Greenhouse Gas Emissions MUSSELS

A Study of BANG'S ISLAND MUSSELS

COMMISSIONED BY: Island Institute
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TABLE OF CONTENTS

FOREWORD FROM ISLAND INSTITUTE

INTRODUCTION

Purpose

Maine's seafood sector is a cornerstone of the state's economy and identity—and increasingly, a vital player in climate solutions. Between 2022 and 2024, Island Institute commissioned greenhouse gas (GHG) assessments—analyses that measure the amount and sources of GHG associated with specific activities—to better understand the emissions footprint of Maine's lobster, mussel, kelp, and oyster supply chains.

Island Institute's GHG assessment reports provide a foundational benchmark for understanding how seafood producers can cut emissions, lower operating costs, and adapt to changing climate and market conditions. Using illustrative case studies and quantified results, these analyses identify practical solutions and highlight clear opportunities to implement state-level policies and programs that encourage energy-efficient, climate-smart practices. These efforts also strengthen the sector's resilience to other climate change impacts, helping to position Maine as a leader in sustainable seafood production.

This report supports many of the recommendations in the 2024 update to *Maine Won't Wait: A Four-Year Climate Action Plan* and the *2025 Plan for Infrastructure Resilience*, produced by the Infrastructure Rebuilding and Resilience Commission. Island Institute highlights specific opportunities closely aligned with these plans and offers meaningful benefits to the sector.

Methodology

To understand the GHG emissions associated with Maine's seafood sectors, third-party analyses of businesses were conducted using standardized lifecycle accounting protocols to quantify carbon emissions across every major stage of production—from bait sourcing and vessel fuel use to processing, storage, and distribution.

While the businesses studied—Luke's Lobster, Bangs Island Mussels, Atlantic Sea Farms, Mook Sea Farm, Deer Isle Oyster Company, Bombazine Oyster Company (formerly Ferda Farms), and Pemaquid Oyster Company—are leaders in their respective fields, the goal was not to produce industry-wide averages. Instead, these businesses served as illustrative case studies, offering a real-world snapshot of emissions sources and reduction opportunities.

Data was collected directly from the companies and supplemented with interviews, site visits, and operational records. Upstream and downstream impacts, such as aquaculture seed production, fuel sourcing, and product distribution, were also modeled where possible. All GHG analyses in these reports follow the steps and guidelines as defined by the International Organization for Standardization (ISO) standards. Results are presented in accordance with ISO standards and categorized based on the GHG Protocol Corporate Accounting and Reporting Standards. Each case study reflects the best available data from a specific point in time and is intended to inform—not define—sector-wide practices.[i] Importantly, all of the findings, connections, and recommendations in these reports are based on analyses of seafood businesses and are meant to be illustrative examples. They are not assumed to be representative of their entire respective seafood industry

i Three separate consultants were used across the reports. While all followed standard GHG protocols, some differences in approach were inevitable.

WHAT'S AT STAKE

Natural resource-dependent businesses like fishing, aquaculture, and other marine-based industries are particularly vulnerable to climate and environmental changes that could significantly impact Maine's economy. Maine's seafood sector alone contributed over $3.2 billion dollars in total economic input to the Maine economy in 2019 and employed more than 34,000 people, but this sector and the jobs it supports is currently facing many harmful impacts from ocean climate change.[ii]

The seafood sector is at the onset of a once-in-a-century energy transition as it looks for ways to decarbonize through electrification, low-carbon fuels, optimization tools, and efficiency technologies.[iii] If Maine is to meet its climate goals, and we are to avoid the worst impacts of change in all sectors, including the marine sector, we must drastically reduce emissions.[iv] By drastically reducing emissions, we will be less vulnerable to environmental and economic risks.

EXECUTIVE SUMMARY

Maine's coastal communities are facing rising seas, stronger storms, aging infrastructure, and increasing energy costs. These challenges threaten not only individual businesses, but the viability of Maine's iconic working waterfronts and the greater marine economy.

At the heart of this effort is a systems-level challenge: How can we sustain and grow Maine's marine economy while modernizing infrastructure, reducing emissions, and increasing resilience—especially when time, funding, and capacity are in short supply?

Drawing on a long history of working directly with community leaders and business owners, Island Institute commissioned a series of GHG analyses to measure the carbon footprint of key seafood supply chains. The goal of these studies is two-fold: first, to assess options that enable seafood businesses to reduce emissions, lower operating costs, and adapt to changing climate and market conditions; and second, to identify practical solutions—supported by illustrative case studies and quantified results—and highlight clear opportunities to implement state-level policies and programs that promote energy-efficient, climate-smart practices.

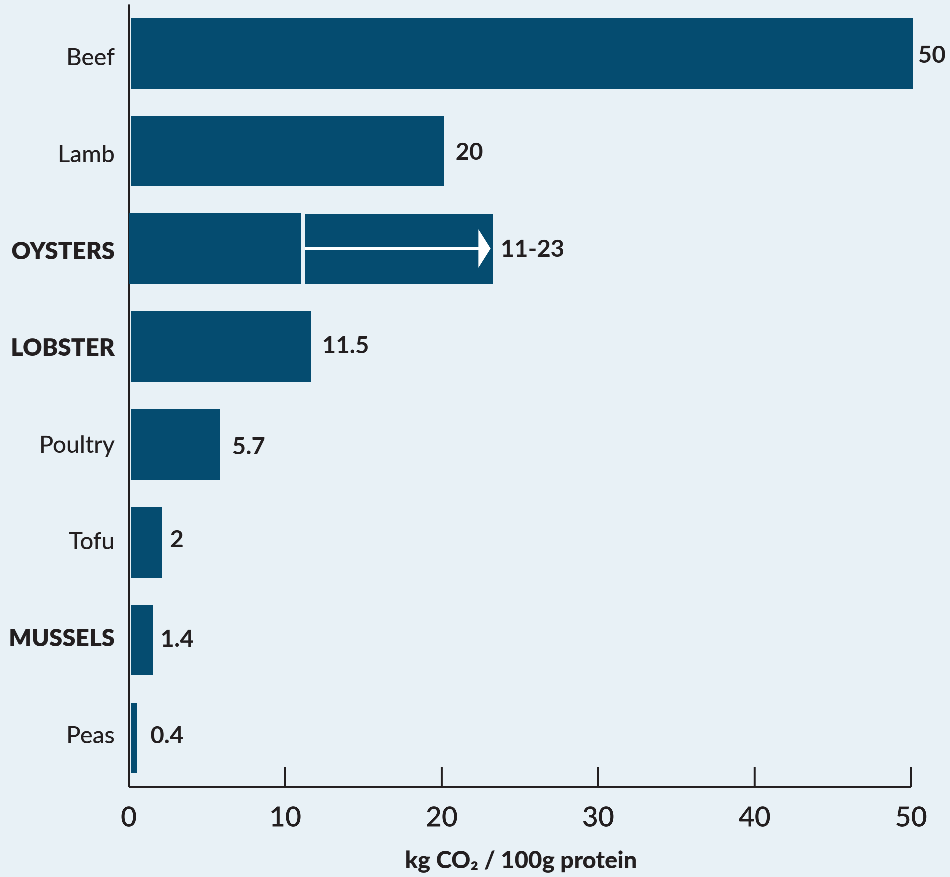
The findings are clear: Maine seafood is already among the lowest-carbon protein sources available (Figure A). At the same time, meaningful opportunities exist to reduce emissions for businesses operating on the front lines of climate change.

Clean energy and decarbonization efforts bring co-benefits to the seafood sector. Through GHG emissions reductions, marine businesses can reduce their contribution to global climate change, a key driver in business uncertainty. Reducing emissions also stabilizes or lowers operating costs, allowing businesses to reinvest in resilient business operations.

Strategic investments—especially in the electrification of work boats and associated shoreside charging and clean energy infrastructure—can significantly cut emissions, lower long-term operating costs for businesses, and strengthen Maine's leadership in sustainable food production. For example, replacing a single 100-horsepower, four-stroke internal combustion outboard engine with an equivalent power electric outboard motor would reduce operations emissions by 11–16 metric tons per year.[v]

ii SEA Maine Roadmap
iii https://www.energy.gov/eere/maritime-decarbonization
iv *Maine Won't Wait Climate Action Plan*
v Estimation based on calculations of real-world electrification projects implemented by Island Institute with partner businesses.

Figure A. Results from GHG assessments of Maine seafood businesses compared to common land-based protein sources.[vi]



Each report underscores the opportunity for targeted investments in this sector to help businesses take advantage of existing State and Federal programs that can reduce emissions in the building envelope and in the transportation sector. These reports also highlight the importance of continued data collection and piloting ways to reduce on-the-water emissions. Cutting emissions through efficiency measures that reduce the need for energy, in any form, results in lower operational costs. For example, phase change materials can help reduce demand from the electrical grid during peak demand hours, reducing costs for the business, and helping to reduce emissions and stress on the grid. In Maine, the mix of electricity on the grid is relatively clean, making the shift from fossil fuels to electricity a cost-effective, climate friendly strategy.

This report offers a path forward. With deeper collaboration, targeted investment, and shared innovation, we can turn these findings into real-world projects that secure Maine's working waterfronts and shape a resilient, sustainable marine economy—one that can serve as a national model.

vi These findings reflect only the results from Island Institute's commissioned studies of individual seafood businesses. They have not undergone third-party verification and should not be used for marketing purposes.

Shared Findings

These in-depth analyses, covering seven Maine seafood businesses, indicate highest emissions in the following three areas:

- Fossil fuel use on fishing and aquaculture vessels.
- On-shore energy consumption for the built environment, including heating, drying, refrigeration, freezing, and hatchery operations.
- Land-based transportation and distribution impacts emissions directly or indirectly for all aspects of business operations. Emissions from distribution activities are highly variable depending on distance covered and distribution method.

Recommendations for Business

- Transition on-land medium-and heavy-duty vehicles, as well as on-the-water vessels, to non-fossil fuel-based energy sources (i.e., electric and hybrid vehicles and vessels).
- Increase charging infrastructure located at or near the water's edge to accommodate vehicle and vessel electrification.
- Improve operational efficiency through process optimization and smart technologies to reduce run time in daily farming operations.
- Improve operational efficiencies on the shore-side processing and handling facilities to lower energy use, GHG emissions, and operational costs.
- Improve crop yields and minimize waste by upgrading farming gear and on-the-water processing equipment.

RECOMMENDATIONS FOR POLICY AND STATE PROGRAMS

Proven solutions exist to tackle some of these high emission areas, while also delivering long-term financial benefits to Maine's seafood businesses. As with many energy efficiency-related improvements, these solutions may require upfront capital costs to see a longer-term shift in operating costs. While existing statewide incentive programs for energy efficiency upgrades and clean energy transition can support this work, there is an opportunity to expand these programs to meet and improve the efficiency of building and shoreside transportation needs for the seafood sector. Tailoring communication and outreach about these opportunities to individuals who work in the working waterfront and on the water could accelerate energy efficient and clean energy adoption and reduce emissions in the sector.

At the same time, emerging technologies—particularly related to transitioning marine work boats from fossil fuels to electric propulsion—hold significant promise and merit further exploration. Electric outboards are currently being piloted by members of the aquaculture industry, and this technology continues to show promise for reducing operational cost and carbon emissions. Using the existing statewide incentive programs as models could help incentivize and de-risk the adoption of newer technologies critical to the transition away from fossil fuels.

These recommendations align with statewide priorities outlined in both the updated *2024 Maine Won't Wait: A Four-year Climate Action Plan*, as well as the *2025 Plan for Infrastructure Resilience*. In many cases, these recommendations reinforce or expand goals already established by the State.

The Infrastructure Rebuilding and Resilience Commission 2025 report outlines recommendations to protect infrastructure, including working waterfronts, from elevated storm impacts related to climate change. The *Maine Won't Wait* plan underscores the importance of helping businesses with clean energy solutions. As noted in the plan: "[making businesses more climate friendly can save on both operating costs and emissions" and we need to "[h] elp Maine businesses and other entities take advantage of electrification, efficiency, electric vehicle, and clean-manufacturing business incentives and recognize exceptional efforts."[vii]

Many seafood businesses, however, lack the time, resources, and technical expertise to implement these solutions on their own. Successfully implementing these recommendations will require substantial capacity-building and technical support from organizations within the sector. With the right assistance at a state-wide scale, Maine's seafood businesses can modernize their infrastructure, lower emissions, enhance resilience, and ultimately strengthen and grow the state's marine economy.

Specific recommendations include:

- Increase awareness and uptake of existing programs, particularly Efficiency Maine Trust's Custom Program, to support efficiency upgrades in the built environment by the seafood sector.[viii]
- Assess whether the seafood sector represents a good use case for medium- and heavy-duty vehicle electrification and prioritize this sector for implementation support because of the co-benefits to adaptation for these businesses.[ix]
- Support the collection of data on the performance and long-term cost and emissions reductions of electric and hybrid work vessels through demonstration projects. Use data to expand existing electric vehicle incentives to cover marine vessels and shoreside infrastructure.[x]
- Maintain and increase access to capital—including low-interest loans with flexible terms and other incentives such as tax credits or grants—to help defray the costs of energy efficiency and beneficial electrification upgrades.[xi]
- Support and incentivize businesses to take advantage of behind-the-meter clean energy generation and storage—such as on-site solar panels that power a business directly without relying on the grid.[xii]
- Support research to better understand the use of kelp aquaculture might help capture and store carbon.[xiii]

> **"Some sectors of Maine's marine economy have electrification and emission reduction opportunities, while others require more innovation and clean-fuel options... Maine and key stakeholders should continue to support innovation and efforts to help commercial marine and small harbor craft adopt electrified propulsion and other low- and zero-emission vessel technologies."**
> ***— Maine Won't Wait, A Four-Year Climate Action Plan for Maine, 2024 Update***

vii *Maine Won't Wait 2.0* (2024) Strategy D2, pages 93 and 98 (2024)

viii *Maine Won't Wait 2.0* (2024) Strategy B1 - Boost efficiency in commercial and institutional buildings through high-efficiency electric heating and water heating systems, building control technologies, and improvements to building envelopes.

ix *Maine Won't Wait 2.0* (2024) Strategy A2 - By 2028, pilot projects for zero-emission trucks, municipal and school buses, ferries, and boats to demonstrate and evaluate performance, reliability, and cost savings. Develop an incentive program for zero-emission medium- and heavy-duty vehicles.

x *Maine Won't Wait 2.0* (2024) Strategy A2 - By 2028, pilot projects for zero-emission trucks, municipal and school buses, ferries, and boats to demonstrate and evaluate performance, reliability, and cost savings. Develop an incentive program for zero-emission medium- and heavy-duty vehicles.

xi *Maine Won't Wait 2.0* (2024) Strategy C-1 Decrease energy burdens while transitioning to clean energy - Expand financing and ownership models for Maine people and businesses to access clean energy and energy efficiency opportunities.

xii *Maine Won't Wait 2.0* (2024) Strategy C-1 Decrease energy burdens while transitioning to clean energy - Expand financing and ownership models for Maine people and businesses to access clean energy and energy efficiency opportunities.

xiii *Maine Won't Wait 2.0* (2024) Increase the total acreage of conserved natural and working lands in the state to 30 percent by 2030.

A NOTE ON GRID INFRASTRUCTURE

A significant barrier to implementing energy efficiency, clean energy, and future electrification technologies is the current grid condition, including aging infrastructure and energy capacity capabilities. Recommendations in both *Maine Won't Wait* plan and the *Plan for Infrastructure Resilience* highlight the importance of strengthening the resilience of the State's electrical grid. This is especially critical for seafood businesses who operate on the edges of the grid, including working waterfronts and islands. Investing in island and coastal grid infrastructure will contribute to improving reliability and capacity, enabling more businesses to tap into clean, grid-powered energy, and support future community and economic development and resiliency. Expanding power capacity in these remote areas will enable the electrification of equipment and charging infrastructure that requires 3-phase power, a type of electrical power commonly used for large commercial or industrial operations. Only approximately 25% of Maine's coast currently has access to 3-phase power.[xiv] Upgrading the infrastructure to accommodate these high-power uses is critical to expand electrification and decarbonization strategies in the seafood sector.

xiv This data comes from a forthcoming shoreside charging infrastructure report comissioned by Island Institute.

ACKNOWLEDGEMENTS

This work would not have been possible without the following funders, seafood businesses, and consultants, whose collaboration was critical for this body of work:

Atlantic Sea Farms	Participating Seafood Business
Bangs Island Mussels	Participating Seafood Business
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Dana Morse	Darling Marine Center
Deer Isle Oyster Company	Participating Seafood Business
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Luke's Lobster	Participating Seafood Business
Merritt T. Carey, Esq	Consultant
Mook Sea Farm	Participating Seafood Business
Nichole Price	Bigelow Laboratory for Ocean Sciences
Pemaquid Oyster Company	Participating Seafood Business
Pure Strategies	Consultant, Bangs Island Mussels and Atlantic Sea Farms Reports
RISE Research Institutes of Sweden	Consultant, Mook Sea Farm, Bombazine Oyster Company (formerly Ferda Farms), Deer Isle Oyster Company, and Pemaquid Oyster Company Reports
Shane Rogers	Clarkson University
Susan Powers	Clarkson University

EXECUTIVE SUMMARY OF MUSSELS STUDY

Bangs Island Mussels (BIM) is a family owned and operated company located in Portland, Maine that grows blue mussels mainly in Casco Bay. In partnership with Island Institute, BIM is interested in better understanding the environmental impact of their farmed mussels and how it compares to other protein sources. The goal of the study is to calculate the product carbon footprint (PCF) of BIM's farmed mussels, identify hot spots within their production, and compare its impact to that of mussels, oysters, and other high protein foods.

Product Carbon Footprint (PCF) is a tool used to quantify environmental impact of a product throughout the entire life cycle, from material extraction, processing, transportation, and end of life. This report contains the full PCF background, methodology, and results documentation for BIM farmed mussels as required by ISO 14067:2018(E) Greenhouse Gases - Carbon Footprint of Products - Requirements and Guidelines for Quantification. Results are also presented in alignment with the GHG Protocol Corporate Accounting and Reporting Standards.

Pure Strategies calculated the annual carbon emissions of 591,431 pounds of BIM farmed mussels in coastal Maine from cradle to local and Boston distribution for the time period of January 2022 to December 2022. The PCF results are also normalized to 1 pound of BIM farmed mussels and 100 g of protein contained in BIM farmed mussels. This normalized impact is compared to the carbon footprint of mussels, oysters, and other protein sources.

The environmental impact is represented by global warming potential (GWP), expressed as kilograms carbon dioxide equivalent (kg CO2e). Greenhouse gas emissions have been calculated for three categories: direct emissions (Scope 1), indirect emissions (Scope 2), and indirect emissions upstream and downstream in the value chain (Scope 3).

RESULTS AND RECOMMENDATIONS

The total annual product carbon footprint is 230,106 kg CO2 for the farming, processing, and storage and distribution locally and to Boston of 591,431lbs of mussels. This is equal to 0.4kg CO2 per pound of BIM mussels. The PCF results in Table 1 are organized by scope and the results in Figure 1 are organized by BIM process, to better understand the drivers of carbon emissions.

Table 1: BIM mussels carbon footprint by GHG Protocol Scope

Scope	Description	Emissions (kg CO2e)	Contribution to total
Scope 1 - Biogenic	Biogenic emissions during mussel farming	77,468	34%
Scope 1 - Fugitive	Fugitive emissions from refrigerants during storage of mussels	4,269	2%
Scope 1 - Mobile Combustion	Boat fuel use from during farming	51,302	22%
Scope 1 - Mobile Combustion	Truck fuel use during distribution	6,836	3%
Scope 1 - Stationary Combustion	Stationary combustion of natural gas used during processing	15,374	7%
Scope 2 - Purchased Electricity	Purchased electricity used during processing	19,690	9%
Scope 3 - Category 1	Consumables used during farming	6,185	3%
Scope 3 - Category 1	Consumables used during processing	6,692	3%
Scope 3 - Category 1	Tap water use during processing	1,001	0%
Scope 3 - Category 1	Packaging materials	9,304	4%
Scope 3 - Category 3	Upstream emissions of diesel and gasoline used in boats	10,499	5%
Scope 3 - Category 3	Upstream emissions of natural gas production	6,037	3%
Scope 3 - Category 3	Upstream emissions of electricity generation and T&D losses	5,331	2%
Scope 3 - Category 3	Upstream emissions of gasoline used for local distribution	1,762	1%
Scope 3 - Category 4	Refrigerated trucking fuel use for distribution	7,236	3%
Scope 3 - Category 5	Waste produced during farming	86	0%
Scope 3 - Category 5	Waste produced during processing	1,034	0%
	Total amount in 2022	230,531	100%
	Amount per 1 pound farmed mussels, 2022	0.4	NA

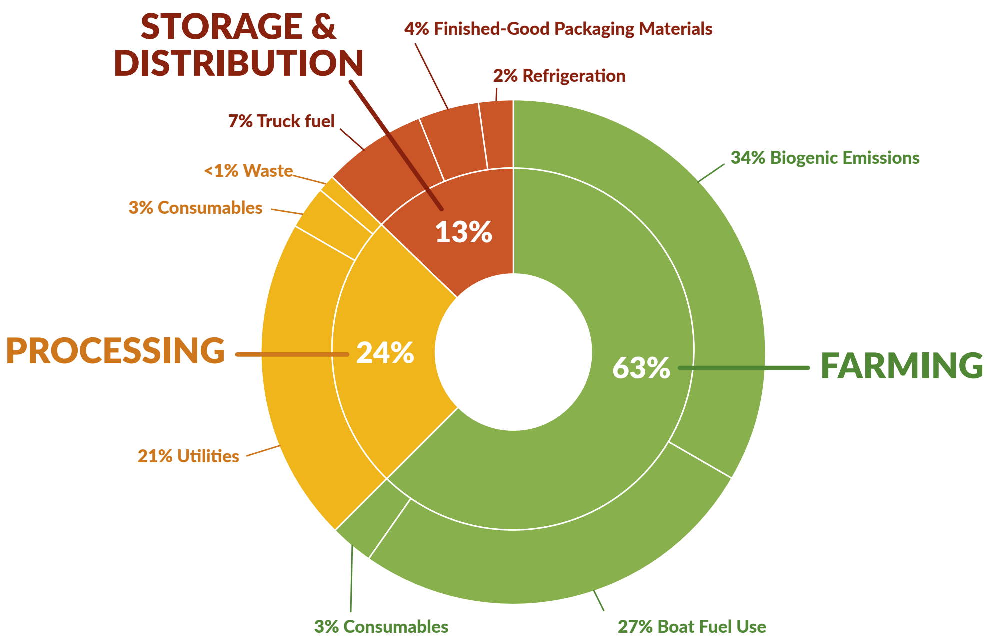


Figure 1.
Process contribution to BIM mussels product carbon footprint

Biogenic emissions resulting from the normal shellfish growth cycle are the largest contributor at 34%. Contrary to popular belief, rather than sequestering carbon, shellfish release greenhouse gasses during the normal growth cycle. Carbon dioxide, methane, and nitrous oxide are released at a rate of 0.25 kg CO2/kg mussel. At BIM, 13% of all mussels harvested are broken during processing, cannot be sold, and are returned to the ocean. Reducing the rate of broken mussels to 5% has the potential to reduce annual carbon emissions by more than 16,000 kg CO2e.

Fuel use for boat and truck transport throughout the value chain contributes 34% of the PCF, with boat use specifically contributing 27%. Biodiesel has about 9% less carbon emissions than petroleum diesel. Replacing boat diesel with biodiesel has the potential to save about 4,000kg CO2 per year. Reducing fuel use across the board by 10% by minimizing idling or increasing efficiency has the potential to save about 6,000kg CO2 annually. Combining these efforts – replacing boat diesel with biodiesel and reducing fuel use in trucks and boats by 10% – has the potential to save about 10,000kg CO2 annually.

Electrically powered motors are expected to have significant carbon emission savings over diesel powered motors. Using electric vehicle and boat motors powered by renewable energy for BIM owned vehicles and boats has the potential to eliminate emissions from transport, saving over 77,000kg CO2.

BIM utilities contribute 21% of the PCF, with electricity specifically contributing 11%. Adopting 25% wind and 25% solar energy has the potential to reduce emissions by about 12,000kg CO2 annually. Increasing to 100% renewable energy (50% wind and 50% solar) has the potential to reduce emissions by about 24,000kg CO2 annually[1].

Farmed mussel yield has a significant impact on the product carbon footprint. A 20% increase in yield has a potential to save about 20,000kg CO2 annually, assuming the same amount of fuel is used for boats as the baseline and refrigerant and utilities at BIM remain equal to the baseline. A 20% decrease in yield has the potential to increase annual CO2 emissions by about 30,000kg.

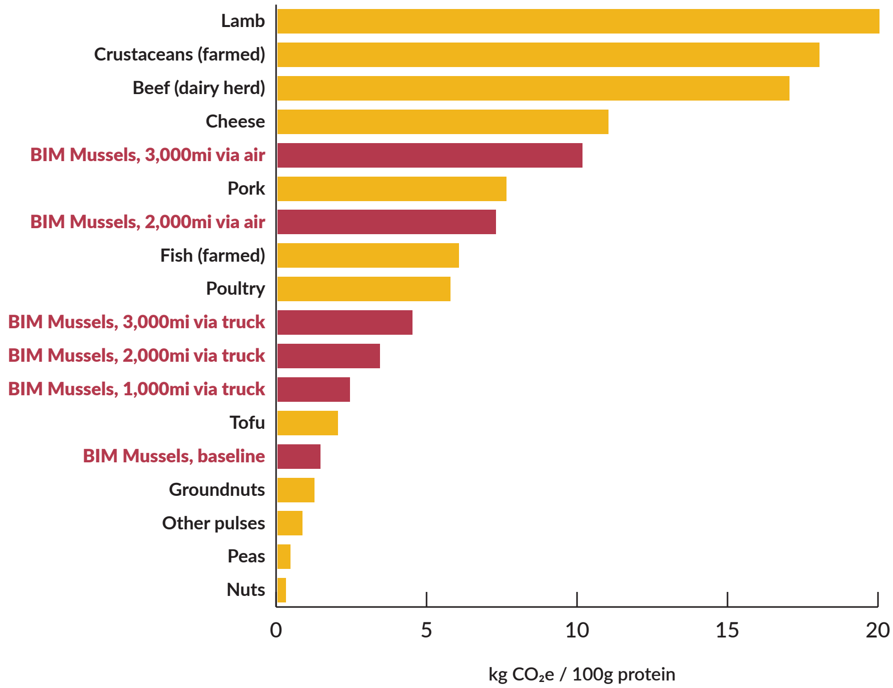


Figure 2.
Product carbon footprint of high protein foods. PCFs from Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science, 360(6392), 987-992.

BIM mussel seed loss due to eider ducks is an ongoing problem and a Nova Scotia farm estimated that eider ducks ate 25% of their mussel seed. Exploring methods to reduce loss and therefore increase farming yield from ducks include underwater recordings of boat engine noise played at random intervals and netting with 6" mesh size.

BIM mussels are a low carbon footprint source of protein. BIM's mussel carbon footprint is 1.4 kg CO2 per 100 grams of protein with local and Boston distribution. This normalized PCF was compared to other high protein sources in Figure 2 on the following page. The other high protein sources include distribution to retail location; if BIM mussels are transported past Boston, BIM mussel footprint would increase above 1.4 kg CO2 per 100 grams protein. Figure 2 includes the carbon footprints of BIM mussels that are transported via refrigerated truck 1,000mi (Chicago), 2,000mi (Denver), and 3,000mi (US west coast) to better understand the magnitude of refrigerated trucking impact.

Carbon footprint of mussels transported via air 2,000mi (Denver) and 3,000mi (US west coast) are included as shipping via air may become a likely scenario as BIM expands to other parts of the country. Transporting mussels via air has more than double the impact of transporting them the same distance via refrigerated truck.

BIM mussels have about the same carbon footprint as mussels grown in other parts of the world, at least 40% less impact than oysters, 90% less impact than other crustaceans, and less impact than all other meat-based proteins. BIM mussels have a higher impact than plant-based protein sources, including pulses, peas, and nuts.

BACKGROUND

Bangs Island Mussels (BIM) is a family owned and operated company located in Portland, Maine. BIM grows blue mussels, hand-raised locally in the cool, clean waters of Casco Bay. For more than 15 years they have been cultivating mussels, striving to operate in complete harmony with the environment. BIM's mussels are rope grown, where they spend their entire life in the water column, suspended above the ocean floor. Positioned away from sandy, silty tidal zones, the mussels mature rapidly and accumulate almost no grit, resulting in premium quality.

BIM in partnership with Island Institute is interested in better understanding the environmental impact of their farmed mussels and how it compares to other protein sources. It is well known that agriculture is estimated to contribute 30% of total greenhouse gas (GHG) emissions.[2] Animal protein sources are known to have higher carbon footprints than plant-based alternatives. Farmed mussels can provide an alternative to animal proteins while acting as a high source of protein, iron, and vitamin B12.[3] Furthermore, farmed mussels are grown with minimal inputs, require no feed, and provide additional environmental benefits, such as water quality improvements.

Pure Strategies calculated the life cycle carbon emissions of all mussels produced in 2022 from cradle to distribution locally and to the Boston distribution hub and normalized those results to one pound packaged mussels and 100 grams of protein. The environmental impact is represented by global warming potential (GWP), expressed as kilograms carbon dioxide equivalent (kg CO2e).

Product carbon footprint (PCF) is a tool used to quantify the carbon impacts of a product, holistically, throughout the entire life cycle, from material extraction, manufacturing and assembly, packaging, transportation, use, and end of life. The impacts associated with the product are assessed by compiling an inventory of relevant energy and material inputs and environmental releases, evaluating the potential environmental impacts associated with identified inputs and releases, and interpreting the results to help make a more informed decision. This PCF was conducted using product specific primary data provided by BIM (e.g. consumables, energy and fuel use, waste streams, etc.), secondary material and process inputs and outputs from the life cycle assessment databases, literature, EPA Emissions Hub, and Intergovernmental Panel on Climate Change (IPCC) 2021 GWP100 impact assessment method, using SimaPro LCA software.

The most widely recognized standardized guidelines for PCF have been developed by the International Organization of Standardization (ISO). This report contains the full PCF background, methodology, and results documentation for BIM farmed mussels as required by ISO 14067:2018(E) Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification, and also aligns with ISO 14040:2006(E) Environmental management – life cycle assessment – principles and framework and ISO 14044:2006(E) Environmental management – life cycle assessment – requirements and guidelines.

GOAL

This study was prepared for Island Institute and BIM. The overall goal of the PCF is to calculate the potential contribution of BIM's mussels to global warming, expressed as carbon dioxide equivalents (or CO2e) by quantifying all significant greenhouse gas emissions and removals throughout the mussel farming, processing, and storage and distribution processes.

The study aims to (1) calculate the PCF of BIM farmed mussels, (2) identify hot spots within their product supply chain, and (3) compare BIM's farmed mussel carbon footprint to the PCF of mussels, oysters, and other high protein foods available in the literature.

This report is compliant with ISO standards 14040, 14044, and 14067, the standards for life cycle assessment and product carbon footprint and aims to objectively present results and conclusions of the PCF with transparency, outlining the methodology, assumptions, and limitations accordingly. The PCF of BIM mussels is intended to be used by Island Institute and BIM for business purposes and customer communication, in alignment with ISO 14026 Environmental Labels and Declarations.

SCOPE

This section defines the products included in the study, the system boundaries, and modeling methodology.

FUNCTIONS AND FUNCTIONAL UNIT

The study period is January 1, 2022 through December 31, 2022, with data provided by BIM for all operations during this time period. The functional unit is all 591,431 pounds of mussels distributed locally or to Boston distribution center during the time period. Scope includes farming off the coast of Maine, processing at a BIM facility, and transport locally and to Boston. Mussels are distributed to restaurants and other commercial customers, so retail is not included in the scope. Mussels are distributed out of the Boston distribution center to other parts of the country.

Annual carbon emissions are normalized to one pound of farmed mussels and 100g of protein in farmed mussels. To calculate protein content, BIM provided their meat-to-mussel ratio (average meat and shell mass), as shown in Table 2. The protein content of blue mussels was obtained from the USDA FoodDATA Central database.[4] Total protein content in sold mussels is calculated using Equation 1.

Equation 1.
Total protein content of sold mussels = (MM/WMM)*MS*(lbs/g)*PC

Where:
MM = average lbs of meat per mussel = 0.15lbs
WMM = average lbs of whole mussel = 0.29lbs
MS = lb mussels sold = 591,431lbs
Lbs/g = conversion factor for lbs to grams
PC = protein content per 100 g raw meat = 11.9 grams

Table 2: Emissions of BIM farmed mussels per 100g protein

Category	Value	Unit
Average meat mass per mussel	0.15	lbs
Average shell mass per mussel	0.14	lbs
Average whole mussel mass	0.29	lbs
Total mussels Sold	591,431	lbs
Protein content of blue mussels	11.9	g/100g raw meat
Total protein content of BIM sold mussels	165,124	100g protein

LIMITATIONS

As with any PCF, there are limitations on how the results should be used. Results should not be considered the only source of environmental information relating to a product or process. There are limits to data quality, especially for production of upstream materials, where information may vary widely.

The life cycle impact assessment results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks. This product carbon footprint is only representative of blue mussels grown off the coast of New England, processed by Bangs Island Mussels, and transported to distribution hubs. This study is not intended to be representative of all mussels farmed globally or in the US as data may vary significantly with the farming process and yield. It is not intended to be representative of the entire mussel or shellfish industry.

BOUNDARY AND DATA SOURCES

This section gives an overview of the operations included in the study, details of the processes included and excluded from the scope of the study, and the data sources.

SYSTEM BOUNDARY

The system boundary is cradle to local and Boston distribution. This includes all inputs and outputs from mussel farming (spat collection, hatchery seed, mussel growth, and harvest) to mussel processing (cleaning and sorting of mussels) to storage and distribution (packaging, refrigeration, and transport of mussels to local Portland, ME customers and Boston distribution hub). Consumption and end of life are excluded from the system boundary.

Bangs Island Mussel process overview

BIM farms their mussels using a space-efficient process called rope growing in Portland Maine's Casco Bay, where long ropes connected to a series of 40-by-40-foot rafts are used. Farming includes spat collection, hatchery seed, and mussel harvest. Mussels are harvested and brought to BIM's processing facility where they are sorted based on size and too small mussels are returned to the ocean where they continue to grow until they reach their full size. BIM has a fleet of 4 boats used for farming.

Mussels are cleaned, sorted, packed, and stored at BIM's processing facility. Broken mussels are returned to the ocean and account for around 13% of mussels harvested. Mussels are distributed locally in Portland and South Portland via company owned truck and to Boston distribution center.

The main PCF stages and their respective inputs are outlined in Figure 3.

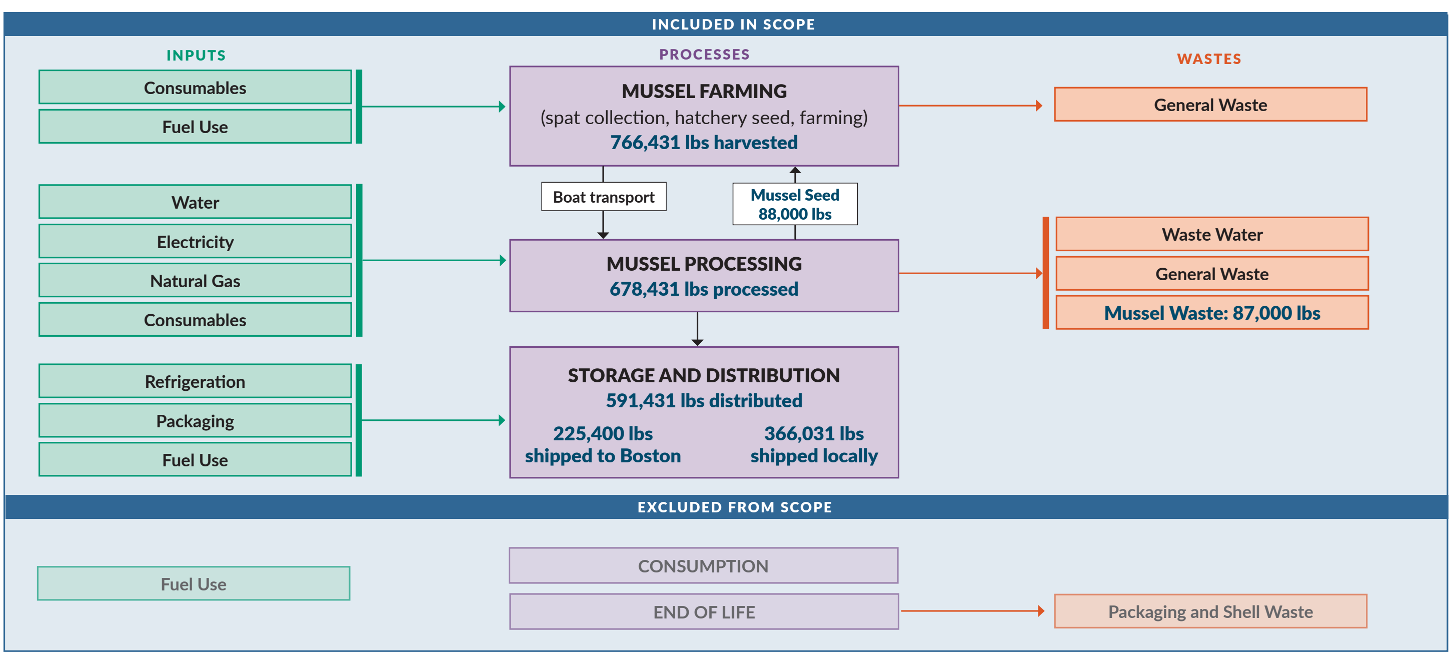


Figure 3.
System boundary for BIM farmed mussels

DATA SUMMARY AND SOURCES

BIM's processing facility is located on the wharf at 72 Commercial St, #15, Portland, ME 04101. Given its location, only boat transportation is needed to harvest the mussels. Mussels are also stored at this facility prior to being shipped either locally within Portland or regionally, to Boston.

The amount of mussels harvested, processed, and distributed throughout the supply chain was provided by BIM records as shown in Table 3.

Input and emission factor sources vary, based on the availability of data and best fit sources. Table 4 is a summary of all data included in the analysis and details are in the respective sections within the Inventory data and footprint section of this report.

Table 3: Total mussels harvested, processed, and distributed

Step	Amount (lbs)	Data Source
Farmed mussel yield	766,431	BIM provided
Mussels transported to BIM via boat	766,431	BIM provided
Small mussels put back to seed	88,000	BIM provided
Mussels processed	678,431	BIM provided
Mussel waste during processing	87,000	BIM Provided
Mussels distributed during the study period	591,431	BIM Provided

Table 4: Data and emission factor sources summary

Process	Sub-process	Input data source	Emission factor source(s)
Farming	Biogenic	Total mussels harvested, mussel lifespan, and meat to shell ratio provided by BIM	Direct GHG release - literature
Farming	Consumables	Mass & material type from BIM purchasing records Manufacturing processes assumed by Pure Strategies based on material and function	Material & manufacturing process - DataSmart, Ecoinvent
Farming	Fuel use	Boat fuel use from BIM purchasing records	Material – Ecoinvent Combustion – EPA Emission Factors Hub
Farming	Waste	Total consumable weight & waste disposition provided by BIM records	Waste treatment & disposal – DataSmart
Processing	Consumables	Mass & material type from BIM purchasing records Manufacturing processes assumed by Pure Strategies based on material and function	Material & manufacturing process - DataSmart, Ecoinvent
Processing	Utilities	BIM electricity usage during the study period from BIM energy bills BIM natural gas usage during the study period from BIM energy bills BIM water usage during the study period from BIM utility bills Facility addresses provided by BIM	Combustion – EPA Emission Factors Hub Energy – DataSmart, US EPA eGRID2021 subregion emission factor, IEA Upstream emission factors 2023
Processing	Waste	Total consumable weight & waste disposition provided by BIM records 90% non-recyclable waste sent to incineration with energy recovery & 10% municipal landfill provided by waste services company BIM total of all recycling sent offsite from waste hauler bills Amount of wastewater sent to offsite treatment assumed equal to process water	Waste treatment & disposal – DataSmart, Ecoinvent, literature
Storage & Distribution	Fuel use	Number of trips, mass of mussels per trip, and miles per trip provided by BIM total fuel use on miscellaneous trips provided by BIM fuel records	Material – Ecoinvent Combustion – EPA Emission Factors Hub
Storage & Distribution	Packaging	Manufacturing processes assumed by Pure Strategies based on material and function Mass & type of material from BIM purchasing records	Material & manufacturing process – DataSmart, USLCI
Storage & Distribution	Refrigeration	Refrigerant capacity at BIM provided by BIM Leak rate assumed 5% by EPA leak repair requirements recharge at BIM provided by purchasing records	Refrigerant – EPA Emission Factors Hub, literature

Data uncertainty

Data for BIM farming represents the 2022 farming and harvest season only. Mussel farming yield fluctuates year over year and this dataset only considers one growing season. Past and future seasons are expected to differ from the data presented in this study. It is difficult to understand how inputs will change with yield, though the relationship is not expected to be linear for all farming inputs, as the same amount of many consumables and boat trips will be needed regardless of yield. It is recommended that additional years of data are collected to increase the precision and representativeness of BIM's operations.

ASSUMPTIONS

Not all data was available to complete the analysis; therefore, some assumptions and surrogate data were required. Details of assumptions are found in section Inventory data and footprint and their impact on the results are discussed in section Sensitivity analyses & recommendations.

SENSITIVITY ANALYSIS

Sensitivity analyses were performed for the results in order to determine if data assumptions significantly impact the results. Detailed results of the sensitivity analyses are included in Sensitivity analyses & recommendations.

CUT-OFF CRITERIA

The system boundary includes all life cycle stages. Approximately 144 lbs of consumable inputs were excluded from this study, including gloves, bibs, life jackets, boots, hearing protection, fuel & oil filters, and shovels. Additionally, the rafts and nets used during the mussel farming process are also excluded as their lifespan is >5 years. Given the carbon footprint of the included consumables across all stages contributes 5% of the annual footprint and excluded consumable weight is less than 2% of total consumable weight, it is not expected that the excluded consumables will have significant carbon impact. All other inputs are included in the study.

ALLOCATION PROCEDURES

For this study, all electricity and natural gas consumed at BIM's facility was categorized under mussel processing. Some farming activities as well as storage occur at this facility, but utility inputs could not be allocated to respective sub-processes. Thus, all electricity and natural gas are allocated to the mussel processing product stage. In addition to farming mussels, BIM farms kelp. BIM was able to segregate out inputs for kelp production, only providing data on mussel production for this study. There are no coproducts produced during mussel farming.

Allocation for recycled materials is the cut-off method. In this model, the pallets that BIM receives have already been used by another company and are reused by BIM. Since the pallets were a waste product, BIM receives the pallets burden free (or with zero impact). For any materials that BIM sends offsite to be recycled at end of life, those products receive zero impact at end of life. The benefit of recycling materials, such as offsetting the production of new materials, is taken by the user of those recycled materials.

DATA QUALITY

This section outlines the data quality requirements, as specified by ISO 14044 section 4.2.3.6.2 and ISO 14067 section 6.3.5.

Time related coverage

Time related coverage describes the age of data and the minimum length of time which data was collected. All data was collected during the study period, January 1, 2022 through December 31, 2022, and represents the impact of 2022 farming, processing, and drying. All data provided by BIM is for the study period.

Geographical coverage

Geographical coverage describes the geographic area from which unit process data is collected for the study. All data is provided directly by BIM and represents the locations where processes are occurring.

US EPA eGRID2021 regional grid specific emission factors for NPCC New England (NEWE) electricity generation were used to calculate emissions for BIM. Most of the Ecoinvent and DataSmart datasets are US data; European datasets are used when US data is not available.

Technology coverage

Technology coverage describes how well the data set used to develop the LCA model represents the true technological characteristics of the system. Materials and processes were identified through BIM specifications and discussions with BIM. Materials were mapped to Ecoinvent and DataSmart processes and surrogate materials were used where material specific data was not available. Transport emissions were mapped to the EPA Emission Factors Hub. Electricity usage was mapped to eGRID2021 data.

Precision

Precision is the measure of the variability of the data values for each data category. Precision cannot be measured as only one data set was provided. Mussel farming yield fluctuates year over year and this dataset only considers one growing season. Past and future seasons are expected to differ from the data presented in this study.

Completeness

Completeness measures the percent of primary data collected and used for each category in a unit process. Consumables for farming and processing, fuel use for boats, packaging materials, and transport distances and weights for shipment of packaged mussels were collected from BIM. BIM electricity, natural gas, and water use was collected via provider bills. In most cases, Ecoinvent or DataSmart data was used to represent impacts from material production, assembly processes, use energy, distribution, and end of life. The EPA Emission Factors Hub was used for calculating the combustion emissions of transportation and fugitive emissions from refrigeration.

Representativeness

Representativeness is the assessment of how the data set used in the LCA model reflects the true system. Data reflects BIM operations during the study period and is considered representative of the study period and 2023 farming, processing, storage & distribution year.

Consistency

Consistency considers how uniformly the study methodology is applied to the various components of the analysis. The methodology was applied to all components of mussel farming and processing consistently, in terms of modeling and assumptions.

Reproducibility

The LCA modeling has been performed and described such that this LCA could be reproduced by another LCA practitioner. This report contains all life cycle inventory data and all assumptions used to calculate the environmental impact of the kelp farming, processing, and drying operations during the study period.

METHODS AND RESOURCES

This section describes the emissions included in the PCF, methodologies used to calculate emissions, and emission factor data sources.

EMISSIONS BY SCOPE

The GHG Corporate Standard categorizes a company's direct and indirect emissions into three scopes, as outlined in Figure 4. Scope 1 emissions relate to a company's direct emissions from facilities or equipment owned or controlled by the reporting company. Scope 2 emissions include the indirect emissions from the generation of purchased energy used by the reporting company, most commonly electricity. Scope 3 emissions encompass all other indirect emissions that occur within a company's value chain and are categorized into 15 distinct categories for reporting purposes.

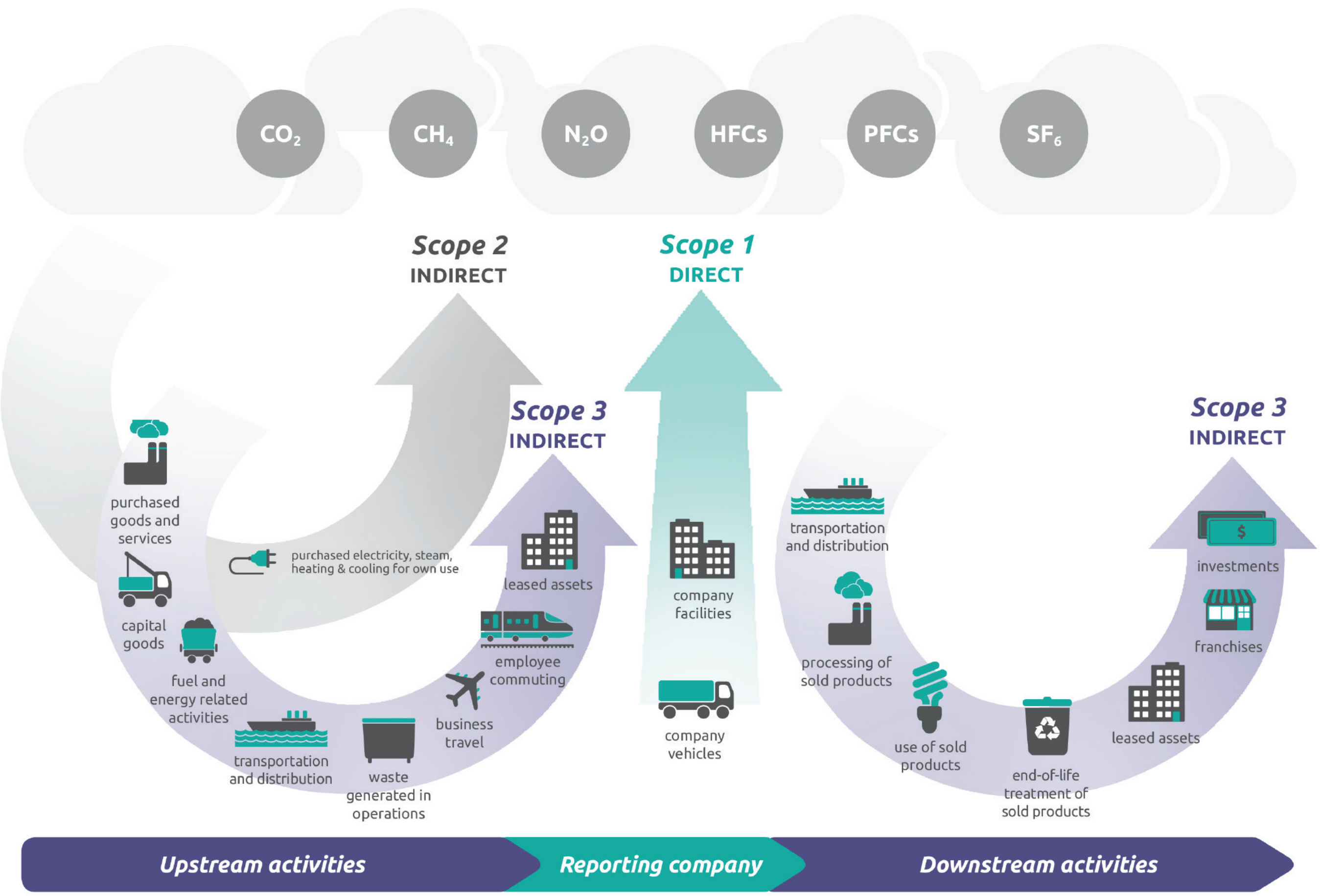


Figure 4.
Overview of GHG Protocol scopes and emissions across the value chain
(WRI, wbcsd. Corporate Value Chain (Scope 3) Accounting and Reporting Standard. Figure 1.1.)

Table 5 provides an overview of the scopes included in this study. The scope of the study is cradle to local distribution and Boston distribution hub of packaged mussels. This includes refrigeration and energy at BIM facilities, biogenic emissions from mussel farming, fuel use from boats, consumables, packaging materials, truck transport, and waste generated in operations. For PCFs, capital equipment (e.g., mussel rafts, boats, processing equipment), business travel, and employee commuting are generally excluded and are also excluded in this study. Furthermore, given the scope is cradle to distribution, downstream emissions such as processing of sold products, use of sold products, and end of life are excluded.

Category 3 covers the fuel and energy related activities that are not included in scope 1 and 2. This includes extraction, production, and transportation of fuels and electricity consumed by the reporting company and the transmission and distribution losses of electricity. For BIM, this includes the upstream emissions electricity, natural gas, and diesel/gasoline used in trucks and boats.

The GHG Protocol separates upstream and downstream transportation and distribution emissions into categories 4 and 9 respectively. These include transportation and distribution that occur in vehicles not owned or operated by the reporting company. Category 4 includes transportation of purchased products and transportation services purchased by the reporting company, including inbound and outbound logistics and transportation within a company's own facilities. Category 9 includes the downstream transportation of sold products that are not paid for by the reporting company. Since BIM pays for the transportation of finished goods to local customers and the Boston distribution center, this is technically categorized as category 4 and are categorized this way in the report. These emissions are however "downstream" of BIM operations. Furthermore, the transportation of purchased goods to BIM facilities was excluded from this study as its impact on overall footprint is negligible.

Table 5: Emission scope and study data included in the scope

Emission Scope	Study data included in the scope
Scope 1 - Direct emissions from sources owned or controlled by BIM	
Fugitive refrigeration	Refrigerant capacity of all refrigeration units via refrigeration specs
Stationary Combustion	Amount of fuel burned onsite via utility bills
Mobile Combustion	Miles driven or gallons of fuel used for all BIM owned boats or vehicles
Biogenic	Total lbs of mussels harvested to calculate direct CO_2, N_2O, and CH_4 released by mussels during growth
Scope 2 - Indirect emissions from purchased energy	
Purchased Electricity	Electricity purchased via utility bills
Scope 3 - Indirect emissions within BIM's value chain	
Category 1 – purchased goods and services	Mass and material of all purchased goods via purchasing records
Category 3 – Upstream emissions from fuel & electricity	Amount of fuel and electricity used to calculate upstream energy emissions
Category 4 - Upstream transportation and distribution	Miles driven or gallons of fuel used for transportation of products in vehicles not owned by BIM
Category 5 – Waste generated in BIM operations	Mass, type, and end of life disposition for all wastes as available

GREENHOUSE GASES

The greenhouse gases included in this study are carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), and fluorinated gases (refrigerants). All gases are converted into CO2 equivalents (CO2e) using the characterization factors outlined in the IPCC Sixth Assessment Report (AR6).[5] These factors represent GWP which is a measure the amount of energy that 1 ton of each gas will absorb over 100 years relative to the amount that CO2 absorbs. The GWP of each gas used in this study is in Table 6.

Table 6: GWP of greenhouse gases in the study

Gas	GWP (kg CO2e/kg)
CO2	1
CH4	28
NO2	273
R-404A	3,922

EMISSION FACTOR DATA SOURCES

Emission factors, or kilograms of carbon dioxide equivalents (kgCO2e) per process or material were sourced from multiple resources as outlined in Table 7. Note that biogenic emissions from shellfish growth have their own unique set of calculations and data sources included in section *Farming | Biogenic emissions* of this report.

Table 7: Emission factor data sources

Source and version	Description	Application to this study
Databases		
DataSmart v2.2	DataSmart data is a combination of USLCI and ecoinvent data, modified specifically to be representative of US operations. Impact assessment method must be used to calculate emission factors. More information at https://longtrailsustainability.com/services/software/datasmart-life-cycle-inventory/	Material, processing, and some transport background datasets are used to calculate emission factors. For example, inventory datasets for polypropylene are used, as the practitioners did not collect primary data on polypropylene production for this study.
Ecoinvent, cut-off by classification, v3.8	Database providing peer reviewed life cycle assessment and data sets, providing background data for materials and processes. Impact assessment method must be used to calculate emission factors. Most ecoinvent data is based on European operations. More information at https://ecoinvent.org/.	Material, processing, and some transport background datasets are used to calculate emission factors. For example, inventory datasets for polypropylene are used, as the practitioners did not collect primary data on polypropylene production for this study.
EPA eGRID2021 NEWE emission factor	The Emissions & Generation Resource Integrated Database (eGRID) is a comprehensive inventory of environmental attributes of electric power systems. The preeminent source of air emission data for the electric power sector, eGRID is based on available plant-specific data for all U.S. electricity generating plants that provide power to the electric grid and report data to the U.S. government. eGRID uses data from the Energy Information Administration (EIA) Forms EIA-860 and EIA-923 and EPA's Clean Air Markets Program Data. Emission data from EPA are carefully integrated with generation data from EIA to produce useful values like pounds of emissions per megawatt-hour of electricity generation (lb/MWh), which allows direct comparison of the environmental attributes of electricity generation. More information and access the data at https://www.epa.gov/egrid/download-data	eGRID utility grid emission factors are from "eGRID subregion annual CO2 equivalent total output emission rate (lb/MWh)"
EPA Emission Factors for Greenhouse Gas Inventories, 18 April 2023	Provides carbon dioxide equivalent emission factors for purchased electricity, mobile combustion, and other transportation. More information and access to the data at https://www.epa.gov/climateleadership/ghgemission-factors-hub.	Emission factors used for burning diesel in boats, gas in F150 truck, and GWP for R-404A refrigerant used at BIM
International Agency Energy (IEA) Life Cycle Upstream Emission Factors 2023 – pilot edition	The pilot database assesses and compiles reliable data to provide a global, harmonized database. More information and access to the data at https://www.iea.org/data-and-statistics/dataproduct/life-cycle-upstream-emission-factorspilot-edition.	Source of upstream emissions from electricity generation

Source and version	Description	Application to this study
USLCI	Database developed by the National Renewable Energy Laboratory (NREL) to analyze the environmental impacts of a material, component, or assembly made in the US. More information at https://www.nrel.gov/lci/.	Some material datasets are used to calculate emission factors. For example, inventory datasets for polypropylene are used, as the practitioners did not collect primary data on polypropylene production for this study.
Literature		
Impact of Vehicle Weight Reduction on Fuel Economy for Various Vehicle Architectures, December 2007	Physics based model developed to consider how vehicle weight reduction impacts fuel economy. Accessible at https://www.h3xed.com/blogmedia/Ricardo_FE_ MPG_Study.pdf.	Source of adding 100lbs of cargo can decrease fuel economy by 1%
Life cycle assessment of New Zealand Mussels and Oysters, v1.6, October 2021	LCA of blue mussels and oysters grown off the coast of New Zealand. Includes a comparison to other shellfish and protein sources. More information at https://www.thinkstepanz.com/resrc/case-studies/a-life-cycle-assessment-of-nz-mussels-and-oysters-lcaaquaculture/.-	Calculations for biogenic carbon emissions during shellfish growth in this study are based on calculations in the NZ study.
Recycle Lincoln, Estimating Material Weight	Masses of materials separated for recycling. Available at https://www.lincoln.ne.gov/files/sharedassets/public/v/1/ltu/utilities/solid-wastemanagement/recycling/commercial-factsheets/estimating-material-weight.pdf	Source of mass of cubic yard of corrugate
US EPA Stationary Refrigeration Leak Repair Requirements, June 2023	Provides refrigerant trigger leak rates for a 12 month period based on the appliance type. Accessible at https://www.epa.gov/section608/stationaryrefrigeration-leak-repair-requirements.	Source for 20% trigger rate for commercial refrigeration.
Software & impact assessment method		
IPCC 2021 GWP 100yr	This method is based on IPCC report "AR6 Climate Change 2021: The Physical Science Basis" and includes the Global Warming Potential (GWP) climate change factors of IPCC with a timeframe of 100 years, where carbon dioxide uptake is implicitly included.	DataSmart, ecoinvent, and USLCI datasets are analyzed with this impact assessment method in SimaPro to calculate material and process specific emission factors
SimaPro v9.4.0.2	Software program that facilitates the calculation of emission factors using IPCC 2021 GWP 100yr for datasets in SimaPro databases.	SimaPro facilitates the calculation of emission factors for DataSmart, ecoinvent, and USLCI datasets using IPCC 2021 GWP 100yr impact assessment method.

ANNUAL CARBON FOOTPRINT METHODOLOGY

The carbon footprint of a material or process is a function of the amount and emission factor, as shown in Equation 2. Material and process carbon footprints are found in the "annual emissions" column of the process inventory tables in section Inventory data and footprint of this report.

Equation 2.
Material or process carbon footprint, kg CO2e = A*EF

Where:
A = annual inventory amount of material or process, typically kg, lb, kWh, number of units
EF = kg CO2e per 1 unit of measure, typically kg CO2e/kg, kg CO2e/lb, kg CO2e/kWh, kg CO2e/1 unit

The annual carbon footprint is a sum of all material and process carbon footprints during the study period.

Equation 3.
Annual carbon footprint = Σ material and process carbon footprints

CARBON FOOTPRINT PER POUND OF MUSSELS METHODOLOGY

The carbon footprint per pound of mussels is a function of the farming, processing, and storage and distribution annual footprints and mass of mussels at each life cycle stage. While 766,431 pounds of mussels are harvested, 88,000 pounds of those are seed mussels that are returned to the ocean to continue growing and an additional 87,000 pounds are broken mussels that are not saleable. Therefore, farming yields 591,431 pounds of saleable mussels and this value is used to calculate the footprint of one pound of mussels.

Equation 4.
kg CO2e per lb. mussels sold = (CF+CP+CD)/MF)

Where:
CF = Annual Carbon Footprint of mussel farming = 145,540 kg CO2e
CP = Annual Carbon Footprint of mussel processing = 55,160 kg CO2e
CD = Annual Carbon Footprint of mussel storage and distribution = 29,406 kg CO2e
MD = annual mass mussels sold = 591,431 pounds

INVENTORY DATA AND FOOTPRINT

The PCF is divided into stages in order to isolate the stages and processes that contribute the most to the carbon footprint. Isolating the stages will in turn enable BIM to continue to improve the environmental performance of their products by concentrating their efforts on the highest impact stages.

For each life cycle stage, Pure Strategies developed a data needs table defining the data used to calculate the inventory inputs. Pure Strategies then worked directly with BIM employees to populate the needs table. Collected data was converted into life cycle inventory model inputs. Details of the life cycle stages and all inputs are below.

FARMING

Farming emissions include biogenic emissions from mussel shell formation and mussel growth, consumables, fuel use from boats, and waste. Overall, farming makes up 63% of total annual emissions. During the study period, 766,431 lbs. of mussels were harvested from the lines and brought back to BIM's processing facility. Of those, 88,000 lbs. were deemed too small to sell and were put back into the ocean as mussels to be harvested in the following year. An additional 87,000 lbs. were broken and unsaleable. The total farming yield, or mass of saleable mussels, is 591,431 lbs.

To yield one pound of saleable mussels, 1.3 pounds of mussels are harvested, with 0.15 pounds of seed mussels and 0.15 pounds of broken mussels.

Table 8: Summary of farming emissions

Farming yield (or saleable mussels) in 2022	591,431 pounds
Farming emissions in 2022	145,540 kg CO2e
Farming emissions per pound of saleable mussels	0.25 kg CO2e

Farming | Biogenic emissions

Biogenic emissions during mussel farming result from two processes:

1. CO2 released during mussel shell formation
2. N2O and CH4 released during the mussel life cycle.

BIM provided data on harvest amount, total mussels sent to seed, mussel life cycle, and meat to shell ratio. Biogenic emissions were only calculated for the total amount of mussels harvested and sent to processing. Mussel seed is excluded, as those emissions would be captured in subsequent years when they are harvested and processed. BIM's average mussel weight is 0.29 lbs., with meat making up 52% of total weight.

Table 9: Faming biogenic emissions inventory and emissions

Scope	Input	BIM Provided Data	Units	Calculation Details	Annual	Units	Annual Emissions (kg CO2e)
Scope 1	Direct CO2 release	766,431	lbs.	Total Mussel weight = .29lbs Shell weight = 0.14lbs Meat weight = 0.15lbs Mussels harvested = 766,431lbs Mussel seed = 88,000lbs returned to ocean	327,518	lbs shell	42,778
Scope 1	Direct N2O and CH4 release	766,431	lbs.	Total Mussel weight = 0.29lbs Shell weight = 0.14lbs Meat weight = 0.15lbs Mussels harvested = 766,431lbs Mussel seed = 88,000lbs returned to ocean	350,913	lbs meat	34,690

To calculate the release of CO_2 during mussel shell formation, an equation developed by Ray et. al.[6] based on the mass of dry shell, shell calcium carbonate ($CaCO_3$) percent, ratio of CO_2 released to $CaCO_3$ precipitated (PSI), and molar mass ratio between CO_2 and $CaCO_3$ was used.

Equation 5.
CO2 release during shell formation =
Shell Mass*PSI*% Shell CaCO3*(MW CO2/MW CaCO3)

Where:
Shell Mass = total mass of the shell (1kg)
PSI = ratio of CO2 released to CaCO3 precipitated = 0.694
% Shell CaCO3 = percent of CaCO3 within shells = 94.42%
MW CO2 = molecular weight of CO2 = 44.01 g/mol
MW CaCO3 = molecular weight of CaCO3 = 100.0869 g/mol

Using Equation 5, CO_2 release during mussel shell formation was calculated to be 0.288 kg CO_2. The percent $CaCO_3$ of mussel shells was calculated to be 94.42% by Barbachi et. al.[7] PSI was calculated to be 0.694 by the carbon footprint of New Zealand mussels using the seacarb library for the statistical analysis program R based.[8]

PSI values are dependent on water temperature and salinity. Per the New Zealand study, the average water temperature in coastal New Zealand is 59F and salinity is 34 psu. Morris & Humphreys calculated CO_2 release to be 0.292 kg CO_2 per kg bivalve. This value was based on mussels farmed in Southern Portugal, where the average water temperature is 57F to 66F and salinity is 36 psu.[9] Comparatively, water temperature in the Gulf of Maine is 54F[10] and salinity ranges from 31.6-33.5 psu.[11] Given the similarity in water temperature and salinity, it is assumed that the release of CO_2 during mussel shell formation is similar for BIM mussels grown in the Gulf of Maine.

To calculate the release of CH_4 and N_2O during the mussel life cycle, production rates of CH_4 and N_2O from Bonaglia et. al.[12] and a 21-month average life cycle for BIM farmed mussels were used. Mussel waste during harvest is not accounted for as the amount is minimal and thus is not measured. For a conservative estimate, it is assumed that all CH_4 and N_2O will reach the atmosphere without further reduction from denitrification. Release of CH_4 and N_2O is calculated as follows:

Equation 6.
Release of CH4 and N2O per kg mussel meat = PRgas*LS*MWgas

Where:
PRgas = production rate of each gas
LS = lifespan of BIM mussels in hours
MWgas = molecular weight of each gas

Bonaglia et. al. calculated production rates of CH_4 to be 3 nmol per gram of bi-valve per hour and N_2O to be 0.5 nmol per gram of bi-value per hour. It is important to note that these rates were calculated from a wild bi-valve species in the Baltic Sea and thus are connected to a large degree of uncertainty. However, better datasets are not currently available. Using Equation 6 and production rates from Bonaglia et. Al. , CH_4 and N_2O release was calculated to be 3.35E-04 and 1.53E-04 kg CO_2 per lbs mussel, respectively.

IPCC Sixth Assessment report GWP values for CH_4 and N_2O were used to calculate total GWP in CO_2 equivalents. Total GWP per pound of meat was calculated using BIM's ratio of whole mussel mass to mass of edible meat as shown in Table 10.

Table 10: CH4 and N2O release during BIM mussel production

Category	Amount	Unit
Mussel mass per lb edible meat	1.93	lbs
CH4 produced per lb mussel	3.35E-04	kg CH4
N2O produced per lb mussel	1.53E-04	kg N2O
CH4 produced per lb meat	6.47E-04	kg CH4
N2O produced per lb meat	2.96E-04	kg N2O
GWP from CH4 per lb meat	0.018	kg CO2e
GWP from CH4 per lb meat	0.081	kg CO2e
Total GWP per lb meat	0.099	kg CO2e

Nitrogen removal is not included in the study as data sources are limited and there are wide seasonal and location specific fluctuations in uptake. Furthermore, there is no carbon sequestration included in the study, as the carbon sequestered in the shell is assumed to be emitted into the atmosphere within a 100-year timeframe during end of life. Some studies have assessed the potential of sequestration for shells that are returned to the sea, essentially sequestering the carbon that was emitted during shell formation through the absorption of aqueous CO_2.[13] However, there is much discussion on whether or not shell carbon truly remains as aqueous carbon or eventually gets emitted back into atmospheric CO_2. Given the variability in regional oceanic chemistry further studies are needed on this subject. For a conservative estimate, this study does not account for carbon sequestration in the 13% of mussel waste returned to the ocean.

Farming | Consumables

Farming consumables include rope, cotton mesh and bobbin, oil and grease for boats, and knives. BIM provided the amount of each input, along with their lifespan as shown in Table 11. For single use consumables, BIM provided the annual amount consumed. In total, 2,085 lbs of consumables from farming are included in the analysis. An additional 127lbs, including gloves, bibs, life jackets, boots, hearing protection, fuel & oil filters, and shovels are excluded. Consumables for the rafts and nets used during mussel farming are also excluded, as their lifespan is >5 years. Given the carbon footprint of the included consumables across all stages contributes 5% of the annual footprint and excluded consumable weight is less than 2% of total consumable weight, it is not expected that the excluded consumables will have significant carbon impact.

To calculate material production emissions, Ecoinvent datasets and IPCC 2021 GWP 100yr were used. Where available, processing emissions (ie. extrusion, blow molding, weaving) are included. The annual amount of consumables with a lifespan longer than 1 year is calculated by dividing the total mass by the lifespan. To calculate the emissions of Knives – Victorinox, equal volumes of poly propylene and steel were assumed for the knife composition. Weights of each material were calculated using density. Woven cotton was used as a proxy for cotton mesh as data for cotton mesh was not available.

Table 11: Farming consumables inventory and emissions

Scope	Input	BIM Provided Data	Units	Calculation Details	Annual amount	Units	Annual Emissions (kg CO2e)
Scope 3 -Category 1	Rope	537,500	ft	59.31 lbs/roll; 1200 ft/roll Lifespan = 20 years	1,328	lbs	1,578
Scope 3 -Category 1	Cotton mesh	88,200	ft	6.35 lbs/roll; 1640 ft/roll	341	lbs	3,684
Scope 3 -Category 1	Cotton bobbin	126,000	ft	1.19 lbs/roll; 1312 ft/roll	114	lbs	755
Scope 3 -Category 1	Oil - Shell Rotella 15W-40	38	gal	Density = 0.87 g/ml 3785.41 ml/gal	279	lbs	144
Scope 3 -Category 1	Grease	6	units	0.97 lbs/tube	6	lbs	3
Scope 3 -Category 1	Gear box oil	1	gal	Density = 0.87 g/ml 3785.41 ml/gal	7	lbs	4
Scope 3 -Category 1	Knives -Victorinox	80	units	0.11 lbs/knife Density PP = 0.91g/cm3 Density stainless steel = 7.89 g/cm3	8	lbs	18

Farming | Fuel use

Farming fuel use included fuel from BIM owned boats. Given BIM's processing facility is located at the wharf, there is no truck transport required for harvest. BIM provided the amount of fuel used during mussel farming in gallons from purchasing records. This includes the fuel used post-harvest to reseed the mussels that were too small to harvest.

Fuel use emissions include fuel production and combustion emissions. Ecoinvent datasets and IPCC 2021 GWP 100yr were used to calculate fuel production emissions, unless otherwise noted. The EPA Emission Factors Hub is used to calculate fuel combustion emissions, unless otherwise noted. For Boats #2-4, the exact fuel mix was unknown and a 50% diesel and 50% gasoline fuel mix were assumed.

Table 12: Farming fuel use inventory and emissions

Scope	Input	BIM Provided Data	Units	Calculation Details	Annual Amount	Units	Annual Emissions (kg Co2e)
Scope 1 - mobile combustion	Diesel from boat #1	3,368	gal		3368	gal	35,145
Scope 1 - mobile combustion	Diesel portion from boats #2-4	1,676	gal	1675.93 gal / 2 = 838 gal diesel	838	gal	8,744
Scope 1 - mobile combustion	Gasoline portion from boats #2-4	1,676	gal	1675.93 gal / 2 = 838 gal gasoline 4 stroke motor	838	gal	7,412
Scope 3 - Category 3	Diesel - Fuel production emissions	4,206	gal		4,206	gal	8,597
Scope 3 - Category 3	Gasoline - Fuel production emissions	838	gal		838	gal	1,902

Farming | Waste

Farming waste includes all farming consumables, including the 127 pounds of consumables that are excluded in Farming | Consumables. BIM provided the mass of waste, end-of-life disposition and facility location for all waste streams.

Ecoinvent datasets and IPCC 2021 GWP 100yr were used to calculate waste emissions. For waste sent to incineration facilities, the only impact is the transport to the facility, as the energy impact is allocated to the end-user of the energy.

Waste to landfill is modeled as generic municipal solid waste, as the exact waste composition (ie. pounds plastic, cardboard, etc) is unknown. Emissions from transport of waste include both fuel production and combustion emissions. Google maps was used to determine the distance between BIM processing facility and waste facilities. Transport impacts are measured in tonmile, one ton of material transported one mile.

Table 13: Farming waste inventory and emissions

Scope	Input	BIM Provided Data	Units	Calculation details	Annual Amount	Units	Annual Emissions (kg Co2e)
Scope 3 - Category 5	Waste oil	39	gal	Waste facility in Turner, ME 48 mi from BIM facility to Turner, ME for incineration with heat recovery Density = 0.87 g/ml	7	tonmi	13
Scope 3 - Category 5	Waste – landfill	2,211	lbs	2,211 lbs consumable waste 10% of waste is sent to landfill	221	lb	62
Scope 3 - Category 5	Waste – incineration with energy recovery	2,211	lbs	2,211 lbs consumable waste 90% of waste is sent to eco-Maine for incineration with energy recovery 7mi from BIM to eco-Maine	6	tonmi	11

PROCESSING

Processing emissions include consumables, utilities for the processing facility, and waste. Overall, processing makes up 24% of total annual emissions. Utilities include electricity, natural gas and water consumption. Some farming activities as well as storage of finished product occur at this facility. However, utilities could not be allocated to respective sub-processes. Thus, processing emissions are likely higher than if energy could be allocated appropriately.

Table 14: Summary of processing emissions

Total mussels sold in 2022	591,431	pounds
Emissions in 2022	55,160	kg CO2e
Emissions per lb mussels sold	0.09	kg CO2e

Processing | Consumables

Processing consumables include plastic totes, oil and grease for machinery, biodegradable plastic bags, xactic coolers, knives, and pallets. BIM provided the amount of each input, along with their lifespan as shown in table 7. For single use consumables, BIM provided the annual amount consumed. In total, 5,679 lbs. of consumables from processing are included in the analysis. An additional 17 lbs., including bibs, hearing protection, and shovels are excluded from processing consumables. Compostable plastic tags were also excluded as the weight is negligeable. Given the carbon footprint of the included consumables in farming and processing makes up 6% of the annual footprint and excluded consumable weight is less than 2% of total consumable weight, it is not expected that the excluded consumables will have significant carbon impact.

Material production emissions were calculated using Ecoinvent datasets and IPCC 2021 GWP 100yr. Where available, processing emissions (ie. extrusion, blow molding, weaving) are included. The annual amount of consumables with a lifespan longer than 1 year is calculated by dividing the total mass by the lifespan. To calculate the emissions of Knives – Victorinox, equal volumes of poly propylene and steel were assumed for the knife composition. Weights of each material were calculated using density. Lubricating oil was used as a proxy for grease as process specific data was not available. Generic base oil was used as a proxy for hydraulic oil given the lack of available data.

Table 15: Processing consumables inventory and emissions

Scope	Input	BIM Provided Data	Units	Calculation Details	Annual Amount	Units	Annual Emissions (kg Co2e)
Scope 3 -Category 1	Plastic totes	75	units	7.7 lbs/tote Lifespan = 5 years	116	lbs	184
Scope 3 -Category 1	Grease	6	units	0.97 lbs/tube	6	lbs	3
Scope 3 -Category 1	Plastic bags	78,000	units	0.05 lbs/bag	3,900	lbs	4,568
Scope 3 -Category 1	Xactic plastic coolers	10	units	115 lbs/xactic	1,150	lbs	1,834
Scope 3 -Category 1	Knives - Victorinox	10	units	0.11 lbs/knife Density PP = 0.91g/cm3 Density stainless steel = 7.89 g/cm3	1	lbs	2
Scope 3 -Category 1	Hydraulic Oil	1	gal	Density = 0.87 g/ml 3785.41 ml = 1 gal	7	lbs	4
Scope 3 -Category 1	Bio-food grade hydraulic fluid ISO 46	1	gal	1 gal/yr. Comes in a 5-gallon bucket 39.90 lbs/5gal bucket	8	lbs	27
Scope 3 -Category 1	Lubrication - WD40	10	units	0.83 lbs/can	8	lbs	4
Scope 3 -Category 1	Pallets	21	units	23 lbs/pallet	483	lbs	66

Processing | Utilities

Processing utilities include electricity, natural gas, and water. BIM provided utility bills for all months during the study period (January – December 2022).

Upstream emissions for both natural gas and purchased electricity are included in total emissions. Upstream emissions include the production of natural gas, the generation of electricity, and the transmission and distribution losses.

Ecoinvent datasets and IPCC 2021 GWP 100yr were used to calculate emissions for water use and the production of natural gas. The EPA Emission Factors Hub was used to calculate emissions from the stationary combustion of natural gas.

For electricity, the NPCC New England (NEWE) regional grid data set was used, as BIM's facility is located within that eGRID region. For upstream emissions from electricity generation, a US country level factor from the International Agency Energy (IEA) Life Cycle Upstream Emission Factors pilot dataset for 2023 was used. Regional or state-level data is not currently available.

Table 16: Processing utilities inventory and emissions

Scope	Input	BIM Provided Data	Units	Calculation Details	Annual Amount	Units	Annual Emissions (kg Co2e)
Scope 1 - stationary combustion	Natural gas	2,789	CCF	0.104 mmBtu/CCF natural gas	303,168	MJ	15,374
Scope 3 - Category 3	Natural gas - upstream emissions	2,789	CCF	108,72 MJ/CCF natural gas	289.4	mmBtu	6,037
Scope 2	Electricity	79,799	kWh	BIM utility bills	79,799	kWh	19,690
Scope 3 - Category 3	Electricity - upstream emissions	79,799	kWh	BIM utility bills	79,799	kWh	5,331
Scope 3 - Category 1	Water	985	HCF	748 gal/HCF 3.79kg/gal water	2,792,396	kg	1,001

Processing | Waste

Processing waste include all waste from processing consumables, recycling, and wastewater treatment. BIM provided waste utility records and the end-of-life disposition and facility location for all waste streams. BIM has a scrap rate of 13% of total harvested mussels. All mussel and seawater waste are disposed of back to the ocean. No impact is assumed as all carbon that was stored in the shell during shell formation is then released back into the ocean within a 100-year timeframe.

Waste emissions were calculated using Ecoinvent datasets and IPCC 2021 GWP 100yr. For waste sent to incineration, recycling, or wood chipping facilities, the only impact is the transport to the facility, as the energy impact is allocated to the end-user of the final product. Waste to landfill is modeled as generic municipal solid waste, as the exact waste composition (ie. pounds plastic, cardboard, etc) is unknown. Emissions from transport of waste include both fuel production and combustion emissions. BIM provided the location of each waste facility, and Google Maps was used to determine the distance between BIM processing facility and waste facilities.

For calculating wastewater treatment emissions, it was assumed that all process water is sent to wastewater treatment.

All municipal waste is sent to Eco-Maine, where 10% of all waste is sent to a landfill and 90% is sent to an incineration facility with energy recovery. Waste disposition percents were provided to BIM by EcoMaine. Because BIM shares a dumpster with other tenants in their building, the exact mass of processing waste is unknown. Given the impact of waste on the total footprint is <1%, total consumable weight for processing was used as a proxy to estimate waste – landfill/ incineration weight.

The total recycling weight was also unknown given that BIM shares a recycling bin with other building tenants. Equation 7 was used to estimate total weight of recycling.

Equation 7.

$$\text{BIM mass to recyling} = \text{BIM\%} * MW_{corrugate} * Bins_{total}$$

Where:

BIM% = BIM's percentage of materials in total bin

$MW_{corrugate}$ = mass of corrugate per 6 cubic yards

$Bins_{total}$ = number of bins emptied per year

BIM provided estimates of their total recycling composition and percent share of the recycling bin. Using BIM estimates, their portion of recycling made up 25% of the recycling bin and was composed of 99% corrugate. To estimate total weight, Equation 7 was used, assuming a 6 cubic yard dumpster was assumed, and the average weight of a cubic yard of corrugate was estimated at 106 lbs.[14]

Table 17: Processing waste inventory and emissions

Scope	Input	BIM Provided Data	Units	Calculation details	Annual Amount	Units	Annual Emissions (kg Co2e)
Scope 3 -Category 5	Wastewater treatment	985	hcf	1 hcf = 1 ccf	985	ccf	782
Scope 3 -Category 5	Waste - Landfill	5,213	lbs	5,213 lbs consumable waste 10% waste sent to landfill	570	lbs	159
Scope 3 -Category 5	Waste - incineration with energy recovery	5,213	lbs	5,213 lbs consumable waste 90% of waste is sent to eco-Maine 7 miles BIM to eco-Maine	18	tonmi	35
Scope 3 -Category 5	Pallet waste	483	lbs	7.8mi from BIM facility to woodchipping facility in Westbrook, ME	2	tonmi	4
Scope 3 -Category 5	Recycling	50	units	50 dumpsters emptied per year 99% cardboard BIM estimated that 25% is theirs (remaining 75% is other tenants) Average dumpster size is 6 yd3 106 lbs corrugated cardboard/yd3 Sent to eco-Maine then to a recycling center to be recycled. 7 mi BIM to eco-Maine	28	tonmi	54

STORAGE & DISTRIBUTION

Storage and distribution emissions include fuel use for shipments of sold mussels, packaging materials, and refrigeration at BIM facilities. Overall, storage and distribution make up 13% of total annual emissions.

Table 18: Summary of storage and distribution

Total mussels stored & distributed in 2022	591,034	pounds
Emissions in 2022	29,406	kg CO2e
Emissions per lb mussels stored & distributed (excludes farming and processing)	0.05	kg CO2e

Storage & distribution | Fuel use

Fuel use includes the regional distribution of mussels within Maine via BIM owned vehicle and the distribution of mussels to Boston via refrigerated box truck. For bi-weekly regional distribution within Portland and South Portland, BIM provided the weight and milage of each trip. For all other miscellaneous trips throughout Portland, BIM provided total gallons used. For the shipping of mussels to Boston, MA, BIM provided the truck type, total shipment weight, distance, and frequency.

Fuel production and combustion emissions are included when calculating total fuel use emissions. Ecoinvent datasets and IPCC 2021 GWP 100yr were used to calculate fuel production emissions, unless otherwise noted. The EPA Emission Factors Hub is used to calculate fuel combustion emissions, unless otherwise noted. Ecoinvent data is used for full refrigerated ground transport emissions.

For the shipment of mussels to Boston, MA, emissions are only calculated for the trip to Boston as it is assumed that the truck will be shipping other goods from Boston. For the shipment of mussels to South Portland and Portland, the total round-trip distance was used. Average miles per gallon for a Ford F150 was determined to be 13 MPG through the fueleconomy.gov.[15] To determine the impact of additional mussel weight on fuel economy, Ricardo, Inc. estimated that an additional cargo weight of 100lbs can reduce fuel economy by 1%.[16] Using this estimate, and the total shipment weight provided by BIM, the fuel economy of a full truckload was estimated. To calculate total gallons for the round trip, the average fuel economy of a full and empty truck was used.

Table 19: Storage and distribution fuel use inventory and emissions

Scope	Input	BIM Provided Data	Units	Calculation Details	Annual Amount	Units	Annual Emissions (kg Co2e)
Scope 3 - Category 4	Shipping mussels to Boston, MA	2,450	lbs	Refrigerated ground transport 2 trips/wk for 46 wks 109.2 mi one way Shipping weight = 2,450 lbs/trip	12,307	tonmi	7,236
Scope 1	Shipping mussels to South Portland, ME	368	miles	2005 F150 pickup truck 2 trips/wk for 46 wks Total trip: 4 mi/trip Shipping weight = 630 lbs	29	gal	257
Scope 1	Shipping mussels within Portland, ME	322	miles	2005 F150 pickup truck 2 trips/wk for 46 wks Total trip: 3.5 mi/trip Shipping weight = 1500 lbs	27	gal	236
Scope 1	Miscellaneous trips	720	gal	2005 F150 pickup truck 720 gal additional fuel use	720	gal	6,343
Scope 3 - Category 3	Gasoline - Fuel production	776	gal	Total gasoline fuel production emissions	776	gal	1,762

Storage & distribution | Packaging Materials

Storage and distribution packaging materials include cardboard, plastic wrap, and plastic bulk liners. BIM provided the total amount of packaging required for total amount of mussels sold during the study period.

Material production emissions were calculated using Ecoinvent datasets and IPCC 2021 GWP 100yr. Where available, processing emissions (ie. extrusion) are included. US datasets were used to model all packaging materials, as all packaging materials are sourced from the US.

Table 20: Storage and distribution packaging materials inventory and emissions

Scope	Input	BIM Provided Data	Units	Calculation Details	Annual Amount	Units	Annual Emissions (kg Co2e)
Scope 3 - Category 1	Cardboard Seafood box	1,830	units	1830 units at 3.3 lbs each	6,039	lbs	3,321
Scope 3 - Category 1	Cardboard Opti bins	570	units	570 units at 15.85 lbs each	9,035	lbs	4,968
Scope 3 - Category 1	Plastic stretch wrap	9	units	9 cases at 4 rolls/case and 6.15lbs/roll	221	lbs	255
Scope 3 - Category 1	Plastic bulk liner	6	units	6 rolls at 100 liners/roll 1.1 lbs/ liner	660	lbs	760

Storage & distribution | Refrigeration

Storage and distribution refrigeration emissions include refrigerant recharge for BIM's cooler and ice machine. All energy emissions from refrigeration are included in utilities emissions in the processing stage. BIM provided refrigerant type and total refrigerant capacity for both units.

Refrigerant R-404A GWP was obtained from the EPA Emission Factors Hub and was used to calculate fugitive emissions. Average leak rates were assumed to be 5%, which is one quarter of the 20% trigger rate for recharge, as obtained from the EPA.[17] Refrigerant production emissions for R-404A were not included as data is not available and total emissions are minimal in comparison to fugitive emissions.

Table 21: Storage and distribution refrigeration inventory and emissions

Scope	Input	BIM Provided Data	Units	Calculation Details	Annual Amount	Units	Annual Emissions (kg Co2e)
Scope 1 – fugitive emissions	R-404A - cooler	18	lbs	Total capacity = 18 lbs 5% average leak rate	2	kg	1,601
Scope 1 – fugitive emissions	R-404A – ice machine	30	lbs	Total capacity = 30 lbs 5% average leak rate	1	kg	2,668

PRODUCT CARBON FOOTPRINT RESULTS SUMMARY

Results represent the product carbon footprint of BIM farmed mussels from cradle to local distribution and the Boston distribution center from January 2022 through December 2022. This includes impacts resulting from material inputs, mussel farming and processing, transportation, and waste streams. Consumption and end of life are excluded from this study.

Product carbon footprint results are presented per product stage and category to facilitate data analysis. A summary of the data included at each life cycle stage and input category follows:

1. Mussel Farming includes biogenic emissions from shell formation and mussel growth, consumables, fuel use from boats, and waste.

2. Mussel Processing includes consumables, utilities at BIM processing facility, and waste.

3. Storage and Distribution includes packaging materials, refrigeration for storage at BIM, and fuel use from transport of finished goods locally and to the Boston distribution hub.

EMISSIONS BY SCOPE

The impact of BIM farmed mussels across all scopes included in this study are outlined in Table 22. A majority of emissions fall under Scope 1 and are thus direct emissions from BIM owned or operated facilities and equipment. Biogenic emissions are also included in scope 1 as they are direct emissions occurring during the farming process. Overall, scope 1 emissions account for 67% of the total footprint. Scope 3 emissions account for 14% of the footprint, with category 3 – upstream emissions from fuel use and electricity making up 10%.

Table 22: GHG emissions by scope

Scope	Description	Emissions (kg CO2e)	Percent of total
Scope 1 - Biogenic	Biogenic emissions during mussel farming	77,468	34%
Scope 1 - Fugitive	Fugitive emissions from refrigerants during mussel storage	4,269	2%
Scope 1 - Mobile Combustion	Boat fuel use from during farming	51,302	22%
Scope 1 - Mobile Combustion	Truck fuel use during distribution	6,836	3%
Scope 1 - Stationary Combustion	Stationary combustion of natural gas used during processing	15,374	7%
Scope 2 – Purchased Electricity	Purchased electricity used during processing	19,690	9%
Scope 3 - Category 1	Consumables used during farming	6,185	3%
Scope 3 - Category 1	Consumables used during processing	6,692	3%
Scope 3 - Category 1	Tap water use during processing	1,001	0%
Scope 3 - Category 1	Packaging materials	9,304	4%
Scope 3 - Category 3	Upstream emissions of diesel and gasoline used in boats	10,499	5%
Scope 3 - Category 3	Upstream emissions of natural gas production	6,037	3%
Scope 3 - Category 3	Upstream emissions of electricity generation and T&D losses	5,331	2%
Scope 3 - Category 3	Upstream emissions of gasoline used for distribution	1,762	1%
Scope 3 - Category 4	Refrigerated trucking fuel use for distribution	7,236	3%
Scope 3 - Category 5	Waste produced during farming	86	0%
Scope 3 - Category 5	Waste produced during processing	1,034	0%

EMISSIONS BY BIM PROCESS

The impact of BIM farmed mussels across all product stages is summarized in Table 23, and product stage and input category percentage breakdowns in Table 24 and Figure 5.

Overall, farming has the highest impact across all product stages, accounting for 63% of the total impact. This is largely due to biogenic emissions which make up 53% of farming emissions and 34% of total emissions. Furthermore, fuel use from both farming and distribution account for 27% of total emissions. Processing has the next highest impact, with utilities making up 90% of processing emissions. Consumables, packaging, refrigeration, and waste have a minimal impact, accounting for only 12% of the total footprint.

Table 23: Annual and product footprint across product stages

Product stage	Annual Footprint (kg CO2e)	Product Footprint (kg CO2e/lb sold mussels)
Farmed mussels	145,540	0.25
Processed mussels	55,160	0.09
Packaged and distributed mussels	29,406	0.05
Total Footprint	230,106	0.39

Table 24: BIM lifecycle stages and associated emissions

Category	Category annual emissions, kg CO2e/yr	Percent of Total Annual Emissions
Farming	**145,540**	**63%**
Biogenic emissions	77,468	34%
Consumables	6,185	3%
Fuel Use	61,801	27%
Waste	86	0%
Processing	**55,160**	**24%**
Consumables	6,692	3%
Utilities	47,433	21%
Waste	1,034	0%
Storage and Distribution	**29,406**	**13%**
Fuel Use	15,833	7%
Packaging Materials	9,304	4%
Refrigeration	4,269	2%
Total Emissions	**230,106**	

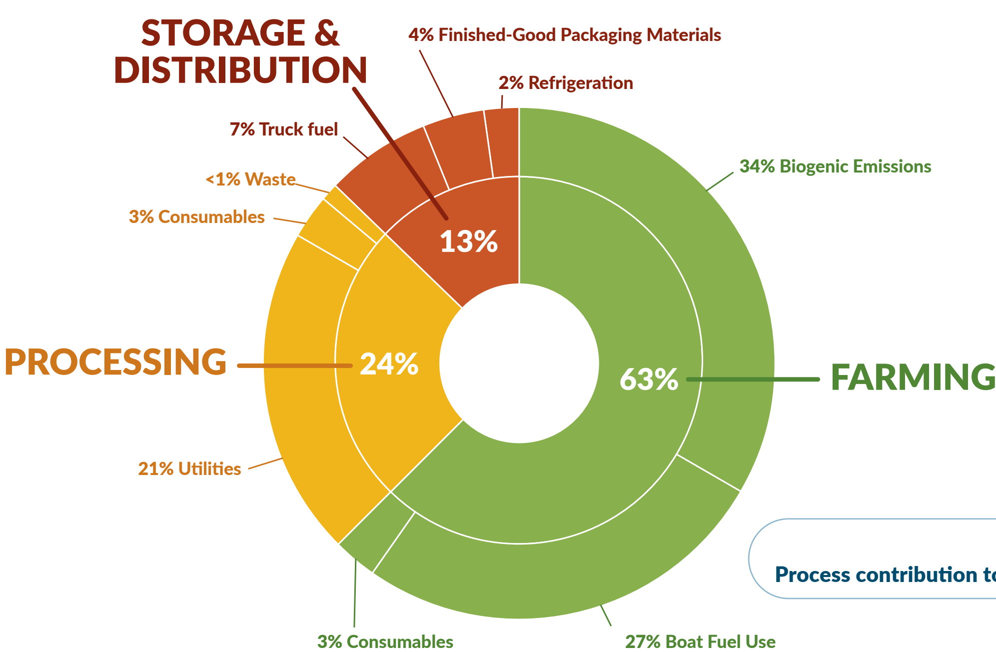


Figure 5.
Process contribution to BIM mussels Product Carbon Footprint

HOTSPOT ANALYSIS

To better understand the primary sources of emissions, a hotspot analysis was conducted. Top emitting inputs from farming, processing, and distribution were identified and are outlined in Table 25. Some inputs have been combined to better understand the total emissions and their impact. Combined inputs include knives – Victorinox, R-404A refrigerant, cardboard packaging, and plastic packaging. Upstream emissions from fuel and electricity have been combined with direct combustion emissions.

Biogenic emissions are the highest emitting category, with fuel use from boats, natural gas, and electricity identified as additional hotspots. Additional minor hotspots include fuel use from regional distribution, fuel use from refrigerated distribution to Boston, and cardboard packaging.

Table 25: Hotspot analysis of inputs. Inputs with >5% of emissions are red text, inputs with >3% and <5% of emissions are bold black, and inputs less than 1% of emissions are light black.

Input Category	BIM process	Input	Annual Emissions (kg CO2e)	Percent of Total Emissions
Biogenic emissions	Farming	Direct CO2, N2O, & CH4 release during growth	77,468	33.7%
Consumables	Farming	Rope (fuzzy rope)	1,578	0.7%
Consumables	Farming	Cotton mesh	3,684	1.6%
Consumables	Farming	Cotton bobbin	755	0.3%
Consumables	Farming	Oil - Shell Rotella 15W-40	144	0.1%
Consumables	Farming	Grease - 6 tubes	3	0.0%
Consumables	Farming	Gear box oil	4	0.0%
Consumables	Farming/processing	Knives - Victorinox	17	0.0%
Fuel Use	Farming	Fuel from boats	61,801	26.9%
Waste	Farming	All farming waste	86	0.0%
Consumables	Processing	Totes - hard plastic	184	0.1%
Consumables	Processing	Grease - 6 tubes	3	0.0%
Consumables	Processing	Biodegradable bags	4,568	2.0%
Consumables	Processing	Exactics - plastic	1,834	0.8%
Consumables	Processing	Knives - Victorinox	2	0.0%
Consumables	Processing	Hydraulic Oil	4	0.0%
Consumables	Processing	Gear oil - Bio-food grade hydraulic fluid ISO 46	27	0.0%
Consumables	Processing	Lubrication - WD40	4	0.0%
Consumables	Processing	Pallets	66	0.0%
Utilities	Processing	Electricity	25,021	10.9%
Utilities	Processing	Gas	21,411	9.3%
Utilities	Processing	Water	1,001	0.4%
Waste	Processing	Wastewater treatment	782	0.3%
Waste	Processing	Municipal waste	159	0.1%
Waste	Processing	Waste - incineration with energy recovery	35	0.0%
Waste	Processing	Pallet waste	4	0.0%
Waste	Processing	Recycling	54	0.0%
Fuel Use	**Storage & Distribution**	**Shipping mussels from Portland, ME to Boston, MA**	**7,236**	**3.1%**
Fuel Use	**Storage & Distribution**	**Regional shipping of mussels within Maine**	**8,598**	**3.7%**
Packaging	**Storage & Distribution**	**Cardboard**	**8,289**	**3.6%**
Packaging	Storage & Distribution	Plastic	1,015	0.4%
Refrigeration	Storage & Distribution	R-404A	4,269	1.9%

ISO 14067 EMISSION REPORTING CATEGORIES

ISO 14067 7.2 requirements for Carbon Footprint of Products study report requires the emissions in Table 26 to be reported. There are no GHG emissions and removals from direct land use change as there is no land use change during farming, processing, and storage and distribution or aircraft transport as no materials are transported via air. The biogenic carbon content of mussels has not been calculated, as mussels have a short life cycle, and the biogenic carbon will be released from the mussel when eaten and the shell when disposed of by the consumer.

Table 26: ISO 14067 emission reporting categories

GHG emission category	GHG emissions per study period, kg CO2e	Description	Application to this study
GHG emissions and removals linked to main life cycle stage in which they occur, including relative and absolute contribution of each	See Inventory Data and Results section	Absolute and relative GHG emissions for each stage are reported	The CO2e for each material and process in the life cycle is reported in the Inventory Data and Results section
Net fossil GHG emissions and removals	152,637	Carbon that is contained in fossilized material	Total emissions, minus biogenic emissions
Biogenic GHG emissions and removals	77,468	Carbon derived from biomass, material of biological origin, excluding material embedded in geological formations and material transformed to fossilized material	Biogenic emissions from direct CO2, N2O, and CH4 release during mussel growth
GHG emissions and removals resulting from direct land use change	0	Change in the human use of land within the relevant boundary; land use change happens when there is a change in the land-use category as defined by IPCC (ie. from forest to cropland)	No direct land use change from mussel farming, production, or storage and distribution
GHG emissions and removals resulting from aircraft transportation	0	GHG emissions from aircraft transportation	No materials are transported via aircraft; mussels are distributed via truck

SENSITIVITY ANALYSES & RECOMMENDATIONS

The goals of sensitivity analyses are to understand how assumptions in data and methodology and uncertainty in the data may affect the PCF results. Sensitivity analysis results are important as they help understand the relative importance of assumptions made and quality of the data.

SENSITIVITY ANALYSIS: ADDITIONAL DISTRIBUTION

The scope of the analysis ends at local and Boston distribution of packaged mussels. To illustrate the importance of refrigerated trucking impacts when transporting longer distances, the impact of three distribution scenarios with additional refrigerated transport was calculated.

The scenarios show that transporting mussels long distances will contribute significant impact. When transporting mussels 1,300 mi via refrigerated truck, half of the impact is from farming and processing and the other half is from distribution. Transporting mussels via refrigerated truck beyond 1,300 miles will result in distribution contributing a much more significant portion of the impact. The carbon impact when transporting via air is about 2.7x more than the impact of transporting the same distance via refrigerated truck. Avoid transport via air where possible to reduce carbon emissions.

SENSITIVITY ANALYSIS: +/- 20% MUSSEL FARMING YIELD

Farmed mussel yield is affected by two factors: eider duck consumption of mussels during growth and normal climate fluctuations in weather, water temperature, and food availability.

Eider ducks are a common problem at mussel farms, where they dive underwater, eating mussels as they grow. BIM is no different, and eider ducks are a big problem. One eider duck is able to eat up to 5.5 pounds of mussels per day[18,19] and at a Nova Scotia mussel farm it was estimated that 25% of mussel seed loss was due to duck predation[20].

BIM currently uses nets to limit eider duck mussel consumption. BIM is constantly repairing nets as ducks break through the nets and eat the mussels. Methods shown to reduce mussel loss and therefore increase yield include playing underwater recordings of boat engine noise at random intervals[21] and nets with a maximum mesh size of six inches and large twine size[22].

A sensitivity analysis was performed for both an increase and decrease of 20% harvested mussels. Modeling assumptions for emissions categories are in Table 27.

Results show that a 20% increase in yield results to a 9% savings of carbon emissions per pound of mussels and a reduction of about 20,000 kg CO2e per year, normalized to 2022 yield. On the other hand, a decrease of 20% yield results in 13% more carbon emissions per pound of mussels or about 30,000 kg increase in CO2 emissions per year, normalized to 2022 yield. This highlights the importance of yield and how fluctuations in yield affects the carbon footprint.

Table 27: Farming yield sensitivity analysis modeling changes

BIM category	20% increase in yield, change vs baseline	20% decrease in yield, change vs baseline
Farming consumables, fuel	Assume equivalent; boats and trucks will make the same number of runs and use the same amount of fuel regardless of change in mass mussels farmed	Assume equivalent; boats and trucks will make the same number of runs and use the same amount of fuel regardless of change in mass mussels farmed
Farming, biogenic emissions	Increase by 20%; mass dependent, so will change with mass of mussels farmed	Decrease by 20%; mass dependent, so will change with mass of mussels farmed
Processing, utilities	Assume BIM utilities are equivalent; no high energy use equipment at BIM, so expect no change based on mass mussels processed	Assume BIM utilities are equivalent; no high energy use equipment at BIM, so expect no change based on mass mussels processed
Processing, waste and consumables	Increase by 20%; mass dependent, so will change with mass of mussels farmed	Decrease by 20%; mass dependent, so will change with mass of mussels farmed
Storage and distribution, refrigerant	Assume equivalent; cooler space will remain unchanged regardless of incremental increase in mussels stored	Assume equivalent; cooler space will remain unchanged regardless of incremental increase in mussels stored
Storage and distribution, fuel use & packaging	Increase by 20%; mass dependent, so will change with mass of mussels farmed	Decrease by 20%; mass dependent, so will change with mass of mussels farmed

SENSITIVITY ANALYSIS: 5% BROKEN MUSSELS RATE

Broken mussels are currently 13% of the total mussels harvested. When the broken mussel rate is reduced to 5% of the total mussels harvested, it is assumed the same total mass of mussels is harvested and a higher portion are unbroken, usable mussels. When the portion broken mussel changes, some processes remain the same, while others change, as shown in Table 28.

Results show that reducing the broken mussels rate to 5% results in a 7% savings in carbon emissions per pound of usable mussel harvested. This equates to a reduction of over 16,000 kg CO2e, when normalized to 2022 yield.

Table 28: Broken mussel rate sensitivity analysis modeling changes

BIM category	20% increase in yield, change vs baseline
Farming consumables, fuel	Assume equivalent; farming does not change, only the mass of usable mussels changes
Farming, biogenic emissions	Assume equivalent; farming does not change, only the mass of usable mussels changes
Processing, utilities	Assume BIM utilities are equivalent; no high energy use equipment at BIM, so expect no change based on mass mussels processed
Processing, waste and consumables	Increase by 9%; mass dependent, so will change with mass of usable mussels
Storage and distribution, refrigerant	Assume equivalent; cooler space will remain unchanged regardless of incremental increase in mussels stored
Storage and distribution, fuel use & packaging	Increase by 9%; mass dependent, so will change with mass of mussels farmed

SENSITIVITY ANALYSIS: +20% MUSSEL FARMING YIELD AND 5% BROKEN MUSSELS RATE

This sensitivity analysis is a combination of two scenarios above: increasing mussel farming yield by 20% and reducing the broken mussel yield to 5%, using the assumptions in Table 27 and Table 28. Results show a 15% reduction in kg CO2e per kg usable mussel yield, equating to a reduction of about 34,500 kg CO2e, when normalized to 2022 yield.

The impact reduction for this combination scenario is less than the sum of the impact reduction for the components separately. This is because once the impact of 20% increase in mussel farming yield is calculated, it is smaller than the baseline.

SENSITIVITY ANALYSIS: BIODIESEL IN BOATS

In the current scenario, fuel use from boats contributes 25% of the product carbon footprint, with diesel accounting for 85% of fuel consumption. According to the EPA Emission Factors Hub, biodiesel has 9% less carbon emissions than diesel. Replacing diesel in boats with biodiesel can reduce annual impact by over 4,000kg CO2e.

SENSITIVITY ANALYSIS: 10% REDUCTION IN FUEL USE

An across the board 10% reduction in fuel use for boats and trucks, through increases in efficiency, minimizing idling, or using more efficient makes/models of equipment, has the potential to reduce annual carbon emissions by over 6,000kg CO2e.

SENSITIVITY ANALYSIS: BIODIESEL IN BOATS AND 10% REDUCTION IN FUEL USE

This analysis assumes that boats are powered by biodiesel and all fuel, including biodiesel, is reduced by 10%. Results show a potential reduction in annual carbon emissions of nearly 10,000 kg CO2e.

The impact reduction for this combination scenario is less than the sum of the impact reduction for the components separately. This is because once the impact of biodiesel in boats is calculated, it is smaller than the baseline. Reducing the value of biodiesel in boats by 10% is less than diesel in boats, given the smaller emission factor for biodiesel.

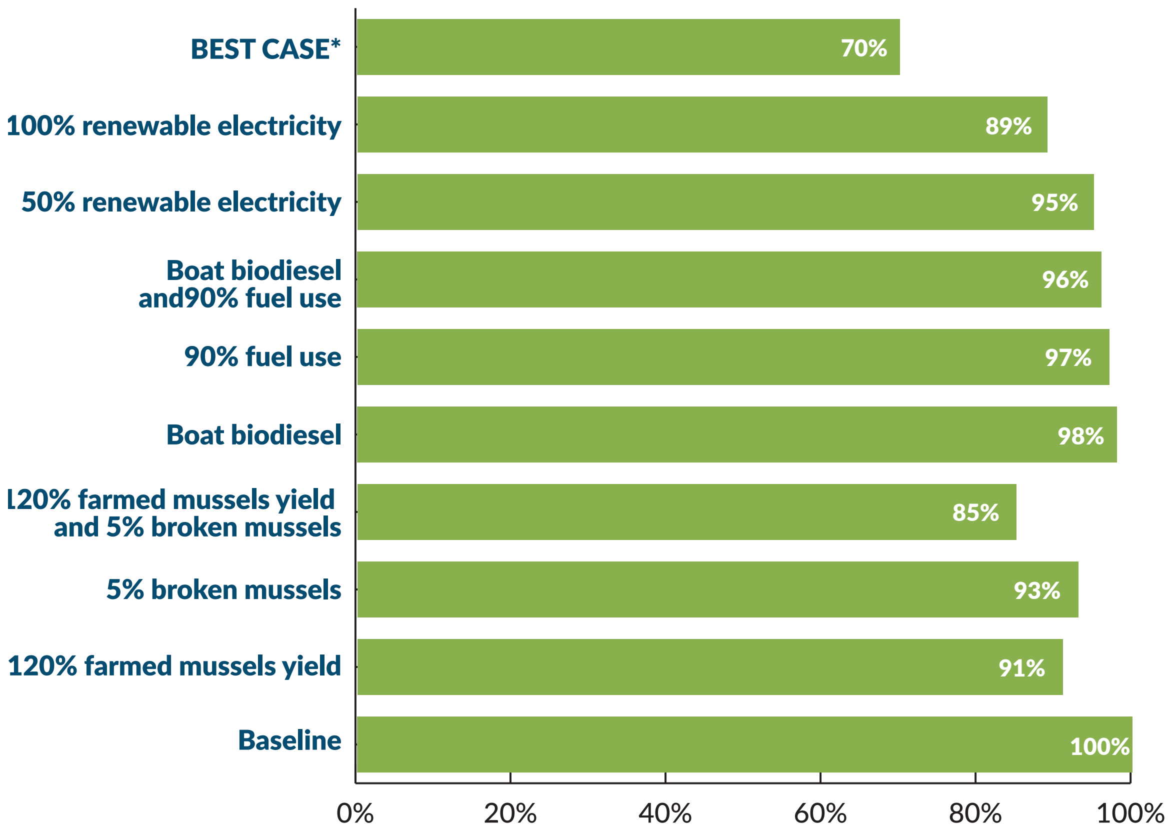
SENSITIVITY ANALYSIS: ADOPT RENEWABLE ENERGY

Purchased electricity, made up of the average Maine grid mix, contributes 11% of the carbon footprint.

Adopting 25% wind energy and 25% solar energy has the potential to reduce annual emissions by over 12,000kg CO2e and doubling the adoption to account for 100% renewable energy has the potential to reduce annual emissions by 24,000kg CO2e.

RECOMMENDATIONS

Figure 7 below shows the reduction in impact associated with the recommendations in the sensitivity analyses in the previous section. Adopting biodiesel in boats and reducing fuel use by 10% has a minor impact on the product carbon footprint, reducing it by 4% when both are adopted. When implemented separately, increasing farmed mussel yield by 20%, decreasing broken mussels rate to 5% and adopting 100% renewable electricity reduces the annual product carbon footprint by about 10%. Exploring ways to drive farmed mussel yield up, broken mussels down, and adopting renewable electricity have the highest potential for impact reduction.



*BEST CASE = 120% farmed mussels yield + 5% broken mussels, boat biodiesel + 90% fuel use, 100% remewable processing electricity.

Figure 7.
Sensitivity analysis results

COMPARISON TO SHELLFISH AND HIGH PROTEIN FOODS

BIM mussel carbon footprint results were compared to PCFs of both shellfish and high-protein foods. Comparisons were made on a 100g protein basis. To convert results to protein, BIM's meat-to-mussel ratio and total protein content of Blue Mussels were used. The total protein content in mussel meat sold by BIM was calculated to be 16,512,400 g protein as shown in Table 2. Refer to Equation 1 for calculation details. Emissions per 100 g protein were calculated to be 1.39 kg CO2/100g protein.

BIM MUSSEL COMPARISON TO OTHER SHELLFISH

This study was first compared to other shellfish product carbon footprints. Two studies were used for this comparison: LCA of New Zealand Mussels and Oysters24 and a Carbon Footprint of Scottish Suspended Mussels and Intertidal Oysters25. Key methodological differences are noted in Table 29.

In order to allow for a more direct comparison, Scotland results were converted into kg CO2e/100g protein and carbon sequestration was removed. In the New Zealand and Scotland studies, emissions from the consumer use phase and end of life were removed. Because Scotland results do not include biogenic CO2 emissions during shellfish growth, it is expected that results from the Scotland study will be lower than BIM's mussels and the New Zealand study. Furthermore, because the New Zealand study represents frozen mussels, it is expected that the New Zealand study will have a higher PCF than BIM and Scotland.

Figure 8 on the following page shows the direct comparison to other shellfish studies, with BIM farmed mussels in yellow. The average impact of mussels is 56% less than the average impact of oysters across all studies. When comparing within mussels, BIM mussels have a 21% lower impact than New Zealand Mussels and a 32% higher impact than Scottish mussels. However, because the Scottish study does not include biogenic emissions, this is not a direct comparison. For a more direct comparison to the Scotland study, when removing biogenic emissions from BIM farmed mussels, the product carbon footprint is 0.9 kg CO2e per 100g protein, equivalent to that of Scottish farmed mussels.

Table 29: Methodological differences in mussel and oyster studies

PCF aspect	BIM Farmed Mussels	New Zealand	Scotland
Functional Unit	kg CO2e/100g protein fresh meat	kg CO2e/100g protein of frozen packaged meat	kg CO2e/kg edible fresh meat
System Boundary	Cradle to distributor	Cradle to grave	Cradle to grave
Biogenic emissions during growth	Included	Included	Excluded
Carbon sequestration	Excluded	Excluded	Included

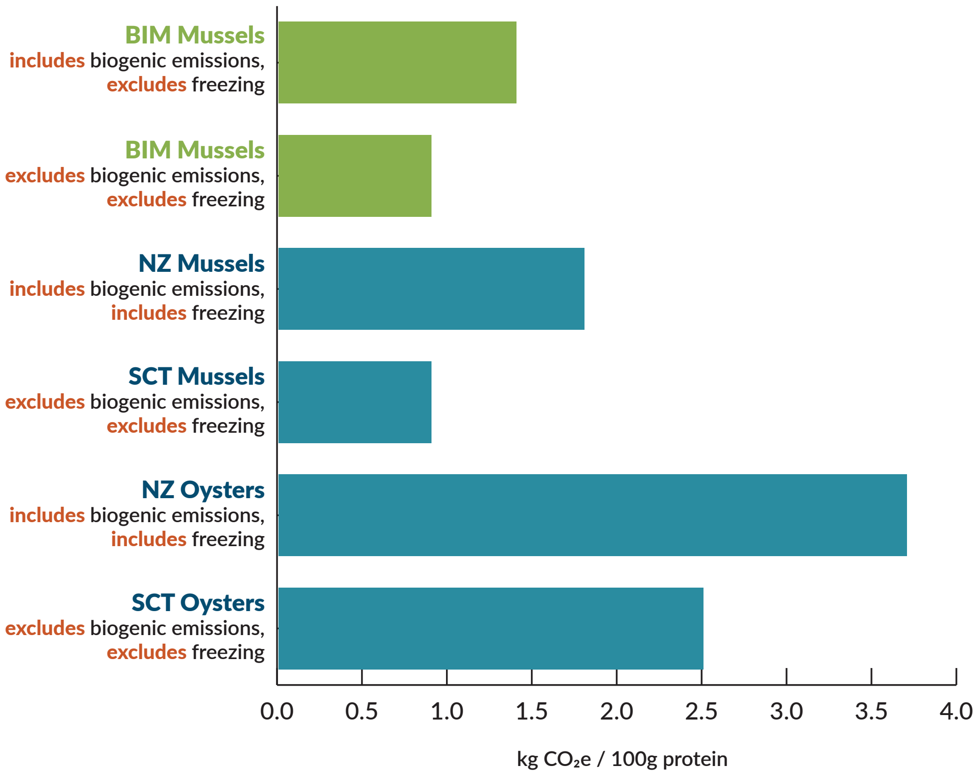


Figure 8.
PCF of BIM farmed mussels compared to other mussel and oyster studies.

BIM MUSSEL COMPARISON TO HIGH PROTEIN FOODS

The results of this study were compared to other protein sources. Poore and Nemecek assessed the cradle to gate environmental impacts of protein-rich foods using consolidated data on global production averages.[23] This is a well-documented and commonly cited study within the LCA community. The product stages covered in Poore and Nemecek were cradle to retail, which includes farming, processing, and distribution to the customer choice at point of sale (ie. typically a grocery store). Given this is the same functional unit, but includes the transport to retail that is not included in the BIM mussel footprint, the carbon emissions for 100g protein from BIM farmed mussels transported 1,000mi (Chicago), 2,000mi (Denver), and 3,000mi (US west coast) have been calculated.

Figure 9 compares the average PCF of high protein foods per 100g protein. BIM farmed mussels is in yellow. The impact of BIM baseline mussels is significantly lower than all animal proteins, about 97% less than beef, about 90% less than pork, and 75% less than poultry. Note that while the impact of BIM mussels increases with additional distribution, mussels still remain lower than all animal proteins.

While BIM mussels have a higher carbon footprint than most plant-based proteins, BIM baseline mussels have a 30% less impact than tofu. Furthermore, when looking at other seafood, the impact of BIM mussels is 92% less than crustaceans and 77% less than farmed fish.

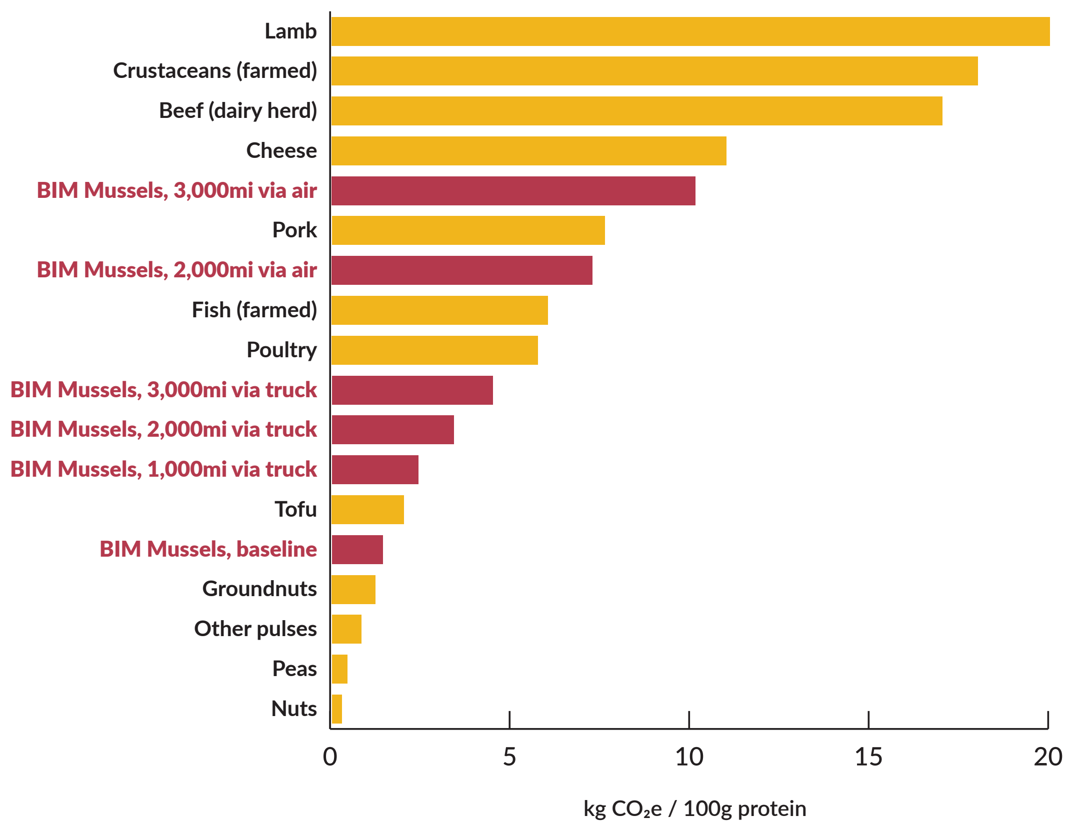


Figure 9.
Comparison of BIM farmed mussels to other protein sources

CONCLUSIONS

The goal of the study was to calculate the product carbon footprint (PCF) of BIM's farmed mussels, identifying hot spots within its production, and comparing it to industry average data of other shellfish and protein sources. This allows for the identification of specific reduction strategies within BIM's operations.

Biogenic emissions, fuel use for transportation, and natural gas and electricity use represent nearly 90% of BIM's total carbon footprint. Biogenic emissions are associated with a high level of uncertainty given the limited amount of research on this topic. Furthermore, these calculations are based on models that are known to vary depending on oceanic and regional conditions.

BIM farmed mussels have a lower carbon impact than all animal proteins and some plant-based proteins compared in this study. BIM farmed mussels also have a lower impact than oysters and are comparable to other mussel studies.

The biggest opportunities for impact reduction are in increasing yield by reducing broken mussels and reducing those eaten by eider ducks and adopting renewable electricity for processing. Boat fuel use contributes more than 25% of the carbon emissions. Reducing boat fuel use by increasing efficiencies, reducing idling, or adopting electric motors could substantially reduce or eliminate these emissions.

ENDNOTES

1 Carbon emissions vary by type of renewable energy. NEWE grid energy emits 0.25 kg CO2/kWh, wind energy emits 0.003 kg CO2/kWh, and solar energy emits 0.01 kg CO2/kWh.

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