Greenhouse Gas Emissions
OYSTERS

A Study of DEER ISLE OYSTER COMPANY, BOMBAZINE OYSTER COMPANY, MOOK SEA FARM, PEMAQUID OYSTER COMPANY

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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.

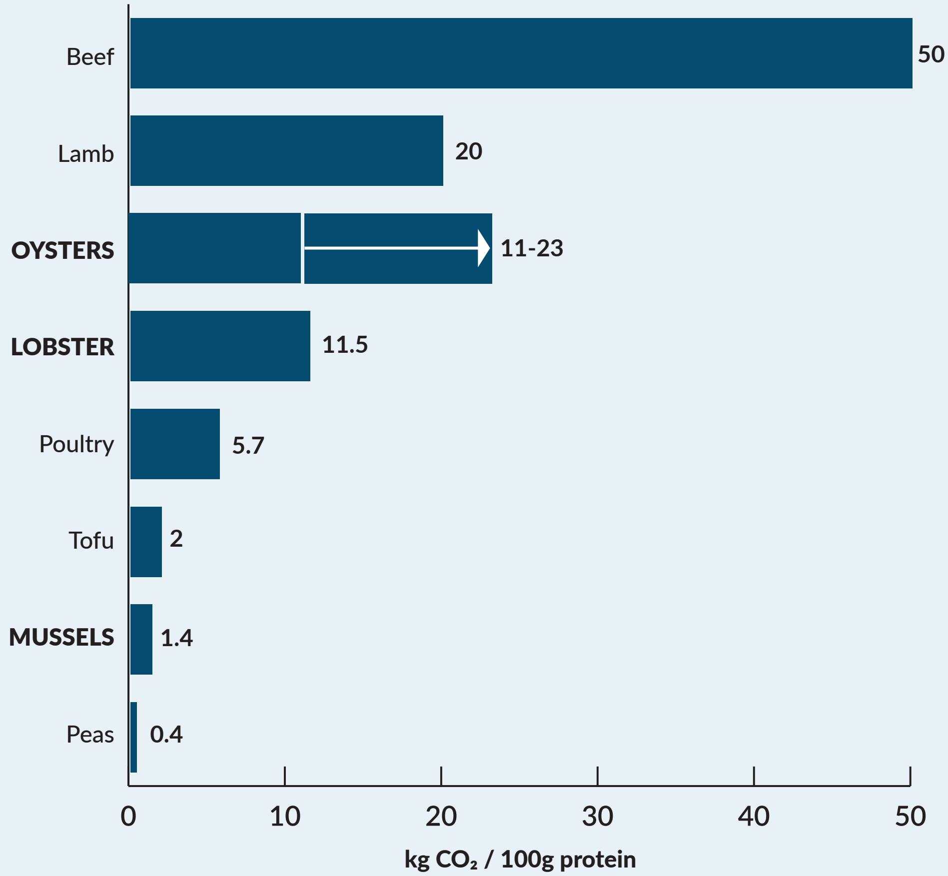
The findings are clear: Maine seafood is already among the lowest-carbon protein sources available (Figure A). At the same time, meaningful opportunities exist to reduce emissions for businesses operating on the front lines of climate change.

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.

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Atlantic Sea Farms	Participating Seafood Business
Bangs Island Mussels	Participating Seafood Business
Bombazine Oyster Company (formerly Ferda Farms)	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 OYSTERS STUDY

This report presents greenhouse gas assessments for four Maine oyster farming operations: Deer Isle Oyster Company, Ferda Farms, Mook Sea Farm, and Pemaquid Oyster Company. Each company uses different farming methods and operates at a unique scale, offering insight into emissions hotspots and opportunities for reduction across Maine's diverse oyster farming sector.

Deer Isle Oyster Company operates in the waters of Long Cove. The company operates its farm and processing facilities with a focus on minimizing plastic use and reducing emissions, actively exploring alternative farming methods. The final product assessed was oysters, packaged and distributed to customers in Stonington and Brooksville, Maine. Ferda Farms is an oyster farming company operating in Brunswick, Maine. The farm produces oysters using floating cage systems, and after processing the packaged oysters are shipped to local customers in the greater Portland, Maine area. Mook Sea Farm is an oyster farming company located in Walpole, Maine. The farm runs their own hatchery, producing oyster spat for their own farming operations and to sell to other farms. The final product assessed was oysters, packaged and distributed to customers in Boston, Massachusetts. Lastly, Pemaquid Oyster Company is an oyster producer focusing on bottom cultured oysters in the Damariscotta River. The company places suitably sized oyster spat on seabed habitats where they grow until harvest with a dredge at market size. The final product assessed was packaged oysters before distribution.

Emissions calculations per oyster varied across operations, ranging from 33 to 88 g CO2 equivalents per oyster. When standardized by protein content, emissions ranged from 10.7 to 23 kilograms of CO_2 equivalents per 100 grams of protein.

The primary emission sources varied between operations. For Deer Isle Oyster Company, the most important sources were oyster spat from a local hatchery, followed by energy related emissions for fuel use and electricity. Ferda Farms showed fossil fuel use for boat operations and farming infrastructure and material use as the most significant sources, with distribution, packaging, and oyster spat of lesser importance. Mook Sea Farm's primary sources were fossil fuel use for heating and boat operations, as well as electricity use during processing, with material use for farming, processing, and packaging of lesser significance. Pemaquid Oyster Company's main sources were fossil fuel use for boat operations and oyster spat from a local hatchery, with packaging in plastic net bags having less impact on the overall carbon footprint.

Scope distribution analysis, as per the Greenhous Gas Protocol corporate accounting and reporting standard (2004), revealed different patterns across operations. Deer Isle Oyster Company showed 28% Scope 1 (direct emissions), 13% Scope 2 (indirect energy emissions), and 59% Scope 3 (goods and services). Ferda Farms demonstrated 56% Scope 1 (direct emissions), >0.5% Scope 2 (indirect energy emissions), and 43% Scope 3 (goods and services). Mook Sea Farm had 51% Scope 1 (direct emissions), 22% Scope 2 (indirect energy emissions), and 27% Scope 3 (goods and services). Pemaquid Oyster Company showed 44% Scope 1 (direct emissions), 11% Scope 2 (indirect energy emissions), and 45% Scope 3 (goods and services).

Protein carbon footprint results indicate that oyster farming generally has a lower climate impact than high-emission animal proteins like beef and lamb. Some operations demonstrated emissions comparable to moderate-impact foods such as cheese, while others had higher impacts, approaching those of farmed crustaceans or pork. Although oyster protein typically has higher emissions than plant-based proteins, farmed fish, and other bivalves, it remains a lower-emission option compared to conventional beef production, especially from meat herds.

Common improvement actions identified across operations include reduction of energy-related emissions through electrification of boating fleets and heating systems, or improved process efficiency. Specific opportunities include switching to electrical or renewable propulsion systems, decreasing mortality rates of oyster spat, remote surveillance of farming sites to reduce fuel use, and using lower-impact materials. Consistent research needs were identified across all operations, including further studies on biophysical properties of eastern oysters, investigation of biogenic emissions under different environmental conditions, and analysis of the effects of improved energy use at farm and processing facilities.

BACKGROUND

Island Institute is a Maine-based organization dedicated to supporting local communities and businesses. With oyster farming emerging as a growing industry in the region, the Institute—working in collaboration with four local oyster farms—aims to better understand the life cycle carbon emissions associated with oyster production in Maine.

Production of seafood in the form of wild-caught crustaceans and fish has a long tradition in the region and in recent decades aquaculture production has been increasing. Throughout coastal communities, a variety of seafood producers at production scales from small family operation to commercial production volumes can be found. With increasing awareness of the environmental impact of foods, the interest in low impact seafood has been increasing in recent years. Oysters and bivalves are good candidates for low impact farming since they require no manufactured feed and do not cause problems related to overexploitation of natural stocks. However, the carbon footprint of farmed oysters is a relatively understudied area in comparison to other seafood.

In this study, the greenhouse gas emissions of oysters farmed by four oyster farmers in coastal Maine, USA were quantified. The four farmers operate at different scales, from small-scale farming on a 3-acre lease to larger-scale farming on multiple leases. The predominant production technique used is floating cage culture, but one farmer also uses bottom culture in their production.

RISE Research Institutes of Sweden has calculated the carbon footprint, another term for life cycle greenhouse gas emission of products, of farmed eastern oysters, using life cycle assessment (LCA). Results are presented per life cycle stage and emission scope for better understanding of emission hotspots and more targeted guidance of improvement actions. Results are furthermore compared with other terrestrial and marine protein sources on the basis of impact per 100g protein.

GOAL

The goal of this study is to calculate the global warming potential (or carbon footprint/greenhouse gas emissions) of oysters produced by four different farming operations in Maine, USA. All relevant lifecycle steps (hatchery, farming, processing, and distribution) are included in the assessment and results are to be used for a baseline assessment, the identification of emission hotspots and subsequent guidance of improvement actions. Different farming techniques are used by the four farms, and the results can also be used to investigate differences between farming systems from a carbon footprint perspective. The primary audience of this study are oyster farmers interested in reducing their greenhouse gas emissions. Due to confidentiality of input data and results, four separate reports for the individual farmers (with different result and sensitivity analysis sections) were prepared.

SCOPE

PRODUCTS AND FUNCTIONAL UNITS

In this study we model multiple functional units representing oysters at key points of the production chain. The following functional units are used in this study:

- 1 market size oyster, at harvest
- 1 market size oyster, before distribution
- 1 market size oyster, distributed to key markets

In addition to fresh weight based functional units, results will be presented per 100 grams of protein to allow for comparison with other animal products. This can be seen as an additional functional unit used.

SYSTEM BOUNDARY

This assessment investigates the oyster farming operations following a cradle-to-retail gate approach. This means that all relevant activities related to the production of supply materials and farming infrastructure (excluding buildings), operation of the farm, processing and distribution of oysters to wholesale will be included. The cut-off after distribution to a wholesaler was chosen because the supply chain after this point becomes very diverse and difficult for the companies to influence. End of life treatment of the oyster products and farming infrastructure is excluded (Figure 1). It is noted however, that in the debate about the role of bivalves in the carbon cycle of the oceans, the fate of the shells has an important influence on bivalve GHG emissions (Pernet et al. 2024).

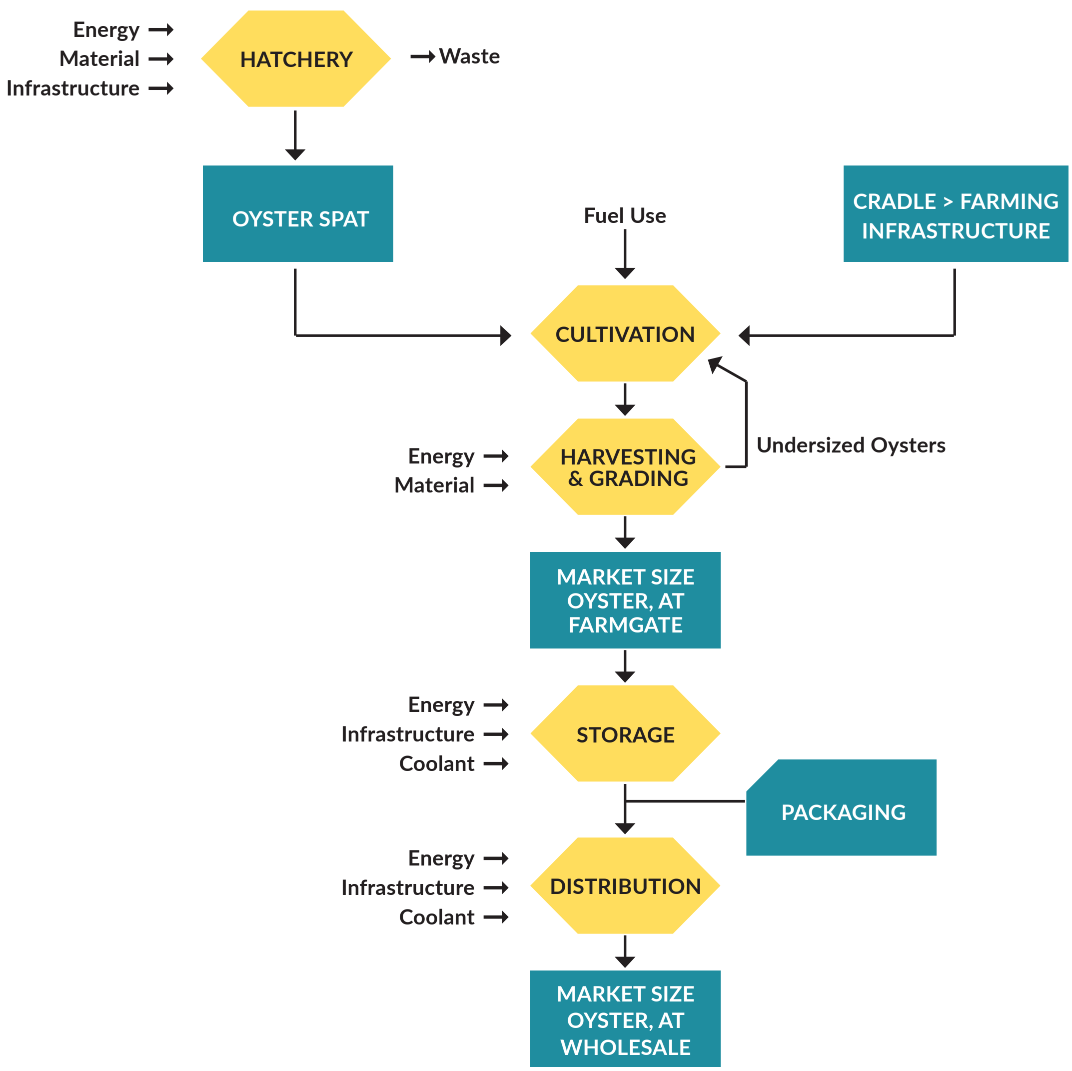

Figure 1.
Flowchart of the oyster production supply chain from cradle to wholesale

Temporal scope

The assessment aims to represent current production at the companies investigated. Three of four companies provided data covering three consecutive years (2021-2023) allowing the use of averages over this timeframe, which improves robustness of data and counteracts the influence of outliers in the form of e.g. a die off events affecting harvest. It also improves the understanding of the variability between years in resource efficiency.

Geographic scope

The oyster production analyzed in this study is located in coastal Maine, USA. Results are therefore applicable to the region, and more general conclusions can be drawn for comparable farming systems in similar climates.

ALLOCATION

Allocation of resource use between co-products of a process is based on product mass as this is prioritized in the relevant ISO standards (ISO 14040 and 14044) when allocation cannot be avoided. Basing allocation on biophysical parameters like mass allows for consistent comparisons with other products and over time and, unlike economic allocation, avoids finding differences in environmental impacts results caused only by changes in market price over time (if the present analysis e.g. is to be followed up in a few years' time).

IMPACT ASSESSMENT METHOD

The global warming potential was assessed using the IPCC 2021 GWP 100a method and results are expressed in kg CO2 equivalents (CO2e). This method bases its conversion factors for different substances (e.g. methane, dinitrous oxide) on the latest IPCC report (Arias et al. 2021) and takes into account the global warming effect of these substances using a time horizon of 100 years.

EMISSIONS PER SCOPE

The Greenhous Gas Protocol corporate accounting and reporting standard (2004) is a widely applied standard for GHG emission calculation and reporting. Within the standard, emissions are divided into three different scopes (Figure 2).

Scope 1: Direct GHG emissions

This scope encompasses all emissions which are directly generated by the entity producing the investigated product. This is most commonly emissions from the combustion of fuels but can also take the form of emissions from chemical processes (e.g. concrete manufacturing) or fugitive emissions like refrigerant leaks from cooling systems.

Scope 2: Energy indirect emissions

Under this scope, all emissions related to the production and transport of a company's purchased electricity are accounted for. It also encompasses the emissions from producing other forms of purchased energy like steam, heating, or cooling.

Scope 3: Other indirect emissions

This category collects the remaining indirect emissions which occur within the production system analyzed, divided into upstream and downstream emissions. Fifteen sub-categories are defined but for the scope of this assessment, only capital goods, transport & distribution, fuel/energy, and purchased goods are of relevance.

Biogenic emissions are reported separately from the three defined scopes following the Greenhouse Gas protocol guidance for scope 3 emissions (2013).

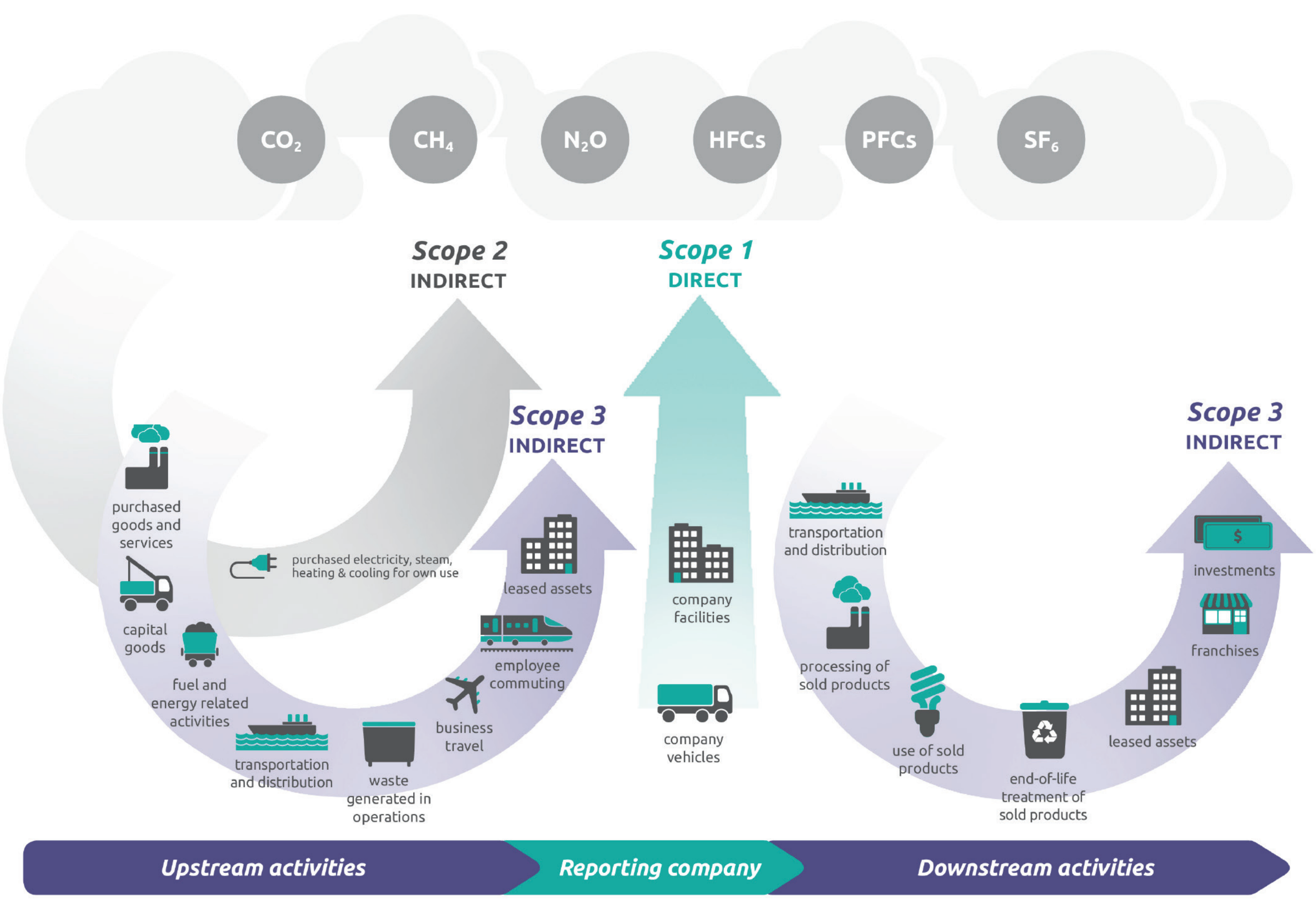

Figure 2.
Overview of the different scopes within the Greenhous Gas Protocol framework[1]

EMISSIONS PER LIFECYCLE PHASE

Dividing emissions by life cycle phase of the investigated production system is a common way to identify hotspots and guide improvement actions within LCA. In this study, GHG emissions were divided into the following life cycle phases: Hatchery, Farming, Processing, Packaging, and Distribution. Within the different categories, the emissions were further divided into energy and material/infrastructure related emissions. See section 4.2 for more extensive descriptions of the different life cycle phases.

BIOGENIC EMISSIONS

Oysters and other bivalves release biogenic emissions during their life cycle during shell formation and as part of respiration and digestion of food. Unlike GHG emissions of fossil origin, the biogenic emissions of farmed oysters are heavily influenced by the conditions present at the farming site such as salinity, water temperature, bottom type, and nutrients available in the water column. Since a site-specific assessment at each individual farm was outside of scope of this study, a more generalized, literature-based method to assess emissions from both shell formation, respiration, and digestion was used. In this simplification, it is assumed that all emissions from the oysters reach the atmosphere and have a direct climate impact. In reality, parts of these emissions are likely to not reach the surface and atmosphere as they are redissolved and taken up by organisms such as phytoplankton (Pernet et al. 2024).

Carbon dioxide emissions from shell formation

Bivalve shells consist of predominately calcium carbonate (CaCO3) and during shell formation carbon dioxide (CO2) is released. This release is calculated following the method used by Ray and colleagues (2018) according to the equation below:

Equation 1.
CO2 release during shell formation

$$CO_2\ Release_{(Shell\ Formation)} = Shell\ Mass \times \Psi \times \%\ Shell\ CaCO_3 \times (MW\ CO_2)/(MW\ CaCO_3)$$

Where:
Shell mass = Shell mass of an average oyster = 53.6g
Ψ = Seawater buffering capacity = 0.759
% Shell $CaCO_3$ = % share of $CaCO_3$ of total shell mass = 96% (Lee et al. 2008)
MW CO_2 = Molecular weight of CO_2 = 44.01 g/mol
MW $CaCO_3$ = molecular weight of $CaCO_3$ = 100.0869 g/mol

The shell mass was calculated using the weight of an average oyster from the assessed farms (67 g), the edible yield of 10% (FAO 1989) and the assumption that 10% of an average oyster's weight is free water in the shell.

Ψ, or the seawater buffering capacity, depends on site specific temperature, pH, salinity and pCO2 data at the individual farms. Since direct measurements were unavailable, the annual water temperature of 7.8 C outside Portland, Maine (www.seatemperature.org), an average pH of 8.1 and salinity of 32 (Feng et al. 2016) was used as a proxy for the calculation. The R package "seacarb" was used for the calculation of Ψ (Gattuso et al. 2020).

When combining all factors described above, a CO2 release from shell formation of 17.2 g CO2 per average oyster farmed in Maine was calculated.

Methane & dinitrogen oxide from respiration & digestion

Emissions from oyster respiration and digestion are highly dependent on the local biogeochemistry at the farming site. Ray and colleagues (2019) found that oyster farming in their studied areas stimulates a short-term increase in GHG emissions from sediments when the farm is established, but the system returns to baseline conditions within a few years. In nitrate limited locations, sediments were even found to take up N2O, leading to negative GHG emissions. As a simplification, emissions from sediments are assumed to be negligible in this study. Carbon dioxide emissions from respiration are ignored in this (and most other) studies as carbon dioxide cycles are comparatively short and, in the process, photosynthetically fixed carbon is returned, and not added, to the environment.

In a meta-analysis of studies on nutrient and gas fluxes of oyster species, a direct release of 0.11 nmol N2O/indiv./hour (standard deviation +/- 0.76) and 2.93 nmol Ch4/indiv./hour (standard deviation +/- 1.23) for market size eastern oysters was reported (Ray et al. 2020). Extrapolating from these numbers (under the assumption that release rates are constant and proportional to an oyster's size), an estimation of N2O and CH4 emissions during a market size oysters lifetime can be calculated using the following equations (assuming linear growth and a time to harvest of two years):

Equation 2.
N_2O release during the lifetime of an average Maine oyster

$$\text{Emitted } N_2O_{lifetime} = \int Rh^{Xu} \times (x/\text{total hours}_{lifetime}) X_1$$

Where:
Rh = Release of N2O (nmol/indiv./hour): 0.11
X = time in hours
X_1 = Lower limit of x: 0
X_u = Upper limit of x: 17520
total hours$_{lifetime}$ = total lifetime until harvest (h): 17520

Equation 3.
CH4 release during the lifetime of an average Maine oyster

$$\text{Emitted } CH_{4(lifetime)} = \int^{X1,Xu} Rh \times (x/\text{total hours}_{lifetime})$$

Where:
R_h = Release of CH_4 (nmol/indiv./hour): 2.93
X = time in hours
X_1 = Lower limit of x: 0
X_u = Upper limit of x: 17520
total hours$_{lifetime}$ = total lifetime until harvest (h): 17520

LIFE CYCLE INVENTORY

DATA COLLECTION

Data collection for this study took place from March to April 2024. All data was collected from the participating farms using an Excel based spreadsheet, collecting key data points during the different lifecycle steps in oyster farming. Additionally, key data points and questions were double-checked in online meetings and via email.

Background data from multiple LCA databases was used in this analysis. Processes from the following databases were used: Ecoinvent 3 (Version 3.9.1, cut-off by classification) and USLCI (Version 09.2015). When similar processes were available in both databases (e.g. production of diesel), the process with the best technical and in some cases geographical relevance was chosen.

PRODUCTION STAGES

Hatchery

A farmed oyster's production cycle often starts in a hatchery, where it grows from fertilized egg to the spat stage at which it is roughly 2 mm across. The spat production begins with the keeping of broodstock oysters, which are used to produce fertilized oyster eggs. These eggs further develop into free-swimming larvae and later settle onto hard substrate, often provided in the form of finely crushed oyster shells. The settled larvae are kept in up-or downwelling systems and continue to grow and develop their shell until they are of sufficient size to be sold and put out on oyster farms. During the growth, the larvae are fed with microalgae, and hatchery operations typically grow multiple types of algae to be fed to the oysters at different developmental stages.

Farming

The farming stage is the most diverse stage of oyster farming with a multitude of systems and farming practices in use for oyster production. The most common system is the use of bags or cages which contain the farmed oyster while still allowing for free flow of water and food particles. These bags are either kept afloat by floats or placed on racks keeping them off the seafloor in tidal environments. During the 2-3 years it takes the oysters to reach a market size of roughly 7.5 cm shell length; they are repeatedly resorted by size and stocking densities are adjusted for optimal growth.

An alternative system to bag and cage culture is bottom culture. Here small oysters are placed directly on the seafloor in suitable habitats and left undisturbed until they reach harvest size. Harvest is done using a dredge.

Processing

Oysters require little processing after harvest, as they are typically sold whole and live. The required processing is therefore related to cleaning the oysters from eventual biofouling (attached algae or organisms like tunicates or tube-forming marine worms) and storing them until distribution to customers.

Keeping the oysters outside of the water is possible for shorter timeframes (1-3 days) when they are kept cool through refrigerated storage or ice. Storage for longer timeframes (weeks) requires the oysters to be placed in tanks with continuous supply of fresh seawater, a process known as depuration, which is sometimes required for oysters to achieve a high quality. A less technical alternative to this is suspending the oyster in net bags or boxes from storage docks, depending on the natural water flow to supply oxygen and food to the oysters.

Packaging

In this study, different forms of oyster packing were utilized. Net bags, based on regular or biodegradable plastic, to package between 25-120 oysters per package were used as customer packaging by the different farms. Packaging in paper bags was also used as an alternative by one farm. For farms producing larger volumes of oysters, secondary packaging of corrugated cardboard or plastic boxes for transport was used for the netted oysters.

Distribution

Distribution to customers of the packaged oysters in this study ranged from customer pickup at the farmers house/processing location to long distance shipping to Boston via refrigerated truck (see also 4.4).

ENERGY

Electricity

Electricity in this study was modelled using the best available data for LCA purposes for electricity production in the study region. A market mix approach was chosen, therefore reflecting the average footprint of electricity available for purchase in the area considering import and export to and from neighboring regions. The Ecoinvent process “Electricity, medium voltage {NPCC, US only} | market for electricity, medium voltage | Cut-off, S” was used.

Some farms had solar electricity generation to run processing machines or refrigeration. Solar-based electricity was assumed to have a negligible carbon footprint and was therefore excluded from this study.

Propane

Propane is used by one farmer to heat processing facilities. Propane combustion emissions (Scope 1 emissions) were sourced from the UK Department for energy security & net zero (2023). Emissions connected to the production of propane were more complex as there is a wider variability in GHG emissions depending on location and production technology used. In this study it is assumed that the propane available on the Maine market predominately originates from Canada and emission data was taken from S&P report (2022).

Diesel

Both scope 1 and 3 emissions for diesel used in boating operations were sourced from the USLCI database (U.S. Life Cycle Inventory Database 2012), which contains LCA data specific for the USA. The process “Diesel, combusted in industrial equipment/US” was modified to obtain either scope 1 or scope 3 missions.

Gasoline

Following the same approach as for diesel, the process “Gasoline, combusted in equipment/l/US” from the USLCI database was used to obtain scope 1 and 3 emissions for gasoline used in boating operations.

Kerosene

Kerosene was used for heating the processing space of one farmer during wintertime. No kerosene specific production process for the USA was available in the relevant LCA databases. Scope 3 emissions were therefore approximated using the production of diesel as a proxy (see 4.3.3). Scope 1 emissions were obtained by modifying the USLCI database process “Transport, aircraft, freight/US”.

Transport

Different forms of transport were relevant in this study, predominately related to processing and distribution. Table 1 details the different processes used:

Table 1: Transport mode and related LCA processes used

Transport mode	Process name	Database
Pickup truck (with cooler)	Transport, light commercial truck, diesel powered, Northeast/tkm/RNA	USLCI
Passenger car	Transport, passenger car, gasoline powered/personkm/RNA	USLCI
Refrigerated truck	Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO5, R134a refrigerant, cooling {GLO}| market for transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO5, R134a refrigerant, cooling | Cut-off, S + Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO5, carbon dioxide, liquid refrigerant, cooling {GLO}| market for transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO5, carbon dioxide, liquid refrig(...)_8 | Cutoff, S	Ecoinvent 3 (50/50 share of R134/CO2 assumed)

INFRASTRUCTURE AND MATERIALS

Infrastructure and material use at all production stages was included in this study using processes from Ecoinvent 3 unless specified otherwise in the supplementary datasheets. Hatchery, farming and processing infrastructure use was calculated by dividing the estimated weight of the different farm or hatchery components (e.g. tanks, ropes, cages, buoys) by their estimated lifetime to obtain the approximate yearly material use. Consumables were included via their weight and primary material.

Buildings, boats, larger machines and pontoons/work floats were excluded from the assessment due to their long lifetimes and diverse material mix, making accurate modelling challenging.

WASTE TREATMENT AND END OF LIFE

End of life, meaning the treatment of materials and products after their intended use, was not included in this study as the scope is defined as cradle to distribution.

Waste treatment for wastes occurring at the hatchery and farm stage from consumables was included using the process "Waste plastic, mixture {RoW}| market for waste plastic, mixture | Cut-off, S" (Ecoinvent 3).

DATA QUALITY ASSESSMENT

The overall data quality of this study was assessed using a Pedigree-matrix following Weidema et al. (2013) approach, also applied within the Ecoinvent database (Tables 2.1-2.4). Data quality evaluation for this study using a Pedigree matrix. Shaded cells represent an estimated score for each indicator, where 1 = best available data and 5 = less representative data (old, unknown, non-specific, etc).

Deer Isle Oyster Company

Table 2.1

Indicator score	1	2	3	4	5
Reliability					
Completeness					
Temporal correlation					
Geographical correlation					
Further technological correlation					

Ferda Farms

Table 2.2

Indicator score	1	2	3	4	5
Reliability					
Completeness					
Temporal correlation					
Geographical correlation					
Further technological correlation					

Mook Sea Farm

Table 2.3

Indicator score	1	2	3	4	5
Reliability					
Completeness					
Temporal correlation					
Geographical correlation					
Further technological correlation					

Pemaquid Oyster Company

Table 2.3

Indicator score	1	2	3	4	5
Reliability					
Completeness					
Temporal correlation					
Geographical correlation					
Further technological correlation					

LIFE CYCLE IMPACT ASSESSMENT

RESULTS FOR KEY LIFE CYCLE STAGES

Deer Isle Oyster Company, at farmgate

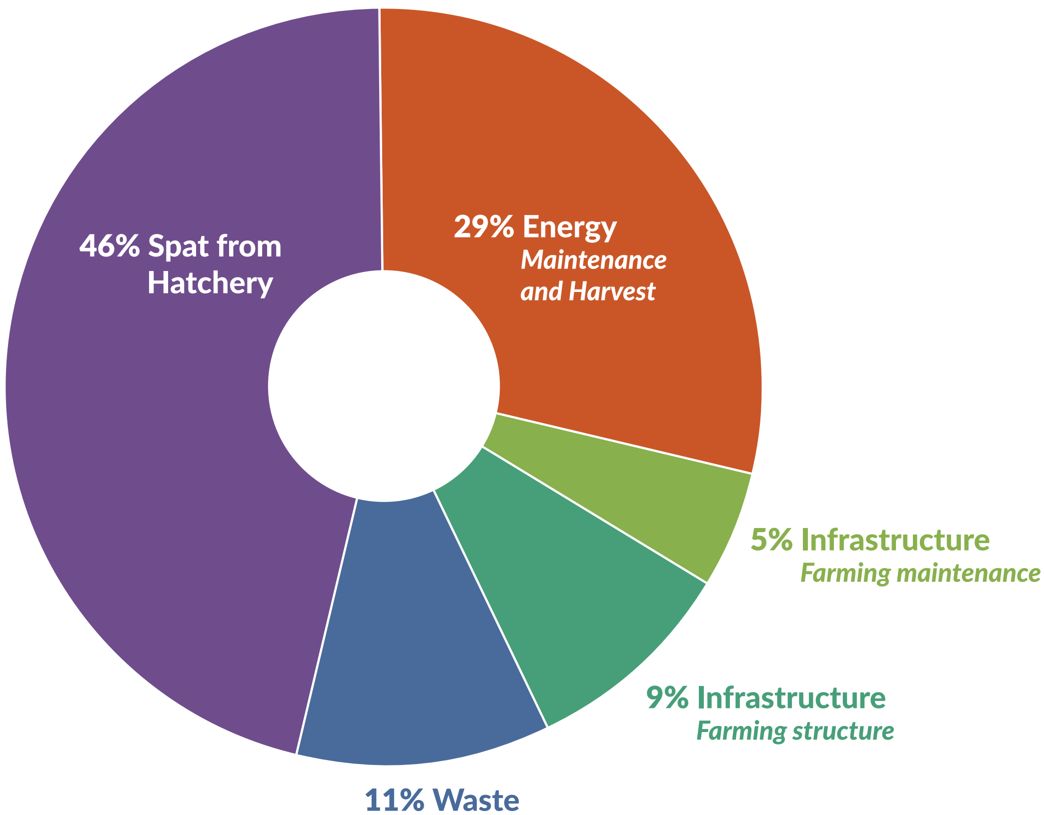

Figure 3.1.
GHG emissions of one oyster at farmgate

Farmgate emissions (Fig. 3.1) are composed by farming infrastructure related GHG emissions (9%), farming maintenance materials (5%), fuel use during harvest and maintenance (29%). Within the farming infrastructure category, most emissions originate from the grow bags (40%) and floats (20%), with the remaining components contributing more evenly distributed. Oyster spat represents the largest contribution, at 46% due to the need for multiple spat per produced oyster. Total emissions at farmgate are 30 g CO2e/oyster.

Deer Isle Oyster Company, final product

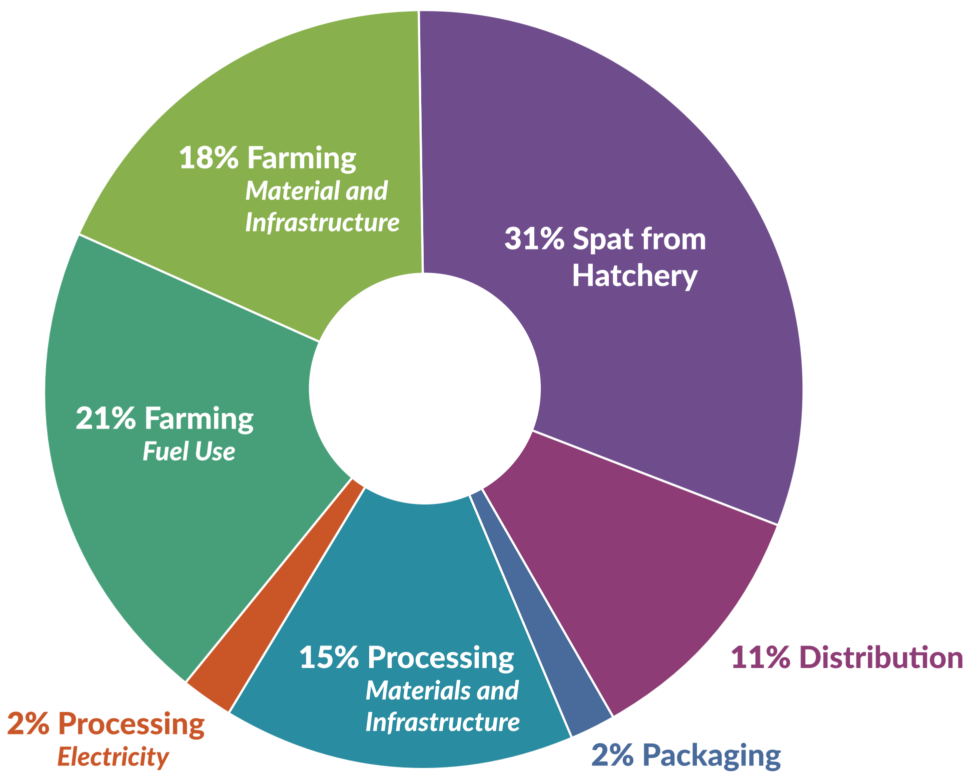

Figure 3.2.
GHG emissions of one oyster, packaged, at local restaurant

The final product assessed in this study are oysters in 100 count net, at customer - which is either a local restaurant or customer in Brooksville, Maine. The total carbon footprint of one oyster at the local restaurant is 42 g CO2e which increases to 48 g CO2e per oyster when distributed to Brooksville, due to the longer transport distance. Before distribution, one oyster in 18 count, paper packaging is emitting 37 g CO2e per oyster.

The oyster spat needed to produce one market size oyster contribute 31% of the total GHG emissions of one oyster delivered to Stonington. Farming material and infrastructure use contribute 18% and fuel use during farming stands for 21% of the total. The processing stage is origin to 17% of total emissions which predominately come from electricity used for refrigeration. Emissions from packaging are less relevant at 2.4% for biodegradable plastic netting. If the 25-count paper bag packaging is used, the total carbon footprint at processing gate increases slightly to 38 g CO2e per oyster.

Ferda Farms, at farmgate

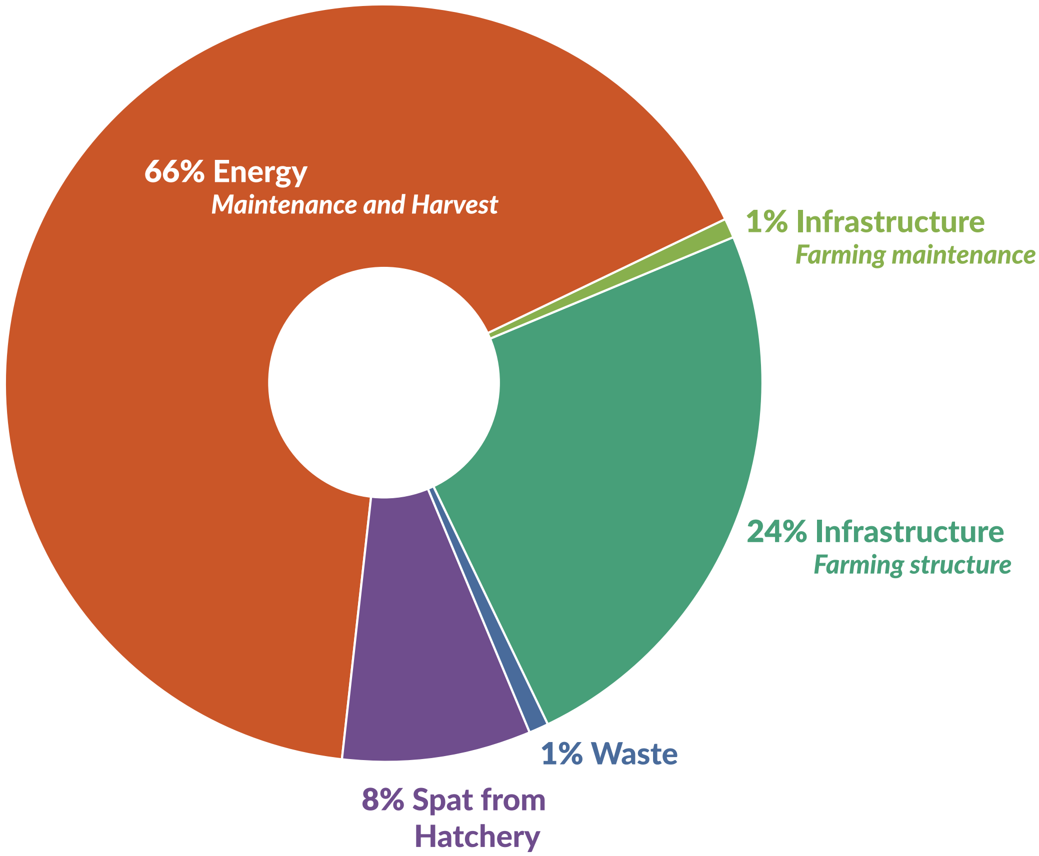

Figure 3.3.
Carbon footprint of one oyster at farmgate

Farmgate emissions (Fig. 3.3) are composed by farming infrastructure related GHG emissions (24%), farming maintenance materials (1%), Oyster spat (9%) and fuel use during farming and harvest at 66%. Total emissions at farmgate are 80 g CO2e /oyster.

Ferda Farms, final product

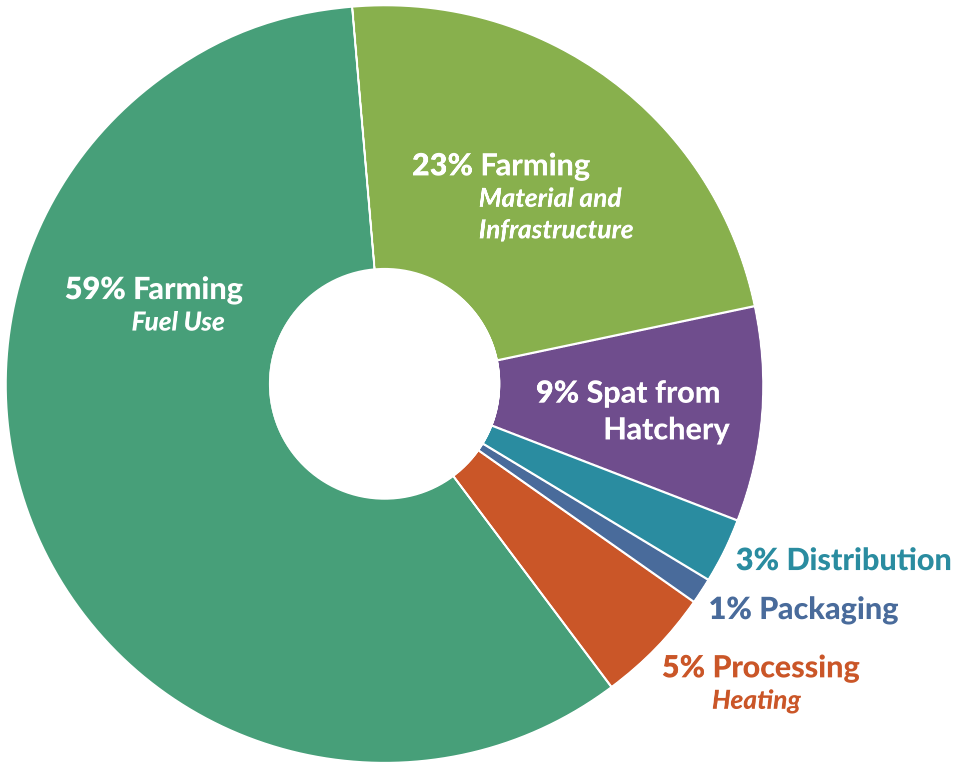

Figure 3.4.
Carbon footprint of one oyster, packaged at customer in Portland, Maine.

The final product assessed in this study are oysters in 100 count net, at customer in Portland, Maine. The total carbon footprint of one oyster to retail is 88 g CO2e. At processing gate, one oyster in 100 count packaging is emitting 85 g CO2e.

The farming phase is the source of over 91% of total emissions, a majority of which originates from fuel use during farming and harvest. Material and infrastructure use during farming is the second largest contributor at 23% followed by oyster spat (9%). Processing related emissions predominately come from the combustion of kerosene for heating the processing facilities (5%) whereas electricity use during processing only contributes marginally (>0.5%). Packaging has only a small contribution of 1% to the total GHG emissions, and emissions from distribution are slightly higher and contribute 3%.

Mook Sea Farm, at hatchery gate

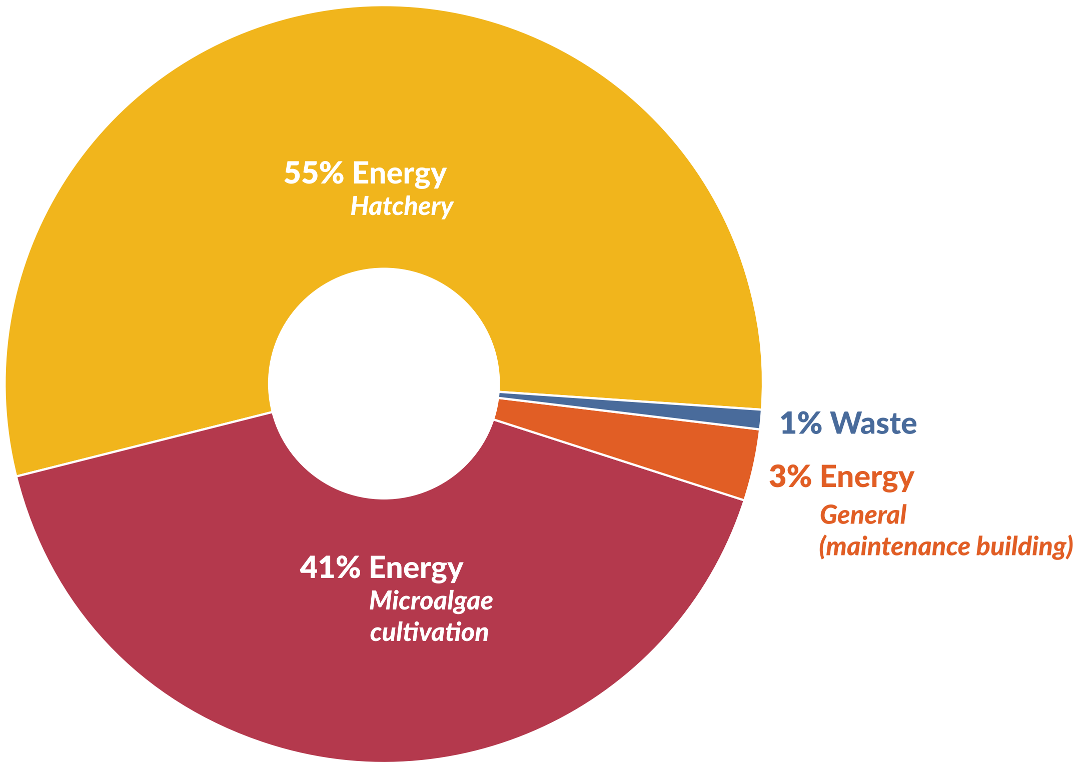

Figure 3.5.
GHG emissions of 1000 oyster spat at hatchery gate.

At hatchery gate, the carbon footprint of oyster spat was calculated to be 3.3 kg CO2e per 1000 spat. Energy use dominates hatchery greenhouse gas emissions (Fig. 3.5), with energy used in the hatchery representing more than half of total emissions, followed by the energy use for microalgae cultivation. Together these two sources of emissions represent 96% of the total emissions. Two thirds of the energy-related emissions originate from the use of propane for heating whereas the remaining third comes from electricity-related emissions. Emissions from consumables or hatchery infrastructure (tanks, lights, etc.) only contributed marginally.

Mook Sea Farm, at farmgate

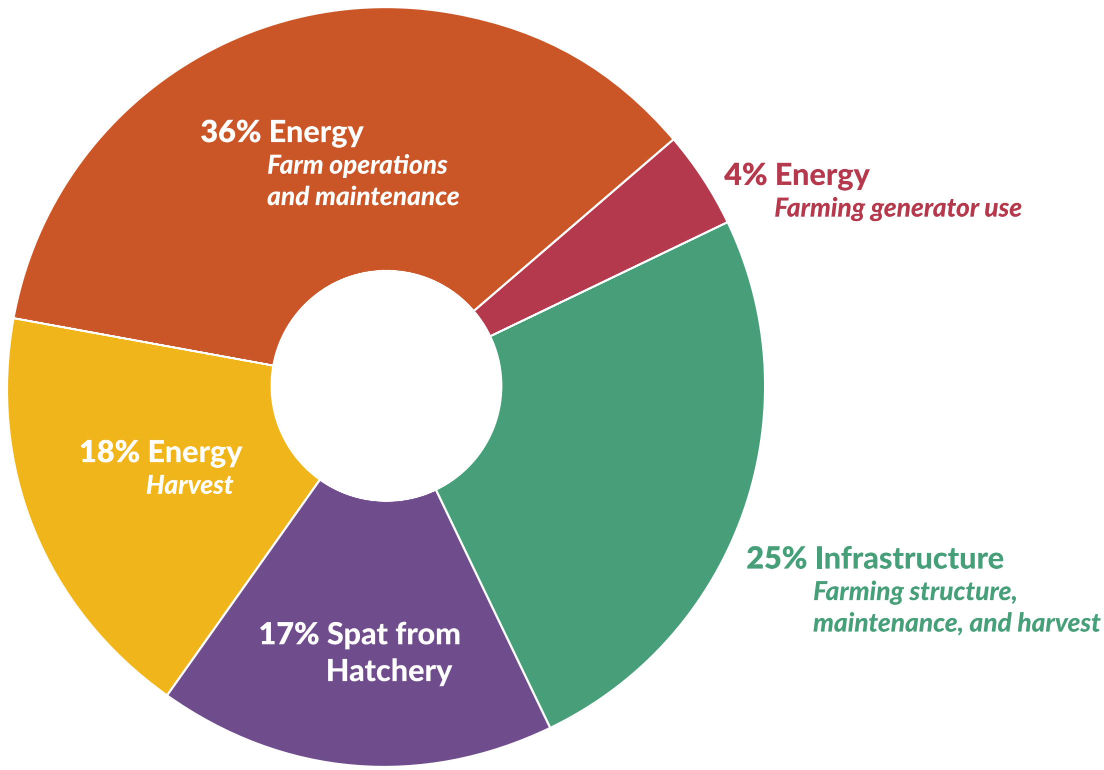

Figure 3.6.
Carbon footprint of one oyster at farmgate

Farmgate emissions (Fig. 3.6) are composed by infrastructure (25%), generator fuel use (4%), boat fuel use in maintenance activities (36%), fuel use on harvesting boats (18%) and waste (<1%). Spat production in the hatchery represents 17%. Total emissions at farmgate are 39 g CO2e /oyster.

Mook Sea Farm, final product

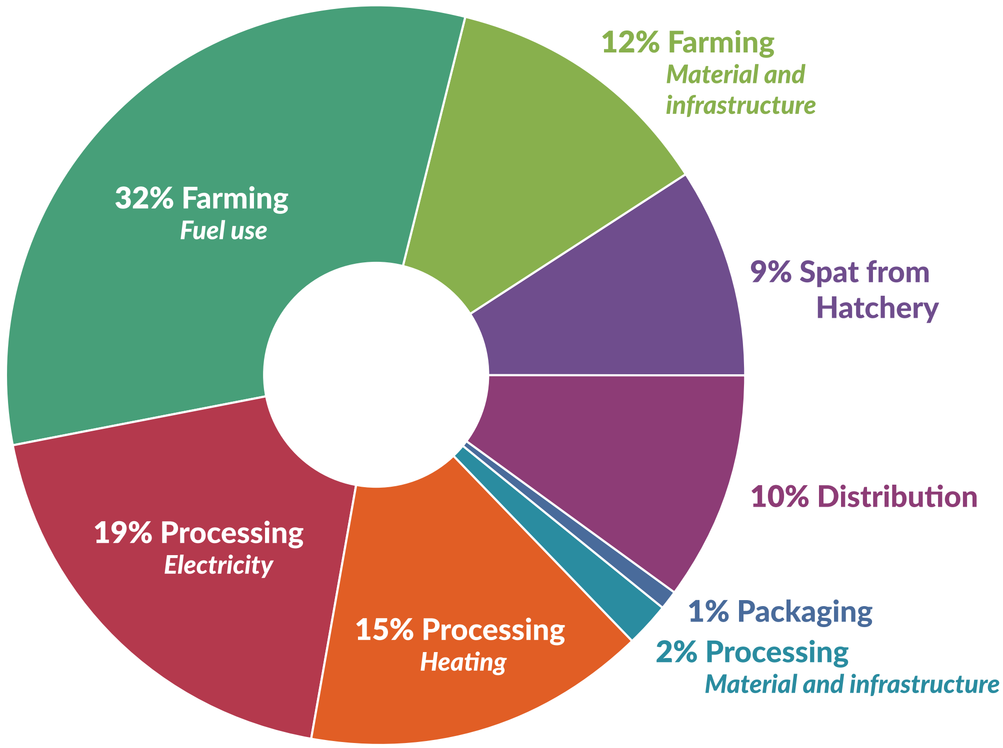

Figure 3.7.
Carbon footprint of one oyster, packaged, at Boston retailer

The final product assessed in this study is oysters packaged in 25 packs, at distribution to a key market, which in this case is a Boston retailer. The total carbon footprint of one oyster at this stage is 74 g CO2e. At processing gate before distribution, the carbon footprint is slightly lower at 67 g CO2e / oyster. The oyster spat needed to produce one market size oyster contribute with 9%. The farming stage (fuel and infrastructure) contributes 44% and processing 35%, which predominately originates from electricity and heating related GHG emissions. Emissions from packaging are less relevant at just over 1% contribution, but the distribution via truck to Boston contributes 10% to the final carbon footprint.

When using the alternative packaging in 100 pack, corrugate plastic boxes, the carbon footprint of one oyster at Boston distributor increases to 83 g CO2e / oyster due to the alternative packaging having a higher carbon footprint compared to the 25-pack net packaging.

Pemaquid Oyster Company, at farmgate

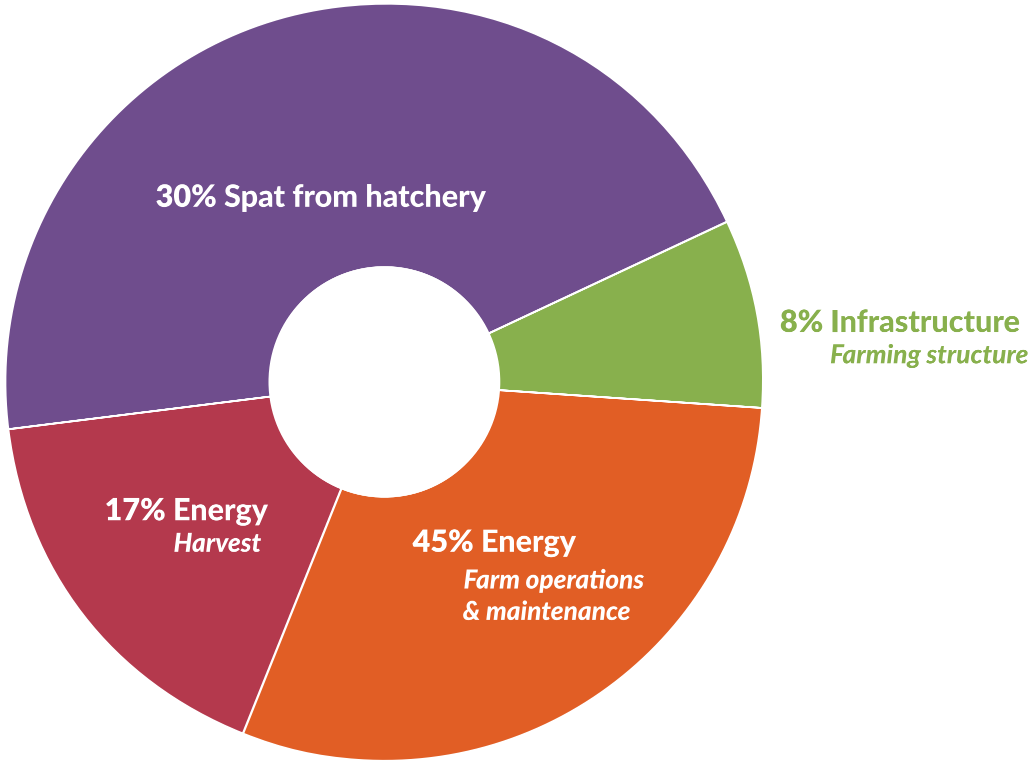

Figure 3.8.
Carbon footprint of one oyster at farmgate

Farmgate emissions (Fig. 3.8) are largely fuel use related, with the gasoline used for maintenance and farm operation contributing 45% of the total farmgate emissions and 17% originating from the diesel used for dredging the bottom cultured oysters. Oyster spat are responsible for just under a third (30%) of the total GHG emissions and farming infrastructure is of lesser importance at 8% contribution. Total emissions at farmgate are 29 g CO2e /oyster.

Pemaquid Oyster Company, final product

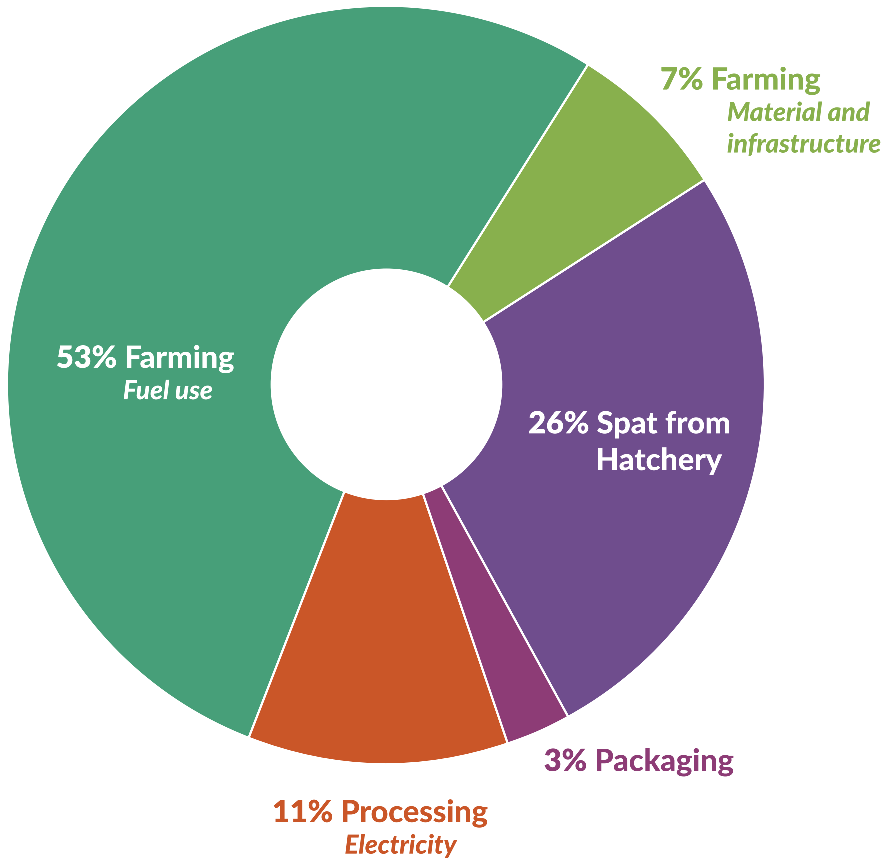

Figure 3.9.
GHG emissions of one oyster, packaged, at processing gate

The final product assessed in this study are oysters in 120 count net packaging, at processing gate. The total carbon footprint of Pemaquid Oyster Company's oysters at this stage is 33 g CO2e per oyster. No data on the distribution of Oysters was available, leading to no carbon footprint at customer being calculated in this study.

The farming phase is the source of over 86% of total emissions, a majority of which originates from fuel use during farming and harvest. Oyster spat are the second largest contributor at 26% of the total followed by electricity use during processing (11%). Material and infrastructure use at the farming stage contributes with only 7%, which is likely connected to the reduced need for farming infrastructure when using bottom culture. The packaging in onion bags contributes the least amount of GHG emissions per oyster at 3% of the total.

RESULTS DIVIDED BY EMISSIONS SCOPE

Deer Isle Oyster Company

Total emissions of an average oyster farmed by Deer Isle Oyster Company was 42 g at the Stonington restaurant. This was split into Scope 1, 2, and 3 emissions (Table 3.1). Scope 1 emissions (direct onsite emissions) represented 28% of the total, Scope 2 (indirect energy-related) 13% and Scope 3 (materials and infrastructure) 59% of the total.

Table 3.1: Emissions per GHG protocol scope and subcategory

Scope	Subcategory	Description	Emissions (kg CO2e)	% of Total
1	Mobile combustion	Combustion of fuels in farming operations	0.0071	17%
1	Mobile combustion	Combustion of fuels during transport and distribution	0.0045	11%
2	Purchased electricity	Purchased electricity (processing)	0.0054	13%
3	Goods/Services	Spats, from local hatchery	0.0137	33%
3	Goods/Services	Material and infrastructure use at farm	0.0073	17%
3	Goods/Services	Ice used at processing	0.0001	0%
3	Goods/Services	Packaging materials	0.0010	2%
3	Fuel/Energy	Upstream emissions of fuels for farming	0.0014	3%
3	Transport & Distribution	Upstream emission of fuel used in transport and distribution	0.0009	2%
3	Waste	Waste produced during farming	0.0003	1%
		SUM	**0.0042**	**100%**

Ferda Farms

Total emissions of an average oyster farmed by Ferda Farms was 88 g at customer. This was split into Scope 1, 2, and 3 emissions (Table 3.2). Scope 1 emissions (direct onsite emissions) represented 56% of the total, Scope 2 (indirect energy-related) >0.5% and Scope 3 (materials and infrastructure) 43% of the total.

Table 3.2: Emissions per GHG protocol scope and subcategory

Scope	Subcategory	Description	Emissions (kg CO2e)	% of Total
1	Mobile combustion	Combustion of fuels in farming operations	0.0438	49.9%
1	Mobile combustion	Combustion of fuels during distribution	0.0020	2.3%
1	Stationary combustion	Combustion of fuels for heating (processing)	0.0035	4.0%
2	Purchased electricity	Purchased electricity (processing)	0.0003	0.4%
3	Goods/Services	Spat, from local hatchery	0.0075	8.5%
3	Goods/Services	Material and infrastructure use at farm	0.0199	22.7%
3	Goods/Services	Packaging materials	0.0009	1.0%
3	Fuel/Energy	Upstream emissions of fuels for farming	0.0086	9.9%
3	Fuel/Energy	Upstream emissions of fuels for heating (processing)	0.0007	0.7%
3	Transport & Distribution	Upstream emission of fuel used in distribution	0.0004	0.4%
3	Waste	Waste produced during farming	0.0001	0.1%
		SUM	**0.088**	**100%**

Mook Sea Farm

Total emissions of an average oyster farmed by Mook Sea Farm were 74 g at the wholesaler. This was split into Scope 1, 2, and 3 emissions (Table 3.2). Scope 1 emissions (direct onsite emissions) represented 51% of the total, Scope 2 (indirect energy-related) 22% and Scope 3 (materials and infrastructure) 27% of the total.

Table 3.2: Emissions per GHG protocol scope and subcategory

Scope	Subcategory	Description	Emissions (kg CO2e)	% of Total
1	Fugitive emissions	Emissions from refrigerants used during distribution	0.000397	0.5%
1	Mobile combustion	Combustion of fuels in farming operations	0.018954	25.5%
1	Mobile combustion	Combustion of fuels during distribution	0.006246	8.4%
1	Stationary combustion	Combustion of fuels for heating (hatchery)	0.00378	5.1%
1	Stationary combustion	Combustion of fuels for heating (processing)	0.008526	11.5%
2	Purchased electricity	Purchased electricity (hatchery)	0.002185	2.9%
2	Purchased electricity	Purchased electricity (processing)	0.014082	19.0%
3	Goods/Services	Material and infrastructure use at hatchery	3.8E-05	0.1%
3	Goods/Services	Material and infrastructure use at farm	0.009838	13.2%
3	Goods/Services	Material and infrastructure use at processing	0.001923	2.6%
3	Goods/Services	Packaging materials	0.000831	1.1%
3	Fuel/Energy	Upstream emissions of fuels for heating (hatchery)	0.000801	1.1%
3	Fuel/Energy	Upstream emissions of fuels for farming	0.00371	5.0%
3	Fuel/Energy	Upstream emissions of fuels for heating (processing)	0.001807	2.4%
3	Transport & Distribution	Upstream emission of fuel used in distribution	0.001078	1.5%
3	Waste	Waste produced at hatchery	1.19E-05	0.0%
3	Waste	Waste produced during farming	5.37E-05	0.1%
		SUM	**0.074**	**100%**

Pemaquid Oyster Company

Total emissions of an average oyster farmed by Pemaquid Oyster company was 33 g at processing gate. This was split into Scope 1, 2, and 3 emissions (Table 3.4). Scope 1 emissions (direct onsite emissions) represented 44% of the total, Scope 2 (indirect energy-related) 11% and Scope 3 (materials and infrastructure) 45% of the total.

Table 3.4: Emissions per GHG protocol scope and subcategory

Scope	Subcategory	Description	Emissions (kg CO2e)	% of Total
1	Mobile combustion	Combustion of fuels in farming operations	0.0149	44%
1	Mobile combustion	Combustion of fuels during distribution	no data	
2	Purchased electricity	Purchased electricity (processing)	0.0037	11%
3	Goods/Services	Spat, from local hatchery	0.0087	26%
3	Goods/Services	Material and infrastructure use at farm	0.0024	7%
3	Goods/Services	Packaging materials	0.0010	3%
3	Fuel/Energy	Upstream emissions of fuels for farming	0.0028	8%
3	Transport & Distribution	Upstream emission of fuel used in distribution	no data	
3	Waste	Waste produced during farming	>0.0000	>1%
		SUM	**0.033**	**100%**

BIOGENIC EMISSIONS

Biogenic emissions from farmed oysters in relation to shell formation and from digestion/respiration were assessed following the methods described in section 3.7.

Carbon dioxide from shell formation

A market size oyster from Maine was calculated to release 17.2 g CO_2 e/oyster during shell formation (Equation 1). When including these emissions into the scope of this study, the carbon footprint of one oyster at farmgate increases to 59 g CO_2 e/oyster, which is an increase of 41%.

Methane and dinitrous monoxide

Based on equation 2, an average oyster emits 964 nmol N2O during its lifetime until harvest. Recalculating this using nitrous oxides molar mass of 44.01 g/mol, the total emissions are 0.000042g N2O which equates to 0.011g CO2e.

Following equation 3, an average oyster emits 51 334 nmol CH4 during its lifetime until harvest. Recalculating this using methane's molar mass of 16.04 g/mol, the total emissions are 0.000082 g CH4 which equates to 0.0023g CO2e.

When including these emissions into the scope of this study, the carbon footprint of one oyster at farmgate increases by 0.013 g CO2e/oyster, which is a marginal increase not significantly influencing the study's results.

In summary it can be noted that direct N2O and CH4 emissions for farmed eastern oyster are subject to high uncertainty (see standard deviation in section 3.7) and emissions over lifetime are small. However, carbon dioxide produced during the shell formation process can have significant influence on the GHG emissions of farmed oysters when included in the scope of the study. The best mitigation option for these emissions from shell formation is to place the shells back in the ocean after processing or consumption (Pernet et al. 2024).

IMPACT PER 100 GRAMS PROTEIN

For comparison of oysters with other protein sources of animal and plant origin, results were recalculated according to the formula below:

Equation 4.
Calculation of GHG emissions per 100g of eastern oyster protein

$$CO2e_{(100g\ oyster\ protein)} = 100/(W_{AO} \times CF_{EO} \times P\%_{EO}) \times GHG_{Oyster}$$

Where:
W_{AO} = Weight of average oyster (g)
CF_{EO} = Conversion factor from liveweight to edible: 0.1 (FAO 1989)
$P\%_{EO}$ = Protein content of eastern oyster meat: 5.7% (USDA 2019)
GHG_{Oyster} = Greenhouse gas emissions per oyster (g CO2e /oyster)

A study investigating the carbon footprints of different foods was used for the comparison of oysters from this study with other types of high-protein foods (Poore and Nemecek 2018). Here, the GHG emissions of important food products were assessed based on existing studies, which were harmonized as far as possible in terms of functional unit, allocation, impact assessment and system boundaries to achieve comparability. Similar to the assessment of Maine oysters, the study applied a cradle to retail approach, including farming, processing and distribution of the different products. Results in Poore and Nemecek were presented per 100g protein. Additionally, GHG emissions per 100g protein from farmed Pacific oysters in New Zealand were taken from Warmerdam et al. (2021) for comparison. By utilizing the recalculated results for eastern oyster protein, a comparison with other protein sources can be made.

In comparison to farmed Pacific oysters, Eastern oysters have a larger carbon footprint per 100g protein. This might be caused by differences in production systems but is also largely influenced by biological differences between Eastern and Pacific oysters. The Pacific oyster has a higher meat yield and flesh protein content than eastern oysters, leading to more protein per oyster and in turn lower GHG emissions per gram of protein (Warmerdam et al. 2021).

Deer Isle Oyster Company

Based on equation 4, the GHG emissions of 100g oyster protein after distribution to the customer from Deer Isle Oyster Company are 11 kg CO2e. In comparison with all assessed protein sources, farmed oysters from Deer Isle Oyster Company have a carbon footprint per 100g which is larger than plant-based protein sources, poultry, eggs, farmed fish as well as pork. The carbon footprint per 100g protein of Deer Isle Oyster Company's oysters is roughly in line with cheese but noticeably below meat from cattle (dairy herd), lamb & mutton and farmed crustaceans. Beef from beef herd raised cattle has much larger GHG emissions at 50 kg CO2e /100g protein.

Ferda Farms

Based on equation 4, the GHG emissions of 100g oyster protein after distribution to the customer from Ferda Farms are 23 kg CO2e. In comparison with all assessed protein sources, farmed oysters from Ferda Farms have a carbon footprint per 100g which is larger than all non-meat protein sources and on the upper end within the meat category, only being surpassed by Beef from beef herd raised cattle which has more than double the GHG emissions at 50 kg CO2e /100g protein.

Mook Sea farms

Based on equation 4, the GHG emissions of 100g oyster protein after distribution from Mook Sea Farm to the customer are 19.4 kg CO2e. In comparison with all assessed protein sources, farmed oysters from Mook Sea Farm have a carbon footprint per 100g which is larger than plant-based protein sources, poultry, eggs and farmed fish. The carbon footprint per 100g protein of Mook Sea Farm's oysters is roughly in line with meat from cattle (dairy herd), lamb & mutton and farmed crustaceans but significantly larger compared to pork or cheese. Beef from beef herd raised cattle has a much larger GHG emissions at 50 kg CO2e/100g protein.

Pemaquid Oyster Company

Based on equation 4, the GHG emissions of 100g oyster protein from Pemaquid Oyster Company before distribution are 10.7 kg CO2e. In comparison with all assessed protein sources, farmed oysters from Pemaquid Oyster Company have a carbon footprint per 100g protein which is larger than plant-based protein sources, poultry, eggs, farmed fish as well as pork. The carbon footprint per 100g protein of Pemaquid Oyster Company oysters is roughly in line with cheese but noticeably below meat from cattle (dairy herd), lamb & mutton and farmed crustaceans. Beef from beef herd raised cattle has much larger GHG emissions at 50 kg CO2e /100g protein. It is important to note that the scope of the GHG assessment of Pemaquid Oyster Company did not include distribution, unlike the other referenced studies.

CONCLUSION

IMPROVEMENT OPPORTUNITIES

Deer Isle Oyster Company

When analyzing the results at different stages of the production system for Deer Isle Oyster Company, multiple key processes and inputs offer the possibility for reducing GHG emissions.

With 31% of the total emissions originating from bought oyster spat, this is an important area to focus on to reduce GHG emissions. While the production of spat and the connected emissions per individual spat are outside of the influence of Deer Island Oyster Company, the best utilization of spat is something that can be improved. On average between 2021 and 2023, 4.2 spat were bought per produced oyster which in turn means that the majority of spat don't turn into market size oysters. By improving survival rates through adjusted farming practices, GHG emission savings can be realized.

Another opportunity for improvement is the replacement of fossil fuel energy sources used for boat operations. By electrifying the boat fleet, large saving of GHG emission can be achieved compared to status quo, even using non-certified, market electricity. These savings can be further maximized by using certified renewable electricity. Electrification of the boat fleet is, however, connected to significant investments and may not necessarily be realistic from an economic standpoint in the short term without financial support.

Actions aiming at increasing the efficiency of current practice are an alternative to the proposed, investment heavy, changes related to fossil fuel-based activities. By reducing the need for boating operations through remote monitoring of farming sites by cameras or sensors, fuel can be saved.

There are ongoing efforts to develop a plastic free oyster farming system to combat ocean pollution but also reduce carbon emissions at Deer Isle Oyster Company. If the development of wood and renewable material-based farming components succeeds, it has the potential to greatly reduce the GHG emissions connected to farming infrastructure due to the lower carbon footprint of such materials.

Ferda Farms

When analyzing the results at different stages of the production system for Ferda Farms, the most prominent area offering improvement opportunities from a carbon footprint perspective is boat fuel use during farming operations. Fuel-related emissions make up 60% of their total carbon footprint, and even small improvements in the area will improve the carbon footprint of the produced oysters.

Replacing the fuel used for boating operations with electric or renewable alternatives offers large carbon footprint reduction potential. The use of electric motors has a smaller carbon footprint compared to their fossil fuel-based counterparts, even when using regular market electricity. By choosing to buy certified renewable energy, the GHG emissions savings can be improved further. The electrification of the boat fleet is, however, connected to large investments. There is currently ongoing development for non-fossil, alternative fuels for vessels (Ammonia, LBG, Methanol, Hydrogen), but none of the alternatives have reached widespread use and require investments in suitable motors and fuel infrastructure.

Actions aimed at increasing the efficiency of current practices are an alternative to the proposed, investment heavy, changes related to fossil fuel-based boating activities. By reducing the need for boating operations through remote monitoring of farming sites by cameras and sensors or improved route planning, fuel can be saved. Per oyster 0.02 liters of fuel are used for boating operations during the farming stage. This is a comparatively high number compared to literature values where 0.005 l/oyster were used by farmers in New Zealand or 0.003 l/oyster for production in Scotland (Warmerdam et al. 2021, SARF 2011). While local conditions and production methods differ between these studies and Ferda Farms' production, the large gap suggests a realistic chance for improvement.

Mook Sea Farm

When analyzing the results at different stages of the production system for Mook Sea Farm, multiple key processes and inputs offer possibilities for reducing the GHG emissions of the production.

Emissions from electricity are a key contributor to the impact of hatchery operations but also the processing stage. Almost a third of the hatchery emissions come from the consumed electricity and of the energy related emissions at the processing stage, and 58% of those emissions originate from used electricity. Actions to reduce electricity consumption therefore have a large potential for reducing the carbon footprint throughout the production systems. The use of more energy efficient lighting and pumps are relevant candidates in this context. One option offering an almost immediate reduction of electricity-related emissions is the switch to certified green electricity (if available in the area). The carbon footprint per kWh for electricity from renewable sources like wind or solar is significantly lower compared to the sources used in the public grid electricity mix, which contains relevant amounts of fossil-based electricity.

Another improvement opportunity is the replacement of fossil energy sources (gasoline) used for boat operations and heating of hatchery and processing facilities. By electrifying the boat fleet, large savings of GHG emission can be achieved even using non-certified, market electricity. Changing the heating systems to electricity-based solutions like heat pumps would also decrease carbon emissions. Both the electrification of the boat fleet and updating of the heating system are, however, actions connected to large investments and not necessarily realistic from an economic standpoint in the short term, without financial support.

Actions aimed at increasing the efficiency of current practices are an alternative to the proposed, investment heavy, changes related to fossil fuel-based activities. By reducing the need for boating operations through remote automated monitoring of farming sites by e.g. cameras or sensors, fuel can be saved or reducing the time oysters spend in the holding tanks at processing could lead to lower electricity and propane consumption.

Pemaquid Oyster Company

When analyzing the results at different stages of the production system for Pemaquid Oyster Company, multiple areas which offer improvement potential arise.

Replacing the fuel used for boating operations with electric or renewable alternatives offers large carbon footprint reduction potential. The use of electric motors has a smaller carbon footprint compared to their fossil fuel-based counterparts, even when using regular market electricity. By choosing to buy certified renewable energy, the GHG emissions savings can be improved further. The electrification of the boat fleet is, however, connected to large investments and not necessarily realistic from an economic standpoint. There is currently ongoing development for non-fossil, alternative fuels for vessels (Ammonia, LBG, Methanol, Hydrogen) but none of the alternatives have reached widespread use and require investments in suitable motors and fuel infrastructure, making them non-ideal candidates.

Actions aiming at increasing the efficiency of current practice are an alternative to the proposed, investment heavy, changes related to fossil fuel-based boating activities. By reducing the need for boating operations through e.g. remote monitoring of farming sites by cameras/sensors or improved route planning, fuel can be saved.

Making up 26% of the carbon footprint at processing gate, oyster spat is an important input to the production system. Per produced oyster, about 2.7 oyster spat are used. While some level of mortality can't be avoided, improvements in survival rate would offer a reduction in GHG emissions while also increasing financial opportunity through reduced cost and more product for sale.

Electricity related emissions during the processing stage could be reduced by investment in more efficient cooling systems (leading to lower electricity consumption) or a change of electricity supplier to certified renewable or low carbon electricity.

ASSUMPTIONS AND LIMITATIONS

Some assumptions had to be made due to a lack of data (see section 4 and supplementary information).

The results from this assessment are only to be used for internal development and guidance at Island Institute and the involved farms. The calculated carbon footprints are not to be used for external communication like advertisements or product labels. If the results were to be used that way, an independent third party needs to assess and verify that this study was done in accordance with the relevant LCA standards (ISO 14040,14044).

RESEARCH NEEDS

This study is, to the authors' best knowledge, the first assessment of greenhouse gas emissions from the farming of eastern oysters. Few LCA studies of oyster aquaculture globally are available in the scientific literature (see section 6.2), and this study adds important data points to the field for four farm sites in Maine. During the work, multiple opportunities for further research were identified to continue building on this assessment or improve background data essential to similar assessments.

A specific research need that was identified is improved data on eastern oyster's biological characteristics in different settings. Edible yield and protein content are likely to be variable depending on the farm's local conditions, season, and the oyster's stage in the reproduction cycle. The data on edible yields used in this study is based on over 30-year-old sources (FAO 1989) and represents average data. Updated measurements would greatly improve the data quality of this key parameter for LCA studies. The protein content of the oyster meat is a similarly central datapoint when the unit of comparison is protein and had to be based on generalized data in this study.

Biogenic emissions, especially from shell formation, were identified as a potentially relevant contributor to GHG emissions of farmed oysters. The available literature, however, shows a large variation in emissions highly dependent on local conditions at the farm. Further research on biogenic emissions from the oysters in different environmental conditions but also the fate of these subsurface emissions of carbon dioxide and the extent to which these will eventually reach the atmosphere would improve the accuracy of calculations in this area. Guidance for how to account for biogenic emissions from farmed bivalves (tissue and shell as well as sediments under farms) in LCA and carbon footprint studies is highly needed, as well as when data from one region and production system (wild/ farmed, bottom farmed/cages) can be applied to another one- and when not.

A research finding from this work was that fuel related emissions from boating operations are of high importance for all assessed farms, and a future research need therefore is quantifying the effect of implementing different improvement measures related to these emissions from vessels. One is to increase energy efficiency by optimizing vessel operation, integrating energy efficiency in the planning of maintenance and harvesting. Installing fuel meters where these are lacking and other technologies (e.g. sensors) that can help reduce fuel use. High-tech and perhaps more long-term solutions to evaluate are monitoring and maintenance by robots and remote technologies (sensors, video), which could reduce the need to use vessels altogether. For the vessel use remaining after that, shifting to alternative fuels is a step that would take out a major part of greenhouse gas emissions of farmed oysters.

Nearshore fleets like smaller vessels operated by bivalve farmers are identified as one of the first and easiest fleets to shift to hybrid operation due to their operational profile. Complementing these environmental calculations with economic assessments would further increase knowledge about the financing approach needed to facilitate the transition to renewable boat propulsion or improved management practices.

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