humility and its ability to purify the body and soul (Madsen & Chkoniya, 2019).

Bacalhau also became seen as a significant economic opportunity for Portuguese and other European fishing fleets. In fact, competition for codfish was at the heart of conflicts between European countries in the 1500s, most notably a 1532 war between England and Germany and a 1585 conflict between England and Spain (Madsen & Chkoniya, 2019).

Bacalhau became even more embedded in Portuguese cuisine in the 1900s. During World War 2, food production in Europe decreased and food became expensive. This was exacerbated by the Portuguese dictatorship during this time period, which yielded illiteracy and poverty for many of the country’s residents. In response to the poverty and food scarcity, the Portuguese government implemented the “Cod Campaigns,” which were a series of laws that protected Portuguese fisheries and associated industries like the drying industry, and also controlled the price of bacalhau (Almeida, 2014). This caused bacalhau intake to triple during this time period (Almeida, 2014). Portuguese fisheries also grew, and during this time the bacalhau fishing fleet increased from 51 to 65 boats (Almeida, 2014). When Portugal transitioned into democracy and joined the European Union (EU), EU fishing regulations led to a significant decrease and the eventual termination of Portuguese codfish fishing in the Northern Atlantic (Madsen & Chkoniya, 2019). However, bacalhau had developed deep roots in Portuguese cooking habits and culture, so the country turned towards outside sources to import the beloved fish.

Although historically cod imports have come from Canadian regions, today most of Portuguese cod imports come from Norway (49%), Denmark (27%), and Iceland (19%) (Madsen & Chkoniya, 2019). Norway, in particular, is a major player in the global codfish trade, responsible for the capture of approximately 326,989 tonnes in 2020, approximately one third of the annual global catch of Atlantic cod (European Market Observatory for Fisheries and Aquaculture Products, 2018; FAO, 2020). Some of the cod that is caught is dried and salted in Norway, while some is transported to Portugal and other countries in a frozen or semi-processed state. 66% of dried and salted cod that is processed in Norway is imported to Portugal (European Market Observatory for Fisheries and Aquaculture Products, 2018). Although Portugal is responsible for the majority of Norwegian exports, these exports still make up a small portion (36%) of dried and salted cod in Portugal (European Market Observatory for Fisheries and Aquaculture Products, 2018). A significant 64% of dried and salted cod in Portugal is processed locally in Portugal from frozen cod and semi-processed cod imports (European Market Observatory for Fisheries and Aquaculture Products, 2018). Today, bacalhau is still hugely significant in Portuguese cuisine. Portugal, along with Greenland, is tied for the greatest annual fish consumption, and approximately 40% of this fish consumption is bacalhau (Oliveira et al., 2016). In fact, a 2013 survey conducted about Portuguese seafood preferences found that 62.6% of respondents consumed bacalhau at least once a week (Cardoso et al., 2013).

Given the huge scale of bacalhau consumption in Portugal, it is important to consider its environmental impacts, particularly given the presumed environmental toll of transporting the fish all the way from the Northern European countries to Portugal. A life cycle assessment conducted by Parker and Tyedmers found that the majority of life cycle greenhouse gas emissions in the fishing industry come from the fuel of fishing vessels, suggesting that fuel can be a good indicator for the carbon footprint of unprocessed fish (Parker & Tyedmers, 2015). Another significant contributor to greenhouse gas emissions
is cooling agent leakage, which was found to represent about 13% of total fishery greenhouse gas emissions (Iribarren et al., 2011). These studies suggest that the capture and transport of bacalhau could result in greenhouse gas emissions that contribute to climate change.

LCAs about the fishing and production of cod have also been conducted in the past. One assessment found that the fishing phase of cod production was responsible for the greatest environmental impact, noting that the effects of trawling on the seafloor were substantial, and not fully explored (Ellingsen & Aanondsen, 2006). Another source echoed this finding, identifying the fishing stage of cod production to have the greatest environmental impact, with fuel consumption and refrigerant leakage being responsible for most of this environmental impact (Svanes et al., 2011). A third assessment highlighted how the use of copper as a biocide applied to the hull of the fishing vessel can threaten the ecosystem due to its ecotoxicity (Ziegler et al., 2003). While these studies have conducted LCAs of cod from fishery to table, these studies do not specifically focus on the life cycle of bacalhau in Portugal, integrating the cultural significance of bacalhau with the environmental impact. The present study will fill this niche, integrating bacalhau as a cultural phenomenon in Portugal with the environmental effects of its production and consumption, quantified through a LCA methodology.

5. Methods

5.1 Life Cycle Assessment

To study the environmental effects of bacalhau production, this study employs a life cycle assessment (LCA) methodology. An LCA is an international standardized methodology, based on ISO 14044, (Technical Committee ISO/TC 207, 2006). The tool is frequently used when studying food and food systems to assess lifetime environmental impacts. The framework is useful in its ability to aggregate and quantify otherwise invisible and unassociated environmental effects of food production and communicate quantitative results to retailers and consumers. It is an ISO standardized framework with four major steps: 1) goal and scope definition; 2) inventory analysis; 3) impact assessment and; 4) interpretation.

In Phase 1, researchers identify a functional unit (FU) which refers to the quantity of product that is studied. All data that is collected in later phases is quantified according to this functional unit. In Phase 1, researchers also identify what is included and excluded within the system they study. In Phase 2, researchers collect data on inputs and outputs of matter and energy throughout the process. This information is integrated into a Life Cycle Inventory (LCI). In Phase 3, researchers aggregate data, either using software or manually through excel and extensive research. In Phase 4, researchers interpret the data and present the results (Muralikrishna & Manickam, 2017). (Figure 1).
5.1.1 Goal and Scope Definition

The goal of the present study is to assess the environmental impacts of the production of bacalhau using a life cycle approach. The scope of this study traces the journey of bacalhau from capture to the day it arrives at the grocery store. This approach is called a “cradle to gate” approach because it traces the product from its “cradle” (the moment the resources are extracted) to the “gate” (the moment it enters the store).

5.1.2 System boundaries

This study begins with the materials used in bacalhau fishing operations. The bacalhau is traced from its capture, to transport, to curing, and to transit, and ultimately to the grocery store.. Due to the low significance in the system evaluated, cod farming, which is a technique that is sometimes used for capturing cod, is excluded. Capital goods, retail, consumption and waste production and ecosystem effects from trawling and other fishing techniques are also not considered. (Figure 2).

5.1.3 Functional unit

The functional unit defined for this study is 1 kilogram of bacalhau.

5.2 System Description

The production of bacalhau can follow a number of pathways. In Portugal, the majority of imports come from Norway, Denmark, and Iceland (Madsen & Chkoniya, 2019). Because Norway is responsible for the largest proportion of imports, the study will focus pathways of bacalhau production from its capture in Norway to its retail in Portugal. In Norway, there are a number of techniques to catch cod. Approximately 31% of Norwegian cod is caught using gillnets, 29% uses bottom trawling, 17% uses Danish seine, 13% uses other coastal fishing methods, and 9% uses long line techniques (Hognes et al., 2012).

When the fish arrive onshore, they can be transported to a Norwegian processing facility for a variety of processing techniques, including pickling, wet salting, or dry-salting. They can also be transported directly to Portuguese factories for Portuguese processing techniques. Because this study endeavors to focus on bacalhau in the context of Portuguese culture and tradition, this study traces the bacalhau that is directly transported to Portugal in a frozen state.

1 Gillnets: a technique in which a wall of netting that hangs underwater, with mesh sizes designed for fish of certain sizes to become entangled in the netting
2 Bottom trawling: a fishing technique in which weighted nets are dragged across the sea floor to catch bottom-dwelling fish
3 Danish seine: a technique in which a large conical net that is dragged behind a boat to catch fish
4 Long lines: a technique that uses long fishing lines with baited fish hooks attached at various intervals
To ascertain the specific data used in this study, this LCA is refined to the processing that frozen cod undergoes at a specific site. In this case, the study is narrowed to Riberalves. Riberalves is one of the largest cod processing companies, processing over 30,000 tonnes of codfish a year, approximately 8% to 10% of codfish that is caught in a given year (Riberalves, 2022).

To quantify traveling distances, this study zooms in on a processing facility in Norway, a processing facility in Portugal, and a grocery store in Lisbon as a sample route that bacalhau can take. The major cod processing companies are typically located near Ålesund, Norway (European Market Observatory for Fisheries and Aquaculture Products, 2018). A company called Lerøy Havfisk AS was identified as a sample starting point for the journey of the frozen cod. Lerøy Havfisk AS is a Norwegian fishing and processing company, with the largest trawling fleet in Norway with 10 vessels (Lerøy Havfisk, 2021). An industrial unit in Moita, Portugal owned by Riberalves was identified as a sample processing site. The factory in Moita is the largest bacalhau factory in the world, which is located just South of Lisbon in Moita (Caetano, 2019). This study will use a local store, Pingo Doce Tomás Ribeiro as a sample retail site. Land transport distances between the locations were calculated using Google Maps. The addresses for each site are listed below. (Table 1).

<table>
<thead>
<tr>
<th>Subsystem #2</th>
<th>Subsystem #3</th>
<th>Subsystem #4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ålesund, Norway:</td>
<td>Moita, Portugal:</td>
<td>Lisbon, Portugal:</td>
</tr>
<tr>
<td>Lerøy Havfisk AS</td>
<td>Riberalves Industrial Unit</td>
<td>Pingo Doce Tomás Ribeiro</td>
</tr>
<tr>
<td>Keiser Wilhelms g. 23, 6003 Ålesund, Norway</td>
<td>Estrada dos Fundilhões Rua da Cidla - Gaio - Rosário 2860-630 Moita</td>
<td>Pingo Doce Tomás Ribeiro, R. Tomás Ribeiro 97, 1050-227 Lisboa</td>
</tr>
</tbody>
</table>

Table 1: Addresses for Selected Sites
Data was collected from a variety of sources, including other LCAs, government data, peer-reviewed articles, and graduate theses and dissertations. The flow chart of the journey undertaken by bacalhau, from its capture to the moment it arrives in the grocery store is displayed in the flowchart above. (Figure 3). To break down this complicated timeline, the bacalhau life cycle is broken into four subsystems. (Figure 4).

1) Capture and pre-processing
2) Transport: Norway to Portugal
3) Curing
4) Transport: processing facility to grocery store

5.3 Subsystems
5.3.1 Subsystem 1: Catch & Preprocessing

Capture

The first subsystem of bacalhau processing is capture and pre-processing. Bacalhau is typically captured aboard a vessel in the Norwegian Sea, Spitzberg, Bear Island, or the Barents Sea (Pascoal, 2018). Some of the major environmental effects of the capture phase stem from diesel emissions from the ship. A study of Norwegian fishing fleets estimated Norwegian cod fishing fleets to consume an average of .24L of diesel per kilogram of landed cod (Hognes et al., 2012). Emissions from this diesel combustion
were estimated from a LCA based on Swedish cod fisheries in the Baltic, which broke down emissions of HC, NO\textsubscript{x}, SO\textsubscript{x}, CO\textsubscript{2}, and CO from Swedish cod fishing (Ziegler et al., 2003). (Table 2).

Anti-fouling paint is another environmental threat associated with industrial fishing. Anti-fouling paints are paints that are applied to a ship's hull to prevent marine life from attaching to the body of the boat. Historically, a hazardous chemical based on tributyltin (TBT) was used for this, but copper has come to replace TBT as a less-toxic alternative (Carić et al., 2016). Although copper is less hazardous, it has been shown to influence ecosystems by inhibiting biological and reproductive processes (Guardiola et al., 2012). Data on anti-fouling paint usage and emissions was ascertained from a study of Swedish cod fisheries, which estimated that approximately 0.5 ml of anti-fouling paint is used per kilogram of landed cod through a study of 30 Swedish fishermen (Ziegler et al., 2003). Data on anti-fouling paint emissions was difficult to find. However, it estimated that 0.02 g copper, which is one of the most dangerous components of anti-fouling paint, was emitted per 200 g of cod, which translates to 0.1 g of copper emitted per FU (Ellingsen & Aanondsen, 2006).

Bycatch is another type of waste associated with fishing practices which refers to the unintended capture of non-target marine animals. Rates of bycatch depend heavily on the fishing technique, with trawling producing significantly less bycatch than Danish seine fishing (Alverson et al., 1994). A study of Swedish cod fisheries estimated that on average, 1.5% of the codfish haul is bycatch (Ziegler et al., 2003). (Table 2).

**Beheading, Gutting, and Bleeding**

After the fish are captured, they are typically beheaded, bled, and gutted aboard the ship (Oliveira et al., 2016). Weight estimations for the mass of fish heads, blood, and guts were estimated using official conversion ratios to calculate the mass of the live catch from the mass of the beheaded and gutted landed fish (CWP, 2022; EU IUU Fishing Coalition, 2021).

**Freezing**

After the fish are beheaded, they are chilled or frozen aboard the vessel. Typically, the cod is frozen into blocks of 25 kg and stored at approximately -30°C onboard the vessel (Aas et al., 2010). A variety of refrigerants are used to keep the product cool. The most commonly used refrigerants on Norwegian fishing vessels are R22, ammonia, and CO\textsubscript{2} (Hognes et al., 2012). Of these three refrigerants, R22 is the chemical with the most significant global warming potential and ozone depletion potential (Hognes et al., 2012). Although R22 is being phased out of newer vessels, as of 2016, 70% of the global fishing fleet still uses R22 as their primary refrigerant (Semaev, 2021). Within the Norwegian fleet of demersal fishing vessels, it has been estimated that .224 grams of R22 are emitted per kg of cod that is caught (Hognes et al., 2012). Demersal fishing vessels target bottom feeding fish, so this estimation is not specific to cod fishing, but can be used to estimate cod R22 emissions.

To estimate the energy that is used to chill and freeze fish aboard fishing vessels, the same study estimated that an average of 133 Kwh of energy are consumed per tonne of fish frozen, which translates to .133 Kwh per kg of frozen fish (Hognes et al., 2012). From contact with processing companies, they estimated that frozen fish was typically stored for approximately 90 days before transport (Hognes et al., 2012). Because frozen storage is estimated to consume 2.6 KJ/kg*day, fish freezing is estimated to consume 234 KJ per kilogram of cod (Thrane, 2004). (Table 2).
### Table 2: Subsystem #1 Inventory

<table>
<thead>
<tr>
<th>Input/Output</th>
<th>Quantity (per FU)</th>
<th>Stage</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input: Material</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anti-fouling paint</td>
<td>0.5 ml</td>
<td>Capture</td>
<td>(Ziegler et al., 2003)</td>
</tr>
<tr>
<td><strong>Input: Energy</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel (for shipping vessel)</td>
<td>0.24 L</td>
<td>Capture</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td>Freezing energy</td>
<td>0.133 kWh</td>
<td>Freezing</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td>Frozen Storage</td>
<td>234 KJ</td>
<td>Freezing</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td><strong>Output: Material</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bycatch</td>
<td>0.015 kg</td>
<td>Capture</td>
<td>(Ziegler et al., 2003)</td>
</tr>
<tr>
<td>R22 (refrigerant)</td>
<td>0.224 g</td>
<td>Freezing</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td>Fish Blood</td>
<td>0.59–1.89 kg</td>
<td>Heading, Gutting, Bleeding</td>
<td>(EU IUU Fishing Coalition, 2021)</td>
</tr>
<tr>
<td>Fish Head and Guts</td>
<td>0.4083 kg</td>
<td>Heading, Gutting, Bleeding</td>
<td>(CWP, 2022)</td>
</tr>
<tr>
<td><strong>Output: Emissions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ship Emissions (HC)</td>
<td>1.92 g</td>
<td>Capture</td>
<td>(Ziegler et al., 2003)</td>
</tr>
<tr>
<td>Ship Emissions (NO(_x))</td>
<td>55 g</td>
<td>Capture</td>
<td>(Ziegler et al., 2003)</td>
</tr>
<tr>
<td>Ship Emissions (SO(_x))</td>
<td>3.11 g</td>
<td>Capture</td>
<td>(Ziegler et al., 2003)</td>
</tr>
<tr>
<td>Ship Emissions (CO(_2))</td>
<td>0.53 g</td>
<td>Capture</td>
<td>(Ziegler et al., 2003)</td>
</tr>
<tr>
<td>Ship Emissions (CO)</td>
<td>2433 g</td>
<td>Capture</td>
<td>(Ziegler et al., 2003)</td>
</tr>
<tr>
<td>Anti-fouling paint emissions (Cu)</td>
<td>0.1 g</td>
<td>Capture</td>
<td>(Ellingsen &amp; Aanonsen, 2006)</td>
</tr>
</tbody>
</table>

#### 5.3.2 Subsystem 2: Transit

Frozen cod is typically transported from Norway to Portugal in a 40 ft lorry, which contains approximately 22.5 tonnes of cod (European Market Observatory for Fisheries and Aquaculture Products, 2018). The most commonly used trucks for transport are a Volvo FH and Scania R500 (Hognes et al., 2012). To calculate inputs and outputs associated per FU of cod, inputs and outputs were first estimated per journey, then divided by 22,500 kg of cod per journey to estimate the FU. The distance from the fishery Lerøy Havfisk AS to the industrial unit in Moita by road is approximately 4000 km. (Appendix B). Though Google Maps estimates the journey to take 42 hours, a Norwegian study found that transportation by road typically takes approximately 5-6 days overall (European Market Observatory for Fisheries and Aquaculture Products, 2018).

**Diesel Consumption and Emissions**

A study of Norwegian cod production estimated diesel consumption for refrigeration to be around .32 L/km on flat European terrain (Hognes et al., 2012). For a 4000 km journey, this translates to approximately 1280 L consumed per journey. Diesel engines produce 2.7 kg of CO\(_2\) per liter of diesel fuel (Natural Resources Canada, 2014). If one journey consumes approximately 1364-1448 L to complete, one journey emits 3682 to 3909 kg of CO\(_2\). (Table 3).
Refrigeration During Transport

The energy used to freeze the cod during transport is derived from the diesel fuel used to power the lorry. Diesel consumption for refrigeration is approximately 2-4 L/h, depending on the load and distance (Hognes et al., 2012). This means 84-168 L of diesel are consumed by the cooling system for a 42 hour journey. Trucks also use refrigerants to keep products cool. The main refrigerants used in Norwegian lorries are R134a and R404a (Hognes et al., 2012). Approximately 6.5 kg of refrigerant is used per truck, 5-10% (or 0.325 kg to 0.65kg) of which is estimated to leak over the course of the journey (Hognes et al., 2012). (Table 3).

Packaging

Frozen fish are typically transported in cardboard boxes, with approximately 25 kg of fish in each box (Hognes et al., 2012). Because one cardboard box weighs approximately 2.0kg, 0.1kg is used per one kilogram of frozen cod (Hognes et al., 2012). (Table 3).

Table 3: Subsystem #2 Inventory

<table>
<thead>
<tr>
<th>Input/Output</th>
<th>Quantity (per kg)</th>
<th>Quantity (per journey)</th>
<th>Stage</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input: Material</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refrigerants: R134a and R404a</td>
<td>0.29 g</td>
<td>6.5 kg</td>
<td>Cooling</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td>Recycled Cardboard</td>
<td>0.1 kg</td>
<td>n/a</td>
<td>Packaging</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td><strong>Input: Energy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel (Lorry)</td>
<td>0.06 L</td>
<td>1280 L</td>
<td>Transport</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td>Diesel (Freezing)</td>
<td>0.004 L - 0.007 L</td>
<td>84 L -168 L</td>
<td>Freezing</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td><strong>Output: Material</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refrigerant leakage: R134a and R404a</td>
<td>0.014 g - 0.028 g</td>
<td>0.325 kg - 0.65 kg</td>
<td>Freezing</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td>Recycled Cardboard</td>
<td>0.1 kg</td>
<td>n/a</td>
<td>Packaging</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td><strong>Output: Emissions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel Emissions: CO₂</td>
<td>0.1636 kg - 0.1737 kg</td>
<td>3682 kg - 3909 kg</td>
<td>Transport</td>
<td>(Natural Resources Canada, 2014).</td>
</tr>
</tbody>
</table>

5.3.3 Subsystem 3: Curing

Thawing

When the frozen fish arrives at the processing factory in Portugal, it needs to be dethawed. The fish are typically dethawed in a thawing tank of chilled running water for a period of 12-20 hours, depending on the size of the fish (Paula Sofia, 2013). For lack of data on cod processing specifically, this study uses an estimation based on generic fish processing of 10 tonnes of water for every 25 tonnes of fish, or 0.4kg water for every kilogram of cod (Business Bliss Consultants FZE, 2018). (Table 5).

Butchering

After the fish is dethawed, it is butchered. The fish are scaled using an automatic mechanical skinner (Santos, 2017). An estimation from Norwegian whitefish processing plants estimates 661 kWh consumed per tonne product in a mechanical skinner (Hognes et al., 2012). After the fish is scaled, it is cut longitudinally down the center and the anterior two thirds of the vertebral column is removed (Piteira,
Data on fish byproducts that are wasted when butchering the fish was calculated using a UN document for converting product weight for fish to live weight (CWP, 2022).

**Washing**

After the fish is scaled, it must be washed to remove any remaining mucus and fish viscera. At Riberalves, there are two primary washing processes. In one process, the fish are placed onto a ramp which leads to a mat covered with a 20 cm layer of running water, under which the fish are immersed for a 10 second period. In the other process, the bacalhau passes through a tunnel filled with sprinklers for 5 seconds, then transitions onto a dry mat to remove some of the moisture (Piteira, 2017). Due to an inability to access company specific data related to these washing techniques, data on typical amounts of water consumed in the washing process was taken from a study of generic fish processing used for the life cycle inventory. One source estimates that the washing process requires 30 tonnes of water for every 19.75 tonnes of fish (Business Bliss Consultants FZE, 2018).

**Salting**

After being cleaned, the fish are typically salted. The fish are salted in big vats, stacked in overlapping layers of fish and salt. During this primary salting step, approximately 0.33 kg of salt is used per FU (Oliveira et al., 2016). The cod is stored in these vats for 7 days, during which the fish are immersed in the brine formed by the salt and water released from the fish tissue (Piteira, 2017). After this period of immersion, the fish are transferred to a pallet, where the brine is allowed to drain away continuously (Oliveira et al., 2016). This maturation period typically lasts approximately 8 months at Riberalves processing units (Piteira, 2017). After this, the fish are washed for a second time (Piteira, 2017). At this stage, the fish are referred to as green salted cod. Then, more salt is added, and the fish mature in refrigerated chambers at a temperature of 4°C for about 8 more months (Piteira, 2017). Different sources estimate different total amounts of fish throughout the entire process. A study of a Norwegian dry-salting technique estimates that approximately 1.5 kg of salt is used throughout the entire salting process (Hognes et al., 2012). Another study estimates that approximately 0.4 - 0.45 kg of salt are used per kilogram of cod (Santos, 2017). A third source estimates that approximately 1 kg of salt is used per kilogram of fish (Caetano, 2019). To estimate the total amount of salt used in the life cycle inventory, these three values were averaged for an estimate of 0.975 kg of salt per kg of cod. Because the fish salting step uses approximately 0.33 kg of salt, it can be estimated that the second salting step uses approximately 0.645 kg of salt per FU. (Table 5).

**Drying**

The machine used for drying at Riberalves is a York Systems evaporator, complete with an air circulation system, humidity sensors and heating and cooling system (Piteira, 2017). At Riberalves, drying can last from 36 to 100 hours, between 18°C and 24°C (Piteira, 2017). A study of Norwegian processing of dried salted fish calculated energy estimates for drying technology. The study identified two main technologies that were used to dry the salted cod, one using 0.164 kWh per kg and one consuming 0.265 kWh per kg (Hognes et al., 2012). For the purposes of this study, energy values were averaged to estimate drying energy per FU. (Table 5).

During this period, the salt content of the fish increases significantly while the water content decreases. (Table 4). These values were used to calculate outputs of the salting and drying stages, including leftover salt and water leached from the fish.
Table 4: Salt and Water Content of Bacalhau at Different Stages

<table>
<thead>
<tr>
<th>Material</th>
<th>Fresh</th>
<th>Salted</th>
<th>Dried and Salted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content (%)</td>
<td>82&lt;sup&gt;1&lt;/sup&gt;</td>
<td>60&lt;sup&gt;1&lt;/sup&gt;</td>
<td>50&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Salt content (%)</td>
<td>0.2 – 0.5&lt;sup&gt;2&lt;/sup&gt;</td>
<td>15 – 21&lt;sup&gt;2&lt;/sup&gt;</td>
<td>14.6 - 20.4&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>1</sup>(Oliveira et al., 2012)  <sup>2</sup>(Aas et al., 2010)  <sup>3</sup>(Oliveira et al., 2016)

**Sizing**

After the bacalhau is dried, the product is sized using industrial and automatic scales. The scales that are used at Riberalves are: Bilencial EV7-S and the Ruby RB60 (Piteira, 2017).

Table 5: Subsystem #3 Inventory

<table>
<thead>
<tr>
<th>Input/Output</th>
<th>Quantity</th>
<th>Stage</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input: Material</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chilled Running Water</td>
<td>0.4 kg</td>
<td>Thawing</td>
<td>(Business Bliss Consultants FZE, 2018)</td>
</tr>
<tr>
<td>Water</td>
<td>1.52 kg</td>
<td>Washing</td>
<td>(Business Bliss Consultants FZE, 2018)</td>
</tr>
<tr>
<td>Sea Salt (1st Salting)</td>
<td>0.33 kg</td>
<td>Salting</td>
<td>(Oliveira et al., 2016)</td>
</tr>
<tr>
<td>Sea Salt (2nd Salting)</td>
<td>0.645 kg</td>
<td>Salting</td>
<td>(Caetano, 2019; Hognes et al., 2012; Santos, 2017.)</td>
</tr>
<tr>
<td><strong>Input: Energy</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automatic Mechanical Skinner</td>
<td>0.661 kWh</td>
<td>Butchering</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td>Drying Tunnel</td>
<td>0.215 kWh</td>
<td>Drying</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td><strong>Output: Material</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wastewater</td>
<td>0.4 kg</td>
<td>Thawing</td>
<td>(Business Bliss Consultants FZE, 2018)</td>
</tr>
<tr>
<td>Fish byproducts</td>
<td>0.28 kg</td>
<td>Butchering</td>
<td>(CWP, 2022)</td>
</tr>
<tr>
<td>Wastewater</td>
<td>1.52 kg</td>
<td>Washing</td>
<td>(Business Bliss Consultants FZE, 2018)</td>
</tr>
<tr>
<td>Salt</td>
<td>0.78 kg</td>
<td>Salting + Drying</td>
<td>(Aas et al., 2010; Oliveira et al., 2016)</td>
</tr>
<tr>
<td>Water (from cod)</td>
<td>0.3 kg</td>
<td>Salting + Drying</td>
<td>(Oliveira et al., 2012)</td>
</tr>
</tbody>
</table>

5.3.4 Subsystem 4: Transit

For the final stage of the journey of bacalhau, the dried and salted product is transported from the processing facility to the grocery store, where it is resold to consumers. Of course, the product is transported to a variety of locations, but this study focuses on Pingo Doce Tomás Ribeiro as a sample retail location in Lisbon. The journey from the industrial unit in Moita to Pingo Doce Tomás Ribeiro in Lisbon is 43 minutes and 43.2 km. The Google Maps estimate for time and distance is displayed in the appendix. (Appendix C).

Information on refrigerants, diesel consumption, and diesel emissions for this subsystem were readjusted from the values ascertained in Subsystem #2 to the scale of the 43.2km journey. (Table 6).

Bacalhau is generally sold in grocery stores without packaging. However, as with Subsystem #2, they are typically packaged in cardboard boxes for transport with approximately 25 kg of fish in each box (Hognes et al., 2012).
Table 6: Subsystem #4 Inventory

<table>
<thead>
<tr>
<th>Input/Output</th>
<th>Quantity (per kg)</th>
<th>Quantity (per journey)</th>
<th>Stage</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input: Material</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refrigerants: R134a and R404a</td>
<td>0.29 g</td>
<td>6.5 kg</td>
<td>Cooling</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td>Recycled Cardboard</td>
<td>0.1kg</td>
<td>n/a</td>
<td>Packaging</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td><strong>Input: Energy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel (Lorry)</td>
<td>0.0006 L</td>
<td>13.76 L</td>
<td>Transport</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td>Diesel (Cooling)</td>
<td>0.00006 - 0.00012 L</td>
<td>1.43L - 2.87L</td>
<td>Cooling</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td><strong>Output: Material</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refrigerants: R134a and R404a</td>
<td>0.014g - 0.029 g</td>
<td>0.325kg - 0.65kg</td>
<td>Cooling</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td>Recycled Cardboard</td>
<td>0.1kg</td>
<td>n/a</td>
<td>Packaging</td>
<td>(Hognes et al., 2012)</td>
</tr>
<tr>
<td><strong>Output: Emissions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel Emissions: CO₂</td>
<td>0.001651 kg</td>
<td>37.15 kg</td>
<td>Transport</td>
<td>(Natural Resources Canada, 2014)</td>
</tr>
</tbody>
</table>

5.4 Modeling
5.4.1 SimaPro Approach

SimaPro is a software that is typically used for LCA. Despite this in-depth life cycle inventory displayed above, it is out of the scope of this four week project to incorporate this data into SimaPro due to time restraints with learning how to put custom values and processes into the SimaPro software. Thus, a different approach was used to estimate effects in SimaPro. To scale the LCA to the scope of this time frame, this study uses generic processes that are already stored within the SimaPro software to estimate the impacts of bacalhau processing. SimaPro is integrated with a database called Ecoinvent, which contains detailed information on energy and matter inputs and outputs for a variety of processes.

To estimate Subsystem #1, two processes related to the capture of hake (a fish closely related to cod) were selected and input into SimaPro. Because Ecoinvent did not have data specific to cod, this study decided to use landed hake as a proxy for cod. Hake was selected because they are in the same taxonomic order as cod: Merlucciidæ, and like cod they are native to colder waters in the Atlantic and Pacific oceans. The first process is entitled “hake, capture by trawler and landing whole, fresh.” This system describes the inputs and outputs associated with hake fishing using bottom trawling. The boundaries of this system include vessel construction, vessel maintenance, consumption of diesel and lubricants, and direct emissions to the water. Any processing after the ship reaches the port is excluded from this system. To supplement this process, a process entitled “hake, captured by long liner and landing whole, fresh” was also selected. This system describes the inputs and outputs associated with hake fishing using long-lining. Although Norwegian cod-fishing fleets use other fishing techniques, including gillnets and Danish seine, bottom trawling and long-lines were the two fishing techniques that were available in the SimaPro software for hake. The two fish were weighted according to their relative use in Norwegian fishing fleets. Because bottom trawling is 3.22 times as prevalent as longline fishing, bottom trawling was estimated to represent about 76% of the mass of landed fish, while long-lining was estimated to represent approximately 24% of one FU of bacalhau. (Table 7).

To represent Subsystem #2, two processes were selected: “market for transport, freight, lorry 16-32 metric ton” and “operation, reefer, freezing, 40-foot, high-cube, R134a as refrigerant.” The first process describes the inputs and outputs associated with transport in a lorry. Because fish are typically transported in a 22.5 tonne lorry, it was appropriate to select the 16-32 metric tonne lorry. The units used
in this process are tonne*km. To estimate this journey, one FU (which is 1/1000 tonnes) is multiplied by 4000 km for a total of 4 tonnes*km. (Table 7). The other process included in Subsystem #2 pertains to the freezing of a 40 foot reefer (refrigerated truck trailer). R134a was selected as a refrigerant over CO2 because most Norwegian trucks have not transitioned to the more environmentally-friendly CO2-based refrigerants. The units for this process are kg*day. Because this 4000 km journey typically takes 5-6 days to complete, the amount was calculated based on an average 5.5 day journey for a value of 5.5 kg*day. (Table 7).

To estimate Subsystem #3, a process entitled “fish curing, small fish” was selected. Although cod is a larger species of fish, this process was selected because the processing steps listed closely resemble the processing steps that are outlined in the life cycle inventory section of this study, and no processes pertaining to large fish were available. This process includes infrastructure construction and maintenance, seafood processing, and direct emissions into the water. The processing step includes heading and gutting, washing/bleeding, salting, pressing, maturation, cleansing, centrifugation, filing, packing, sealing, and storage. (Appendix D). Because these steps resemble the steps taken in bacalhau processing, this system was deemed the most appropriate.

To estimate Subsystem #4 a system entitled market for transport, freight, lorry with refrigeration machine, cooling was selected. This process was selected because at this stage in the life cycle, the cod does not need to be frozen but cooled, and less information is available about the types of trucks used to transport the bacalhau for this leg of the journey. Thus, a more generic system for lorry transport with a refrigeration unit was selected. The units for this process are metric tonne*km, so to transport 1/1000 tonnes for 43.2 km, a value of 0.0432 metric tonnes*km were input into SimaPro. (Table 7).

Table 7: SimaPro Input Values [Ecoinvent 3]

<table>
<thead>
<tr>
<th>Process</th>
<th>Amount</th>
<th>Unit</th>
<th>Calculations</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>hake, capture by long liner and landing whole, fresh</td>
<td>0.23684</td>
<td>kg</td>
<td>1kg * 0.09/ (0.09 + 0.29)</td>
<td>Europe: Spain</td>
</tr>
<tr>
<td>hake, capture by trawler and landing whole, fresh</td>
<td>0.76315</td>
<td>kg</td>
<td>1kg * 0.29/ (0.09 + 0.29)</td>
<td>Europe: Spain</td>
</tr>
<tr>
<td>market for transport, freight, lorry 16-32 metric ton, EURO3</td>
<td>4</td>
<td>tonne*km</td>
<td>1 tonne /1000 kg * 4000 km</td>
<td>Europe</td>
</tr>
<tr>
<td>operation, reefer, freezing, 40-foot, high-cube, R134a as refrigerant</td>
<td>5.5</td>
<td>kg*day</td>
<td>1 kg * 5.5 days</td>
<td>Global</td>
</tr>
<tr>
<td>fish curing, small fish</td>
<td>1</td>
<td>kg</td>
<td>n/a</td>
<td>Global</td>
</tr>
<tr>
<td>market for transport, freight, lorry with refrigeration machine, cooling</td>
<td>0.0432</td>
<td>tonne*km</td>
<td>1 tonne /1000 kg * 43.2 km</td>
<td>Global</td>
</tr>
</tbody>
</table>

5.4.2 Methodology

The ReCiPe 2016 method was used to determine the impacts of bacalhau production. The ReCiPe method is a LCA method that is well accepted in the scientific community. It was developed in 2008, by RIVM, Radboud University Nijmegen, Leiden University and PRé Sustainability, and updated in 2016 in collaboration with the Norwegian University of Science. The technique is used to transform the results of the life cycle inventory into a finite list of indicators. The scores for each of these indicators express the relative severity of the processes on each impact category.

There are two types of indicators that can be calculated using the ReCiPe method: midpoint indicators and endpoint indicators. There are 18 midpoint indicators, which express specific environmental categories like climate change or freshwater eutrophication. There are 3 endpoint
indicators, which are used to express the effect these midpoint categories have on the three damage categories: 1) Human health; 2) Ecosystems; 3) Resources Cost. The ReCiPe 2016 framework displays the transformation of information from the primary data to the 18 midpoint impact categories and eventually to the three endpoint categories. (Figure 5). Midpoint indicators are translated into the three endpoint indicators using damage pathways, like “increase in respiratory diseases” or “damage to freshwater species.”

6. Results

6.1 Impact Assessment: Environmental Impact Categories (Midpoint)

Using SimaPro, an analysis was conducted to evaluate the relative impact of each process involved in cod production on each of the 18 midpoint categories. Figure 6 displays the percent impact of each of the six processes relative to the other processes involved.

Figure 5: adapted from (Huijbregts et al., 2016)
6.1.2 Curing

Of all the processes included within the SimaPro analysis, curing was responsible for the greatest impact in the majority of impact categories in comparison to the other processes involved in cod production. In particular, curing was responsible for over 90% of impact in the half of the categories, including ionizing radiation (93.65%), freshwater eutrophication (99.55%), marine eutrophication (99.68%), freshwater ecotoxicity (94.43%), human carcinogenic toxicity (97.46%) human non-carcinogenic toxicity (92.39%), land use (99.45%), mineral resource scarcity (98.55%), and water consumption (99.08%). (Table 8). The curing process was responsible for over 99% of impact in the categories: freshwater eutrophication (producing 0.02 kg P eq) marine eutrophication (producing 0.00381 kg N eq), land use (occupying 8.8 m² a crop eq), and water consumption (consuming 0.243 m³). (Appendix D).

6.1.3 Capture: Long Liner

Capture using a long liner was responsible for the greatest relative impact in two impact categories: ozone formation (human health) and ozone formation (terrestrial ecosystems). Capture using long liner was responsible for 45.28% of ozone formation regarding human health and 44.87% of ozone
formation regarding terrestrial ecosystems relative to the other processes. (Table 8). This translates to the formation of 0.0253 kg NO$_x$ eq and 0.0254 kg NO$_x$ eq for human health and terrestrial ecosystems respectively. (Appendix E). Additionally, for the damage category of terrestrial acidification, capture by long liner and curing are within one percent of one another, suggesting capture via long liner was responsible for a significant portion of contributions to terrestrial acidification. In addition to the aforementioned impact categories, capture by long liner was responsible for more than 25% of stratospheric ozone depletion and fine particulate matter formation.

6.1.4 Capture: Trawler

Capture by trawler was responsible for the most significant proportion of damage for marine ecotoxicity, with values of approximately 29.95% relative to the other processes, or 0.331 kg 1,4-DCB (Table 8). (Appendix E). Aside from marine ecotoxicity, capture by trawler was responsible for over 10% of ozone formation (human health), ozone formation (terrestrial ecosystems), and terrestrial acidification.

6.1.5 Transport: Lorry (Subsystem #2)

Transport by lorry (Subsystem #2) had the greatest impact on terrestrial ecotoxicity, with 14.07% of the total impact. (Table 8). Aside from terrestrial ecotoxicity, transport by lorry was responsible for over 5% of global warming (6.13%), ozone formation (human health) (8.27%), ozone formation, (terrestrial ecosystems) (8.32%), and fossil resource scarcity (10.95%).

6.1.6 Other Processes

The processes entitled “transport: (Subsystem #4),” and “transport: reefer (Subsystem #2)” are responsible for the smallest proportion of environmental impacts, with less than 1% of impact in all categories. Transport by reefer (Subsystem #2) describes the process of freezing the product across its journey from Norway to Portugal. Out of all the endpoint categories, this process is responsible for the greatest impact in ozone formation (human health) and ozone formation (terrestrial ecosystems) at 0.75% of impact in both categories. Transport: (Subsystem #4) refers to the last step of the journey of bacalhau from the processing facility to the grocery store. Of all midpoint impact categories, this process is responsible for the greatest relative impact in fossil resource scarcity, at about 0.29%.

Table 8: Percent Impact on Midpoint Damage Categories

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>Capture: Trawler</th>
<th>Capture: Long Liner</th>
<th>Curing</th>
<th>Transport: (Subsystem #4)</th>
<th>Transport: Reefer (Subsystem #2)</th>
<th>Transport: Lorry (Subsystem #2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming (%)</td>
<td>3.31</td>
<td>14.08</td>
<td>76.03</td>
<td>0.19</td>
<td>0.27</td>
<td>6.13</td>
</tr>
<tr>
<td>Stratospheric ozone depletion (%)</td>
<td>0.49</td>
<td>40.12</td>
<td>57.98</td>
<td>0.05</td>
<td>0.14</td>
<td>1.23</td>
</tr>
<tr>
<td>Ionizing radiation (%)</td>
<td>0.71</td>
<td>2.35</td>
<td>93.65</td>
<td>0.07</td>
<td>0.09</td>
<td>3.14</td>
</tr>
<tr>
<td>Ozone formation, Human health (%)</td>
<td>13.85</td>
<td>45.28</td>
<td>31.68</td>
<td>0.16</td>
<td>0.75</td>
<td>8.27</td>
</tr>
<tr>
<td>Fine particulate matter formation (%)</td>
<td>8.99</td>
<td>29.44</td>
<td>57.28</td>
<td>0.09</td>
<td>0.41</td>
<td>3.8</td>
</tr>
<tr>
<td>Ozone formation, Terrestrial ecosystems (%)</td>
<td>13.74</td>
<td>44.87</td>
<td>32.15</td>
<td>0.16</td>
<td>0.75</td>
<td>8.32</td>
</tr>
<tr>
<td>Terrestrial acidification (%)</td>
<td>12.65</td>
<td>41.37</td>
<td>41.53</td>
<td>0.09</td>
<td>0.33</td>
<td>4.03</td>
</tr>
<tr>
<td>Freshwater eutrophication (%)</td>
<td>0.05</td>
<td>0.16</td>
<td>99.55</td>
<td>0.01</td>
<td>0.01</td>
<td>0.22</td>
</tr>
<tr>
<td>Marine eutrophication (%)</td>
<td>0.04</td>
<td>0.13</td>
<td>99.68</td>
<td>0.01</td>
<td>0.02</td>
<td>0.12</td>
</tr>
<tr>
<td>Impact Category</td>
<td>Capture: Trawler</td>
<td>Capture: Long Liner</td>
<td>Curing</td>
<td>Transport: Reefer (Subsystem #4)</td>
<td>Transport: Reefer (Subsystem #2)</td>
<td>Transport: Lorry (Subsystem #2)</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>------------------</td>
<td>---------------------</td>
<td>--------</td>
<td>----------------------------------</td>
<td>----------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity (%)</td>
<td>0.44</td>
<td>1.42</td>
<td>83.79</td>
<td>0.22</td>
<td>0.06</td>
<td>14.07</td>
</tr>
<tr>
<td>Freshwater ecotoxicity (%)</td>
<td>0.78</td>
<td>2.25</td>
<td>94.43</td>
<td>0.13</td>
<td>0.2</td>
<td>2.22</td>
</tr>
<tr>
<td>Marine ecotoxicity (%)</td>
<td>29.95</td>
<td>1.84</td>
<td>65.87</td>
<td>0.09</td>
<td>0.13</td>
<td>2.12</td>
</tr>
<tr>
<td>Human carcinogenic toxicity (%)</td>
<td>0.42</td>
<td>1.05</td>
<td>97.46</td>
<td>0.03</td>
<td>0.09</td>
<td>0.95</td>
</tr>
<tr>
<td>Human non-carcinogenic toxicity (%)</td>
<td>0.88</td>
<td>2.04</td>
<td>92.39</td>
<td>0.1</td>
<td>0.14</td>
<td>4.45</td>
</tr>
<tr>
<td>Land use (%)</td>
<td>0.03</td>
<td>0.1</td>
<td>99.45</td>
<td>0.01</td>
<td>0</td>
<td>0.4</td>
</tr>
<tr>
<td>Mineral resource scarcity (%)</td>
<td>0.23</td>
<td>0.68</td>
<td>98.55</td>
<td>0.02</td>
<td>0.03</td>
<td>0.49</td>
</tr>
<tr>
<td>Fossil resource scarcity (%)</td>
<td>5.38</td>
<td>17.68</td>
<td>65.28</td>
<td>0.29</td>
<td>0.42</td>
<td>10.95</td>
</tr>
<tr>
<td>Water consumption (%)</td>
<td>0.1</td>
<td>0.32</td>
<td>99.08</td>
<td>0.01</td>
<td>0.02</td>
<td>0.47</td>
</tr>
</tbody>
</table>

6.2 Impact Assessment: Damage Assessment Categories (Endpoint)

In addition to midpoint analysis, endpoint analysis was also conducted to synthesize the damage in each of the 18 impact categories into three primary categories: impact on resources, emissions, and human health. Figure 7 displays the percent impact of each of the six processes has on the three endpoint categories relative to the other processes involved.

![Figure 7: Relative Impact on Endpoint Damage Categories](image-url)
6.2.1 Overview

Figure 7 shows that over the course of the life cycle, curing is once again responsible for the greatest proportion of impacts by far to all three categories. Of the three, curing is responsible for the greatest percent of impact on ecosystems (85.94%), then human health (76.26%), and then resources (55.56%). (Figure 7). Second to curing, capture by longliners had the greatest relative impact in each category, at 22.89% for resources, 15.38% for human health, and 8.93% for ecosystems. (Table 8). Capture by trawler was also responsible for a significant portion of damage in each category, with 6.96% for resources, 4.53% for human health, and 2.56% for ecosystems. Transport by lorry (Subsystem #2) was responsible for a significant proportion of the resources endpoint category at 13.73% (Table 8).

<table>
<thead>
<tr>
<th></th>
<th>Capture: Trawler</th>
<th>Capture: Long liner</th>
<th>Curing</th>
<th>Transport (Subsystem #4)</th>
<th>Transport: Reefer (Subsystem #2)</th>
<th>Transport: Lorry (Subsystem #2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Health (%)</td>
<td>4.53</td>
<td>15.38</td>
<td>76.26</td>
<td>0.09</td>
<td>0.26</td>
<td>3.47</td>
</tr>
<tr>
<td>Ecosystems (%)</td>
<td>2.56</td>
<td>8.93</td>
<td>85.94</td>
<td>0.06</td>
<td>0.13</td>
<td>2.38</td>
</tr>
<tr>
<td>Resources (%)</td>
<td>6.96</td>
<td>22.89</td>
<td>55.56</td>
<td>0.35</td>
<td>0.51</td>
<td>13.73</td>
</tr>
</tbody>
</table>

6.2.2 Total Impact to Damage Categories

An examination of damage categories reveals that, in total, the production of 1 FU of bacalhau contributes 0.0000438 disability-adjusted life years (DALY) to the damage category of human health. One DALY represents the equivalent of the loss of one year of full health, so the production reduces a human lifespan by 0.0000438 years of perfect health. (Appendix F). In regards to ecosystems, the production of 1 FU results in a reduction of 0.000000147 species per year. (Appendix F). For scale, this is approximately equal to 15 species per kg per 100 million years. When it comes to resources, the production of 1 FU of bacalhau uses approximately 0.0996 USD. (Appendix F)

6.2.3 Long-liner vs Trawler Analysis

In the SimaPro analysis, capture by long-lining and by trawling were weighted to represent the proportion of landed cod by fishing technique. Trawling was weighted about 3.22 times greater than longlining to represent the actual ratio of the two fishing types in Norway. Despite being weighted about thrice the values included for longlining, the relative impact for longlining is greater than that of trawling for every endpoint category except ecotoxicity. (Figure 8). Long lining is also consistently more impactful than trawling in each endpoint category. (Appendix G). The broader implications regarding the sustainability of the two techniques will be discussed in the discussion section.

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5 DALY is a time-based unit that combines years of life lost due to premature mortality as well as years of life lived in a state of less than full health. Thus, one DALY represents the loss of one year of perfect health (World Health Organization, 2022).
7. Discussion

7.1 Critical Processes

The results from SimaPro reveal that curing is overwhelmingly responsible for the majority of environmental damage associated with the production and importation of bacalhau in Portugal. This means that targeting intervention techniques to reduce emissions at the curing stage of the process may be most effective. For example, improving the efficiency of the last step of transportation will not have an effect on the same scale as an intervention at the curing stage, because environmental hazards associated with the last subsystem of the production process are responsible for less than 1% of impact in all 18 damage categories. In particular, the curing process has huge effects on freshwater and marine eutrophication, land use, and water consumption.

In addition to the curing process, the fishing process is critical due to its large proportion of environmental effect in key environmental impact categories. In particular, fishing activities are responsible for a large proportion of ozone formation and depletion. Although long lining tends to have a greater effect on most midpoint and all endpoint damage categories, trawling is responsible for a significant proportion of marine ecotoxicity, so interventions to trawling may involve targeted techniques to reduce the ecotoxicity of the process.

Figure 8: Percent Impact of Trawler compared to Long Liner (Midpoint)
7.2 Improvements to Bacalhau Processing

7.2.1 Improvements to Subsystem #1

Subsystem #1 involves the capture of *bacalhau*. The comparative analysis of the two processes shows that long lining has a significantly greater impact in all midpoint damage categories except marine ecotoxicity. Because long lining is associated with greater impact to human health, ecosystems, and resources, a transition to trawling-based fishery activity may reduce the impacts associated with the capture stage of production. Although trawling is associated with significantly greater impacts in marine toxicity, its significantly smaller impact in other categories suggests it may be a more sustainable fishing technique. In order to reduce levels of ecotoxicity associated with trawling vessels, biocide-free paint can be adopted as an alternative to anti-fouling paints (Ytreberg et al., 2021).

The fishing stage of production is particularly associated with high rates of ozone production and stratospheric ozone depletion. Thus, an intervention to reduce ozone production from shipping vessels could significantly reduce the ozone formation and depletion associated with fishing. An LCA of a pelagic fishing fleet found that >92% of the contribution to all impact categories was associated with the fuel burned (Sandison et al., 2021). Thus, interventions should focus on reducing the amount of fuel burned by each ship, whether this means improving fuel efficiency, or reducing mileage traveled by ships.

7.2.2 Improvements to Subsystem #2

Subsystem #2, which consists of transit from Norwegian fisheries to Portuguese processing facilities, is not responsible for a large proportion of emissions in most midpoint and endpoint categories. That being said, this stage does have relatively large impacts on marine ecotoxicity, ozone formation and terrestrial acidification, global warming and fossil resource scarcity. The impacts specifically associated with ozone, global warming, and fossil resource scarcity are likely related to the combustion of diesel and subsequent emissions. Simple techniques to improve vehicle efficiency include reducing vehicle speed to reduce drag, keeping tires inflated, reducing AC usage, and reducing engine idling (Sheridan, 2019). However, these simple changes are unlikely to incur changes on a scale large enough to significantly impact vehicle emissions.

One way to cut down the emissions related to this stage of transport is to cut the distances traveled. The 4000 km journey from Norway to Portugal certainly amplifies the impacts of this stage of the process. Since Atlantic cod is not available in the warmer seas closer to Portugal, this intervention would likely mean significantly reducing the amount of *bacalhau* that is imported into Portugal. This would certainly be an effective way to reduce the footprint of Subsystem #2. That being said, *bacalhau* plays a major role in Portuguese cuisine and cultural identity. Cutting *bacalhau* importation would require a transformation of the consumption habits of hundreds of thousands of Portuguese people. A social mobilization on such a scale is not a feasible or efficient way to ascertain the intended environmental impacts. This is only amplified by the fact that this stage of processing is not responsible for the most significant portion of environmental impacts in any category. Thus, improvements to the materials used and technological efficiency in Subsystems #1 and #3 may be a more efficient way to improve the environmental footprint of *bacalhau* production.

7.2.3 Improvements to Subsystem #3

Subsystem #3 is responsible for the greatest portion of waste produced. Thus, it follows that curing techniques should be optimized to reduce unnecessary energy and material consumption through the processing of *bacalhau*. A 2013 study identified the following types of waste at a cod production company: overproduction, waiting time, transport and excessive movement, overprocessing (such as storage, reprocessing, and inspections), and excess stock (Paula Sofia, 2013). In particular, the author
found that disorganization throughout the factory resulted in repeating work that has already been done, for example relabeling batches when a product switches to another machine. This results in wasted material, labor, and time. Increasing the efficiency of production by redesigning and organizing processing done at the factory is recommended to reduce the energy and materials required throughout the processing stage and ultimately reduce the damage to the environment.

7.3 Limitations

This study has a number of limitations. One limitation of this study is related to the fluctuation in product weight over the life cycle of bacalhau. As bacalhau undergoes the processing steps outlined in the methods section, its weight fluctuates. This means the units collected in the life cycle inventory are associated with the relative weight of the bacalhau at that stage in the process. Therefore, values throughout the fishing stage may be associated with the weight of 1kg of landed cod, while values collected at the curing stage are relative to the reduced weight of the bacalhau at this stage in production. The inability to account for changes in product weight may skew results.

Another limitation is the inability to account for the ecosystem impacts of fishing techniques, particularly trawling. Although this assessment concluded that trawling is a more environmentally sustainable practice than long-lining, trawling is hugely damaging to the environment. Trawling can affect an area of 1711 m² of the sea floor per FU of cod (Guttormsdóttir, 2009). This practice can damage the animals and habitats that are towed over, particularly the sedimentary living organisms on the seafloor (Guttormsdóttir, 2009). Typically, marine ecologists study seafloor impacts by collecting small samples from the bottom of the sea (Sandison et al., 2021). Because the SimaPro software cannot account for all ecosystem effects of trawling practices, the impacts of trawling on the seafloor are not included within the environmental impacts, which may lead to an underestimation of environmental effect of the fishing stage, particularly for trawling. The SimaPro analysis did find that trawling had a much more significant impact when it comes to ecotoxicity. However, this study concluded that trawling was a more environmentally-friendly procedure because it had significantly smaller impact in all other midpoint impact categories. Given the difficulty in weighing these different midpoint impact categories, it may be untrue to conclude that trawling is more sustainable even though it performed better in the majority of indicator categories.

The study also has a variety of limitations associated with the application of the SimaPro software. Because the Ecoinvent dataset did not have any processes available related to the production of cod specifically, hake fishing and production processes were used as a proxy for cod, because hake and cod are of the same taxonomic order. This creates a limitation with the data, because it is not specifically related to the production of cod.

Another limitation related to the Ecoinvent dataset is the curing process. Although the curing process in the Ecoinvent dataset closely resembled the curing process of bacalhau, the processes did not align across a few key steps. Namely, typical Portuguese salting and drying processes require multiple stages of salting and drying, while the process in SimaPro only salts and dries the fish once. Additionally, the SimaPro process includes centrifuging, pressing, packing, and sealing, none of which are included in the Portuguese process that was researched in the life cycle inventory. This means the data ascertained from SimaPro does not actually represent the Portuguese curing process as this study had intended. Instead, the data is based on the related, but not identical curing process of small fish including anchovies, herrings, sardines, and mackerels, which are not closely related to bacalhau. This could overestimate the processing required to process 1 kg of cod, because, for example, processing 1kg of anchovies may require the descaling of 10 fish while processing 1kg of bacalhau only requires the descaling of 1 fish.

A third limitation of the process employed in SimaPro is that the processes were not specific to the Northern Atlantic ocean nor the Iberian Peninsula. The processes entitled, hake, capture by long liner
and landing whole, fresh, and hake, capture by trawler and landing whole, fresh and market for transport, freight, lorry 16-32 metric tonne were based in Europe, while the other processes were based on global averages. Because of the lack of regionally specific data, the results do not perfectly represent the local processing bacalhau undergoes in Norway and Portugal.

7.4 Recommendations for Future Research

There are a variety of directions future studies could take to supplement the work done in this study. This study provides a comprehensive inventory analysis, the data of which is ultimately not put into the SimaPro software to conduct the midpoint and endpoint analyses. Future studies could provide a more in-depth exploration of the pathways outlined in the methods section using the data collected in the life cycle inventory as a starting point. This would enable researchers to better evaluate the processing industry specific to Portugal, as this study originally set out to specifically study the impacts of Portuguese processing techniques.

As capture by trawling and long lining are weighted according to their relative prevalence in this study, there are limitations to the comparisons that can be drawn between the two techniques. Future studies could weight the fishing techniques equally in order to compare the environmental damage associated with each technique. Studies could include other commonly-utilized cod fishing techniques in Norway including gillnets and Danish seine. This could provide direction on more sustainable fishing techniques in order to advance the sustainability of fisheries in the long run.

Future studies could also compare the effects of producing 1 kg of bacalhau with the environmental effects of producing other types of fish. This is extremely useful because it provides context to the study. It is important to know not only what environmental effects are associated with the production of bacalhau, but how this compares to the sustainability of other species of fish. This knowledge would allow consumers to base decisions about fish consumption on the relative sustainability of the species. It could also provide a basis for policymakers to make decisions to promote the import and export of certain species using media-based techniques to appeal to consumers and cost-based techniques to influence the behavior of companies.

8. Conclusion

This study explores the environmental effects of bacalhau, fished by trawling and long lining in Norway, transported by lorry to Portugal, then dried, salted, and sold in Portuguese grocery stores. The results found that for bacalhau, the stage with the greatest effect in the majority of the impact categories was curing. Midpoint analyses revealed curing to be responsible for the majority of environmental impacts, although fishing by trawling and long lining were also responsible for significant impact, particularly regarding ozone formation and ozone depletion. Endpoint analysis also showed that curing had the greatest effect on all endpoint categories, with the greatest impact on the ecosystems endpoint category. This finding emphasizes the need to identify techniques to improve the sustainability of the curing process that bacalhau undergoes. Some improvement techniques include improving the efficiency of bacalhau processing facilities by reorganizing work flows and taking stock of unused capital, but further research is warranted to improve the sustainability of production using novel technologies and curing techniques. In the words of Joana Dionísio, “There’s nothing more Portuguese than bacalhau.” Thus, it is imperative to improve the sustainability of bacalhau production to support Portuguese consumption habits and maintain its role in national identity as we transition to a more sustainable world.

(United Nations Environment Programme, 2003)
(Huijbregts et al., 2016)
9. References


Almeida, C. P. (2014). *Seafood consumption in Portugal: Patterns, drivers and sustainability* [Ph.D., Universidade de Lisboa (Portugal)]. http://www.proquest.com/docview/2009336228/abstract/1AE84FD05A1642A0PQ/1


10. Appendix

A. Detailed Flow Chart of Bacalhau Production Process with Inputs and Outputs

INPUTS | PRODUCTION STEP | OUTPUTS
--- | --- | ---
anti-fouling paint, diesel | capture | bycatch, R22, ship emissions, anti-fouling paint emissions
heading, gutting, bleeding | freezing | fish blood, fish heads and guts
freezing energy, frozen storage |  |  

SUBSYSTEM #1:

recycled cardboard | packaging | recycled cardboard
refrigerant (R134a & R404a), diesel (for lorry), diesel (for freezing) | transport | refrigerant leakage (R134a and R404a), diesel emissions (CO2)

SUBSYSTEM #2:

water | thawing | wastewater
energy for automatic mechanical skinner | butchering | fish byproducts
water | washing | wastewater
sea salt | salting | sea salt
energy for drying tunnel | drying | sea salt, water (from fish)
sizing |  |  

SUBSYSTEM #3:

recycled cardboard | packaging | recycled cardboard
refrigerant (R134a & R404a), diesel (for lorry), diesel (for freezing) | transport | refrigerant leakage (R134a and R404a), diesel emissions (CO2)
grocery store |  |  

SUBSYSTEM #4:
B. Distance from Norwegian Fishery to Portuguese Processing Facility on Google Maps

C. Distance from Portuguese Processing Facility to Lisbon Grocery Store on Google Maps
D. Flowchart of Process for fish curing, small fish on ecoinvent 3

1. Fresh anchoveta
2. Heading, partial gutting
3. Washing/bleeding
   1 h in saturated brine
4. Salting
   ~30% salt
5. Pressing
6. Maturation
   Resting at 18°-25°C 1
   or 4°-5 months
7. Cleansing/scalding
   At 80°C for 5 seconds
8. Centrifugation
9. Filleting
10. Vegetable oil,
    Tinplate cans
11. Lids
    Boxes
12. Storage

Figure from (Avadi, 2017)
### E. Table of Total Effect of Each Process on Midpoint Impact Categories

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>Units</th>
<th>Capture: Trawler</th>
<th>Capture: Long Liner</th>
<th>Curing</th>
<th>Transport: Reefer (Subsystem #4)</th>
<th>Transport: Lorry (Subsystem #2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming</td>
<td>kg CO2 eq</td>
<td>0.357</td>
<td>1.52</td>
<td>8.21</td>
<td>0.0201333</td>
<td>0.029689</td>
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<tr>
<td>Stratospheric ozone depletion</td>
<td>kg CFC11 eq</td>
<td>9.39E-08</td>
<td>7.75E-06</td>
<td>1.12E-05</td>
<td>8.711E-09</td>
<td>2.71E-08</td>
</tr>
<tr>
<td>Ionizing radiation</td>
<td>kBq Co-60 eq</td>
<td>0.00369</td>
<td>0.0122</td>
<td>0.487</td>
<td>0.000344</td>
<td>0.000458</td>
</tr>
<tr>
<td>Ozone formation, Human health</td>
<td>kg NOx eq</td>
<td>0.00774</td>
<td>0.0253</td>
<td>0.0177</td>
<td>8.978E-05</td>
<td>0.00042</td>
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<tr>
<td>Fine particulate matter formation</td>
<td>kg PM2.5 eq</td>
<td>0.00248</td>
<td>0.00812</td>
<td>0.0158</td>
<td>2.351E-05</td>
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<td>Ozone formation, Terrestrial ecosystems</td>
<td>kg NOx eq</td>
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<td>0.0254</td>
<td>0.0182</td>
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<tr>
<td>Terrestrial acidification</td>
<td>kg SO2 eq</td>
<td>0.00786</td>
<td>0.0257</td>
<td>0.0258</td>
<td>5.733E-05</td>
<td>0.000203</td>
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<tr>
<td>Freshwater eutrophication</td>
<td>kg P eq</td>
<td>1.04E-05</td>
<td>3.20E-05</td>
<td>0.02</td>
<td>1.689E-06</td>
<td>2.34E-06</td>
</tr>
<tr>
<td>Marine eutrophication</td>
<td>kg N eq</td>
<td>1.72E-06</td>
<td>5.05E-06</td>
<td>0.00381</td>
<td>3.191E-07</td>
<td>7.2E-07</td>
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<tr>
<td>Terrestrial ecotoxicity</td>
<td>kg 1,4-DCB</td>
<td>0.366</td>
<td>1.17</td>
<td>69.1</td>
<td>1.84E-01</td>
<td>4.93E-02</td>
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<tr>
<td>Freshwater ecotoxicity</td>
<td>kg 1,4-DCB</td>
<td>0.00452</td>
<td>0.0131</td>
<td>0.549</td>
<td>0.0007467</td>
<td>0.001138</td>
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<tr>
<td>Marine ecotoxicity</td>
<td>kg 1,4-DCB</td>
<td>0.331</td>
<td>0.0203</td>
<td>0.728</td>
<td>0.0010356</td>
<td>0.001476</td>
</tr>
<tr>
<td>Human carcinogenic toxicity</td>
<td>kg 1,4-DCB</td>
<td>0.0175</td>
<td>0.0438</td>
<td>4.07</td>
<td>0.0013511</td>
<td>0.003747</td>
</tr>
<tr>
<td>Human non-carcinogenic toxicity</td>
<td>kg 1,4-DCB</td>
<td>0.0933</td>
<td>0.216</td>
<td>9.78</td>
<td>0.0100889</td>
<td>0.014667</td>
</tr>
<tr>
<td>Land use</td>
<td>m2a crop eq</td>
<td>0.00291</td>
<td>0.00905</td>
<td>8.8</td>
<td>0.0006533</td>
<td>0.000438</td>
</tr>
<tr>
<td>Mineral resource scarcity</td>
<td>kg Cu eq</td>
<td>0.000556</td>
<td>0.00162</td>
<td>0.236</td>
<td>4.533E-05</td>
<td>8.18E-05</td>
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<tr>
<td>Fossil resource scarcity</td>
<td>kg oil eq</td>
<td>0.113</td>
<td>0.371</td>
<td>1.37</td>
<td>0.0060444</td>
<td>0.008756</td>
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<tr>
<td>Water consumption</td>
<td>m³</td>
<td>0.000248</td>
<td>0.000774</td>
<td>0.243</td>
<td>3.551E-05</td>
<td>0.000052</td>
</tr>
</tbody>
</table>
F. Table of Total Effect of Each Process on Endpoint Impact Categories

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Total Impact</th>
<th>Capture: Trawler</th>
<th>Capture: Long liner</th>
<th>Curing</th>
<th>Transport (Subsystem #4)</th>
<th>Transport: reefer (Subsystem #2)</th>
<th>Transport: lorry (Subsystem #2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Health</td>
<td>DALY</td>
<td>4.38E-05</td>
<td>1.98E-06</td>
<td>6.73E-06</td>
<td>3.34E-05</td>
<td>4.04E-08</td>
<td>1.15E-07</td>
<td>1.52E-06</td>
</tr>
<tr>
<td>Ecosystems</td>
<td>species*yr</td>
<td>1.47E-07</td>
<td>3.75E-09</td>
<td>1.31E-08</td>
<td>1.26E-07</td>
<td>9.02E-11</td>
<td>1.88E-10</td>
<td>3.49E-09</td>
</tr>
<tr>
<td>Resources</td>
<td>USD 2013</td>
<td>7.25E-01</td>
<td>0.0505</td>
<td>0.166</td>
<td>0.403</td>
<td>0.00253778</td>
<td>0.00372889</td>
<td>9.96E-02</td>
</tr>
</tbody>
</table>

G. Percent Impact of Trawler compared to Long Liner (Endpoint)

![Chart showing the percentage impact of Trawler compared to Long Liner for Human Health, Ecosystems, and Resources]

- **Human Health**: Trawler: 4.53%, Long Liner: 2.56%
- **Ecosystems**: Trawler: 15.38%, Long Liner: 8.93%
- **Resources**: Trawler: 6.96%

**Total Impact**: Trawler: 22.89%