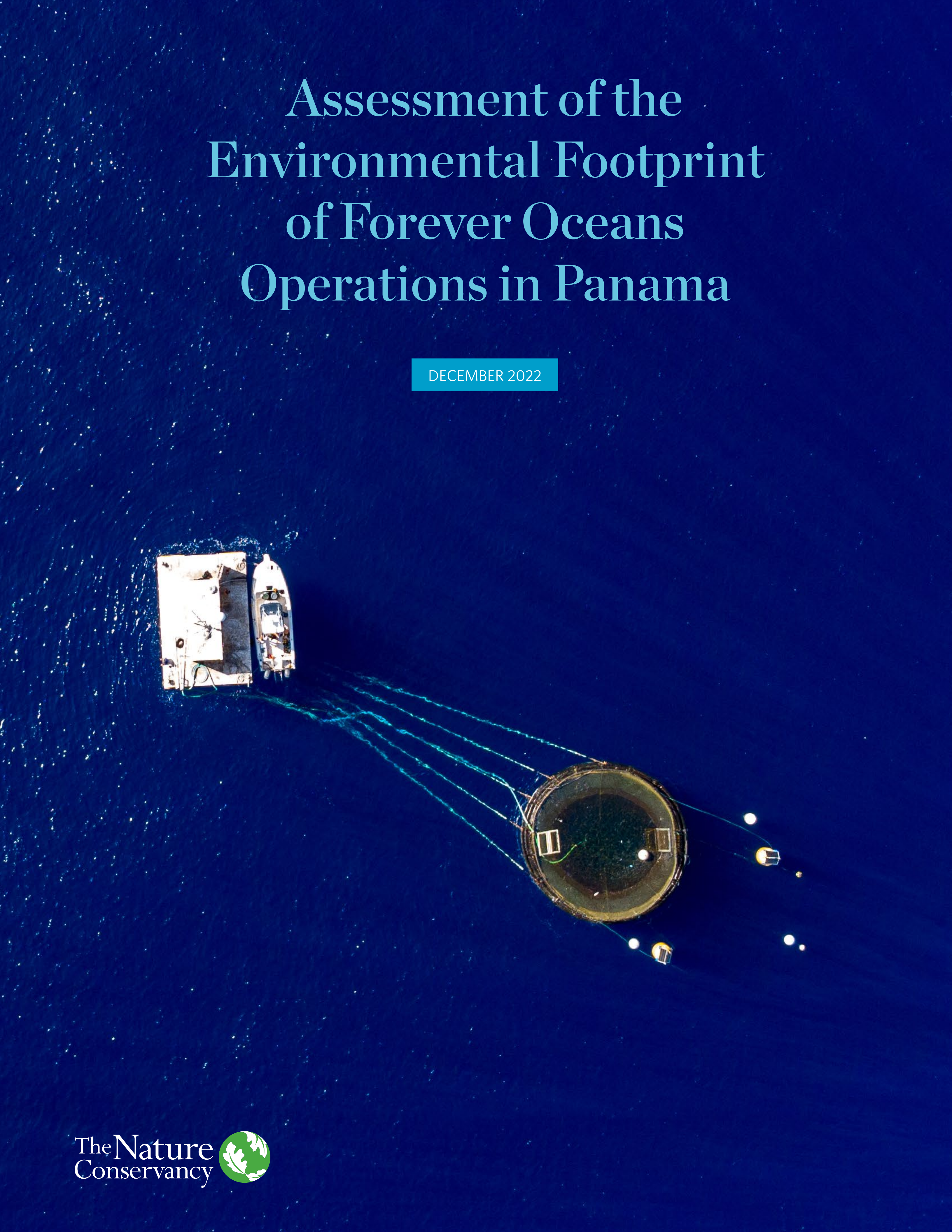
Assessment of the Environmental Footprint of Forever Oceans Operations in Panama

DECEMBER 2022



The Nature Conservancy

Report prepared by:

Heidi Alleway (PhD) and Robert Jones
Global Aquaculture Program, The Nature Conservancy

Lisa Tucker
Tucker Consulting Services, LLC

Disclaimer

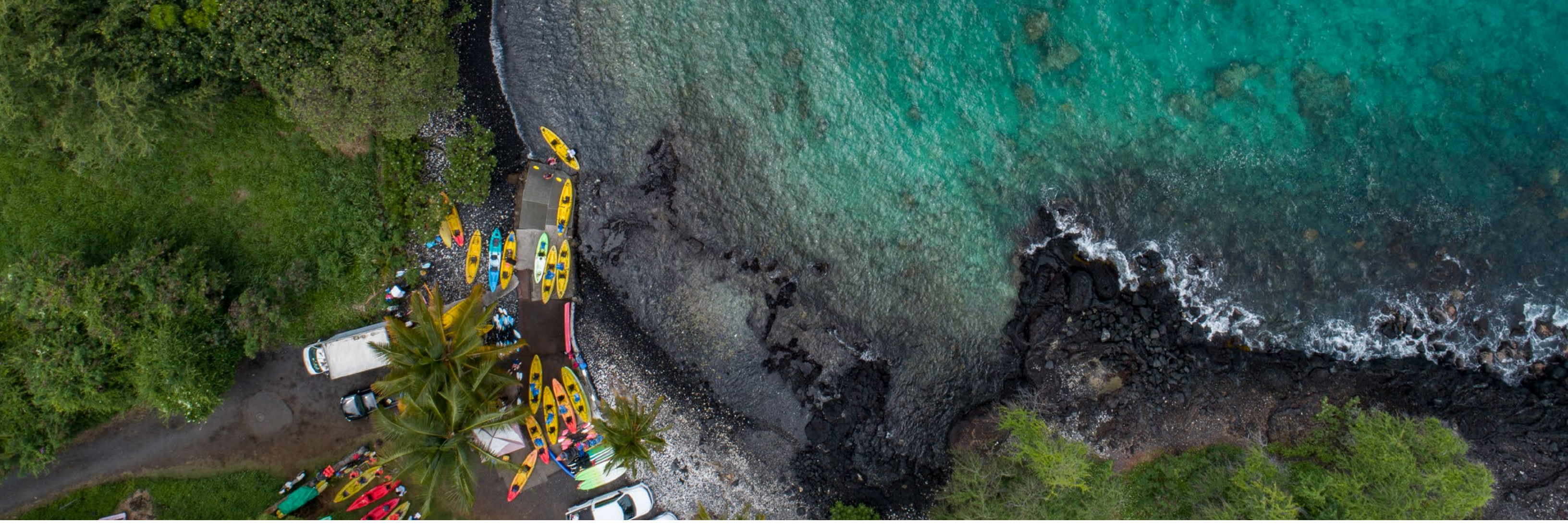
The information contained in this report is based on the best available information at the time of assessment. The data used to make the assessment has been compiled and analysed in collaboration with Forever Oceans in good faith, and while all reasonable care has been taken to ensure that the information contained herein is truthful and not misleading, The Nature Conservancy makes no guarantee of its accuracy or completeness. All estimates made and subsequent recommendations should be considered representative of the information provided and subject to change. This report should not for any purpose be reproduced or published by others in a public domain.

All photos: © Forever Oceans

Contents

LIST OF TABLES

LIST OF FIGURES



1. Executive Summary

Food production is a major contributor to environmental challenges, accounting for nearly one quarter of global greenhouse gas (GHG) emissions, 70 % of freshwater usage, and 80 % of habitat degradation (Poore and Nemecek, 2018). The imperative to find, develop and expand food systems that have a lower environmental footprint is pressing. Fortunately, it is known that making changes in the way we produce food will significantly reduce its resource requirements, making production more efficient and helping to meaningfully mitigate the drivers of climate change and biodiversity loss (FOLU, 2019).

This report highlights the results of an assessment of the environmental footprint of Forever Oceans production of *Seriola rivoliana* in the Bay of Charco Azul, on the Pacific Coast of Panama. It describes the results of Life Cycle Assessment (LCA) quantifying the environmental impacts of the resources and activities required to produce this species through aquaculture, and the primary results of an Environmental Social and Governance (ESG) assessment made by The Nature Conservancy (TNC) of these considerations in the company's operations.

Forever Oceans open ocean Panama site and unique grow out technology have the potential to produce *S. rivoliana* in a way that may avoid or substantially reduce many of the environmental issues commonly associated with coastal net pen finfish aquaculture, especially the effects of fish and feed waste. The depth of water of the company's offshore operations (net pens are positioned 75 to 100m above the sea floor) and use of a single mooring which enable net pens to pivot, will likely result in lower deposition of particulate and dissolved waste to the sea floor over time, and the potential for negative impacts to arise in benthic habitats.

The benefits of farming in an offshore, open-water environment do not appear to have been offset by an increase the resources needed to maintain the site, especially fuel, because of the use of remote systems for feed and monitoring. A GHG emissions impact of 7.13 kg CO_2 equivalent per kg of edible product was calculated, inclusive of GHG emissions to the farmgate and land use, basic processing, and distribution to international markets. This GHG emissions footprint is comparable to similar seafood production systems, including salmon aquaculture, and highly competitive in comparison to many terrestrial animal foods.

Importantly, the LCA was effective in identifying 'hot spots' of environmental concern, providing a quantitative evidence-base for the development of sustainability strategies. Forever Oceans GHG emissions appear sensitive to several key mitigation strategies, including reducing the quantity of feed used and the proportion of product that is distributed to market via air freight. If implemented, these strategies could enable Forever Oceans to reduce its GHG impact to an estimated 4.15 kg CO_2 equivalent per kg of edible product and become one of the lowest GHG emission marine finfish proteins currently available. Yet, because Forever Oceans plans to increase their quantity production markedly in the next 10 years, regardless of the per kg equivalent it must be a priority for the company to move decisively on mitigation strategies, including strategies they can directly implement to reduce scope 1 and 2 GHG emissions as well as strategies that will reduce GHG emissions associated with feed use and the transport phases of production (scope 3).

To take full advantage of Forever Ocean's offshore activities and the large area of the concession (i.e. lease), the environmental footprint assessment was paired with a review of practices that could enable positive ecological benefits to be generated in the broader environment through restorative aquaculture. The company may be able to positively influence local biodiversity through a restorative approach.

2. Introduction

2.1 Background

As the world looks to fill greater demand for nutritious food seafood has emerged as a key sector for meeting demand, at the same as meeting environmental sustainability targets. Yet, development of aquaculture over the last several decades has seen growth in this industry occur at rate greater than most other forms of food production (FAO, 2022a), and this growth has come with considerable environmental impact, including negative effects on water quality, habitats, and the introduction invasive species and diseases (Naylor et al., 2000). Concerted effort has seen gains in increasing the efficiency of feed used for farming, and implementing effective operational strategies and practices to reduce the threat of a range of environmental risks (Naylor et al., 2021). But continued development of new species, farming systems, and operational strategies that can continue to improve the efficiency of resources used in aquaculture is needed.

In parallel with a growing emphasis on seafood to achieve a higher level of sustainability in food systems the global imperative to decarbonize all industries has arisen. Food production (terrestrial foods and seafood) accounts for nearly one quarter of global greenhouse gas (GHG) emissions and 80 % of habitat degradation (Poore and Nemecek, 2018). Changes in the way we produce food could significantly reduce its resource requirements, making production more efficient and helping to mitigate the drivers of climate change and biodiversity loss (FOLU, 2019). The High Level Panel for a Sustainable Ocean Economy has highlighted fisheries and aquaculture as a key action for reducing carbon emissions, these industries having the potential to jointly contribute a 20% reduction in GHG emissions of global mitigation targets, if a greater portion of current food consumption can be shifted toward seafoods (Hoegh-Guldberg et al., 2019).

To support industries in their transition to a low carbon/carbon neutral future, methodologies that identify, measure and support monitoring of resource requirements throughout the life cycle of a product have become a focus of environmental and GHG emissions accounting. LCA is an approach to account for the multiple inputs and potential impacts from aquaculture, especially fed aquaculture. Frameworks that provide a methodology to assess the supply chain, from cradle-to-gate, also enable comparison between products, both seafood products and to other industries such as animal agriculture, and repeated LCA's can illustrate the relative size of effect of specific variables or processes, such as the species farmed, product forms, or modes of transport and proximity of markets. Variability within and between assessments is, however, high, arising from inherent differences in species and production systems and technology use (Bohnes et al., 2019; Ziegler et al., 2021). To increase standardization across studies standards, including seafood-specific standards, are emerging, such as the Publicly Available Specification (PAS) 2050-2:2012, *Assessment of life cycle greenhouse gas emissions: Supplementary requirements for the application of PAS 2050:2011 to seafood and other aquatic food products* (BSI Standards Limited, 2012) and the *European Product Environmental Footprint Category Rules* (PEFCR), including a draft *PEFCR unprocessed Marine Fish Products* (European Commission, 2022). All of these methodologies and frameworks support more comprehensive accounting of the full scope of the environmental footprint of food production and approaches to identify key 'hotspots' of environmental impacts in the production chain.

2.2 Offshore aquaculture and Forever Oceans operations

Commercial-scale offshore aquaculture has been in the sights of the aquaculture industry and regulatory agencies for decades. During the last 5-10 years this interest has intensified, and the potential advantages and barriers of this approach have been made clear (Lester et al., 2018). Infrastructure and technologies have advanced, with numerous pilot projects working to validate and normalize operation of aquaculture facilities in open-ocean environments. This is driven, to a degree, by the global salmon industry, however, the majority of operational systems that have been deployed are the result of smaller, independent companies producing emerging species. These companies are often working with newly developed technologies and are navigating regulatory systems that may not be directly applicable to offshore operations. Forever Oceans is using a unique net pen design that employs a single-point mooring rather than a grid of moorings, that can be raised and lowered in the water column. Feeding is fully automated, and is monitored remotely, rather than by personnel at a feed barge at the offshore site. The company has a strong interest in reaching a carbon neutral and regenerative status, and is uniquely placed to do so given their use of this technology.

Forever Oceans operations include a land-based hatchery and broodstock facility in the community of Manaca Civil in the Rodolfo Aguilar Delgado district, Barú district, Chiriquí province. Offshore marine net pens are located in the Bay of Charco Azul, in the Gulf of Chiriquí at a depth of approximately 15-36 meters below the sea surface. Through its hatchery and broodstock management systems, Forever Oceans has closed the lifecycle for *S. rivoliana*, however feeds are produced externally by a feed supplier and processing occurs at a facility located in Panama City. The hatchery portion of the production cycle is approximately 70 days, and relies on rotifers and artemia, with pelleted feed only used to wean juveniles as they are prepared to be transferred to the offshore sites, which rely solely on pelleted feed. The offshore portion of the production cycle lasts approximately 10 months. At the offshore sites, net pens use a single-point mooring system and are equipped with technology allowing them to be submerged in the water column. Automated feeding systems are used and sensors monitor key water quality parameters in real-time. There are 29 commercial production net pens approved for use within the concession, with four net pens currently deployed and 10 used for research and trials. The commercial net pens have a 50m diameter, are 16m high, and drift across an area with a radius of approximately 200m. Net pens for research and trials have a diameter of 12m and are 10m high with a similar pivot footprint. Upon harvest, fish are transported to the processing facility where they are filleted, and then shipped to markets in Miami, Florida and Los Angeles, California, USA.

Based on species characteristics (e.g. FCR, growth rate, water quality tolerances), operational considerations (e.g. availability of fry, availability of disease interventions), and market considerations, *Seriola* species have been identified as a commercially ready candidate for offshore production at the regional scale, with room for expansion (O'Shea et al., 2019). Globally the majority of *Seriola* is currently produced in coastal net pens in Japan (85% of the 2020 global total 160,941 mt; FAO, 2022b). However, it is an emerging species among independent offshore producers such as Forever Oceans, and thus represents an important pathway for greatly increasing the output of a wider range of finfish species in an environmentally sustainable way.

2.3 Basis of the assessment

The aim of the environmental footprint assessment was to provide Forever Oceans a scientifically-grounded and quantifiable method to assess the environmental impacts of their business and the production of *S. rivoliana* in Panama. The framework used, and results of the assessment, are intended to be used to guide how the company can make decisions about sustainability strategies in addition to environmental and other monitoring already employed and improve in the future, while substantially increasing production attaining its business objective.

The assessment framework is comprised of an LCA to evaluate the environmental impacts of key resource requirements and activities throughout the production chain and a 360-degree review ESG considerations of the company's operations. Life cycle impacts assessed included GHG emissions, fresh water use, land use, eutrophication, and biodiversity.

The LCA was completed consistent with ISO standards, specifically 14044 Environmental management—Life cycle assessment—Requirements and guidelines (International Organization for Standardization, 2006), following the four phases described in this standard:

a. the goal and scope definition phase,

b. the inventory analysis (Life Cycle Inventory, LCI) phase,

c. the impact assessment phase, (Life Cycle Impact Assessment, LCIA), and

d. the interpretation phase.

In completing the assessment, the European Union Product Environmental Footprint Category Results (PEFCR) methodology, specifically draft guidance on data that should be collected to make a comprehensive assessment of environmental footprint from the draft Marine Fish PEFCR, was also considered. The PEF describes an LCA-based method to quantify the relevant environmental impacts of products (goods or services). As of July 2022, the Marine Fish PEFCR remains in draft form (version 5) and is being used to guide supporting studies, including comprehensive inventorying of activities and data[1].

---

[1] Marine Fish PEFCR Supporting Studies; https://www.marinefishpefcr.eu/supporting-studies

3. LCA methods

3.1 Goal and scope

The goal of the LCA was to provide an initial estimate of the likely and projected environmental impacts associated with Forever Oceans aquaculture operations in Panama for the production of *S. rivoliana*. Forever Oceans is in the initial stages of establishing commercial production in Panama and has targets for significant growth in production over the next 5 years, from the current scale of production to an estimated output of 20,000 tonnes by 2029 and 26,000 tonnes by 2032.

Completing the assessment on operations at an early stage increases the visibility of likely 'hot spots' for environmental impacts, particularly GHG emissions, and provides a quantifiable baseline of the company's potential overall environmental footprint. The assessment is intended to provide the company an evidence base from which it can make informed decisions about the development and adoption of sustainability strategies to reduce impacts.

The current scale of Forever Oceans Panama operations does, however, introduce some limitations to the extent to which impacts can be accurately quantified. The assessment has been made on the production of a single cohort and several data points have been projected, such as total feed usage and product yield from harvest. Further, some key areas of risk are not yet sufficiently detailed and were excluded from the assessment, such as the use of packaging and handling of waste (see section 3.6 for further discussion on data limitations, exclusions and assumptions).

As such the results of the assessment should be viewed as a basic baseline estimate, representative of the initial environmental footprint of operations but sensitive to changes in the scope and intensity of activities as the company scales up its production. The trade-off between conducting an LCA in an early enough stage to influence decision making versus operating under complete information is a commonly recognized quandary, sometimes referred to as the Collingridge dilemma. It is widely understood within academic communities that constructive sustainability assessments should be completed before companies enter a scale up phase, and that such asssessments will often face data limitations (Matthews et al., 2019).

Also, uncertainty analyses to assess the effect of variances in the data on the results have not been completed given the limited data available and current combination of primary data with projected estimates for key inputs, specifically feed and production. Once further data is collected the assessment could be updated and a range of uncertainty analyses, and a greater range of sensitivity tests to the potential influence of selected improvements, could be completed. Several initial sensitivity tests were run to broadly test the efficacy of reductions in feed use and air freight on mitigating the GHG emissions impact, and their perceived priority as key sustainability strategies.

The LCI developed in the assessment provides a framework for data collection and monitoring. The timing and timeframe of data collection in the future should be guided by what is reasonable based on staff resources but sufficient to adequately capture the inputs required for production, particularly in areas identified as 'hot spots' for environmental impacts in the production chain.

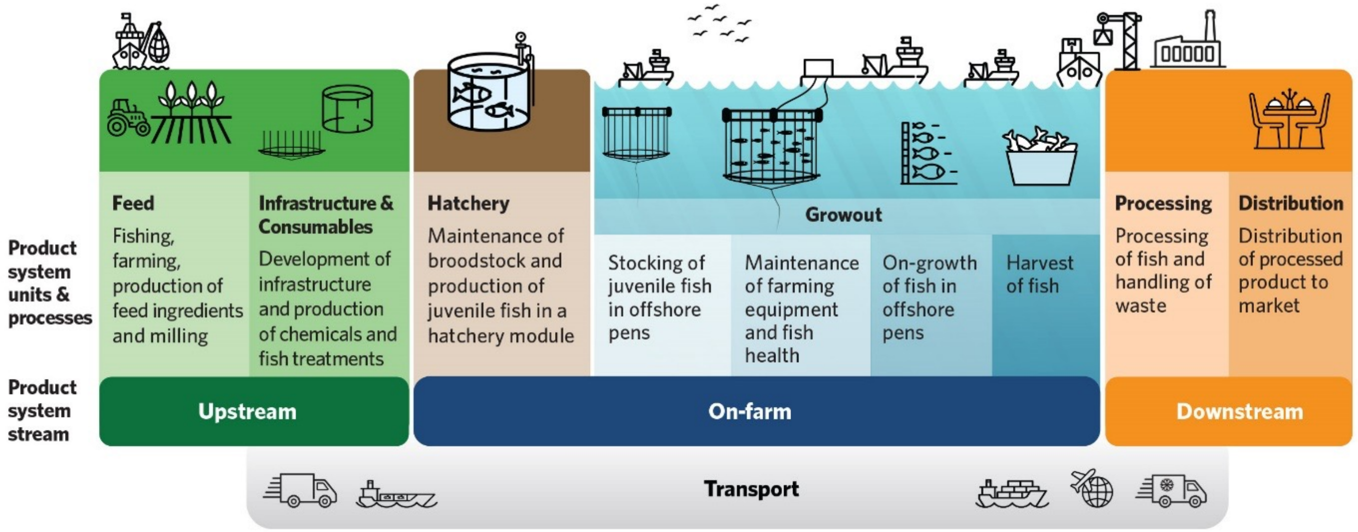


Figure 1. Life cycle map of production associated with Forever Oceans operations in Panama

→ **TNC RECOMMENDS** *that data on the processes and activities identified in the LCI should continue to be collected through a standardized data collection and monitoring program, to support future updates to the LCA and inclusion of sensitivity analyses to generate more robust results for comparison.*

The scope of the LCA included potential environmental impacts from processes and activities required to produce one kilogram of edible seafood of the species *S. rivoliana,* from cradle (pre-production, upstream processes) to market, produced from a single cohort in a land-based hatchery and then outgrown offshore in a net pen supported by an in-situ barge. This includes consideration of material, energy and natural resource processes required for upstream (e.g. feed, infrastructure and chemical production), on-farm (e.g. hatchery activities, stocking, grow out, harvest), and downstream (e.g. post-harvest processing, distribution to market) activities, and transport required throughout (Figure 1).

3.2 Functional unit

The primary functional unit is one kg of edible product, unpackaged, delivered to market. Assessment of this functional unit includes data on notable upstream processes, including feed, chemical and infrastructure production, on-farm activities as well as basic processing, and then distribution to market.

In addition to assessing this functional unit, the LCA was based on activities required for the production of a 'cohort' of fish, reflecting a cohort as a secondary functional unit, i.e. total quantities and impacts are representative of a cohort. A cohort includes production of the total quantity of fish in a hatchery, raised in this facility for 3 months, and then outgrown in a single offshore net pen for 10 months.

Foreground data from the production of cohort 4 was used to make the assessment. Cohort 4 was produced in the hatchery mid- to late-2021, deployed to a single offshore net pen in November 2021, and on-grown throughout 2022 to the beginning of harvest late August 2022. At the time of assessment fish were being harvested under a 'harvest when ready' strategy and biomass from cohort 4 remained on site.

Data from production of cohort 3 was not included in the assessment, either as the modelled cohort or to generate a mean across cohort 3 and 4, because production from cohort 3 was substantially less—approximately half—of the biomass already held on site from cohort 4. It was considered that including data from cohort 3 would underestimate production and feed usage, which would make the assessment less representative of the environmental footprint than that which would be calculated using data from cohort 4 only.

The early stages of production by Forever Oceans means the modelling and estimates made may be subject to change, as production increases and operational adaptations in farming arise. For example, Forever Oceans has indicated that two net pens will ultimately be tethered to a barge to form a 'site'. It is possible that the inputs required to maintain two pens will scale linearly, but it is also possible that the addition of a second net pen to a barge will decrease or increase fuel use in a non-linear way. Changes in the inputs required to farm a greater biomass and multiple net pens should be monitored closely for any significant increase in resource use, especially electricity usage in the hatchery and diesel usage at the offshore marine sites.

→ **TNC RECOMMENDS** *that activities associated with on-farm operations should be closely monitored during the scale-up of production and compared to the benchmarks established in this assessment, to identify any unforeseen disproportional increases in energy requirements. The results of the LCA should be updated if significant variances are identified.*

3.3 System boundaries

A system boundary refers to the units and processes that have been considered in the life cycle, adopting the categorization and terminology of units, processes and subprocesses, and activities. This assessment considered the full life cycle for production of *S. rivoliana* in Panama, from the production of feed, infrastructure, and chemicals, to a range of activities associated with on-farm production (hatchery and offshore marine grow out), and then processing and distribution to two identified markets (the point of entry to these locations, not distribution to wholesalers/restaurants and their handling of the product), these being Miami, Florida and Los Angeles, California, USA. A single product of one kilogram of filleted fish was assessed.

The production of co-products and by-products was not included within the system. Similarly, waste recovery, reuse and recycling were not included. Activities associated with co/by-product production and waste treatment and recycling have not yet been identified or consistently applied by Forever Oceans in Panama. As such, while these activities will form a part of the life cycle, and recycling a part of the company's sustainability requirements, sufficient description around these activities and data is not available to effectively assess their impacts. As operations advance, handling of waste and by-products is addressed, and data becomes available on these processes, a more comprehensive approach to allocation and impact assessment will be possible and should be included in any future LCA.

Because the system assessed is currently considered to give rise to a single product only a simplified model with mass allocation was used, that allocates the impact of inputs in full to the fish product. For feed production, data was made available by the feed supplier that quantified the impacts of feed production using the EF 3.0 method.

3.4 Life cycle inventory analysis and data collection

Processes and activities forming the life cycle of finfish production were mapped and inventoried in discussion with Forever Oceans. An inventory and analysis of data on the resources required to complete production (e.g. materials, chemicals and energy), and outputs to the environment (e.g. GHG emissions) associated with these processes and activities was completed by:

- reviewing existing company materials associated with operational development and permitting (e.g. business case development and EIS documentation required by the Government of Panama) ;
- reviewing documents associated with recent ASC certification;
- using targeted data collection surveys to record foreground data; and
- structured questioning to address data gaps and seek clarification on activity interpretation, including correspondence, regular face-to-face discussions and workshops.

Foreground data on the system and operations (e.g. quantity of feed used, energy used, infrastructure deployed, fish biomass) was provided by Forever Oceans, in the form of applicable data logs (e.g. Activity Logs for the cohort recording information on biomass, feed type, date and quantity, mortalities, and logs for especial activities such as parasite treatments).

Forever Oceans facilitated the collection of data from the feed supplier and basic activity information from the processor. Data on the potential waste outputs from fish grow out in the offshore marine environment were provided through a separate study. That project modelled three environmental footprint scenarios accounting for particulate organic carbon (POC) loading from fish faeces and waste feed for four Forever Oceans growing sites in Charco Azul Bay, providing a quantitative assessment of the farming emissions for nutrient loading and organic particle deposition.

Where foreground data was not available, projections were made based on data available at the time of assessment. Importantly, key data on production and feed quantity for cohort 4 was projected. Data on the total harvested biomass was not available because fish were still on site at the time of assessment, and therefore still being fed. These data were 700,000 kg total biomass produced (live weight) and a total of 1,624,000 kg of feed used[2].

Output data associated with GHG emissions was sourced from the ecoinvent Database (version 3.8), except for data for GHG emissions from feed production and transport of feed, which was supplied directly from the feed supplier.

---

[2] Projections made on 15 September and confirmed by Forever Oceans.

3.5 Data limitations, exclusions and assumptions

Based on the status of Forever Oceans operations, which reflect initial, early-stage commercial production—the cohort assessed was the first to be used for commercial sale—several processes were not included in the LCA. This limits the comprehensive of the processes that can reasonably be included in the assessment. Notable processes and activities not able to be adequately quantified, and as such excluded from the assessment, were:

- waste treatment, recovery and use of by-products;
- foreground data on processing operations;
- accurate estimates of product yield from live weight;
- data on the weight of product transported to the processor and then to market; and
- information on the types and quantity of materials used for packaging.

→ **TNC RECOMMENDS** *that Forever Oceans begins a data collection process to gather foreground data on processing activities, yield from processing, and weight/volume of product transport, inclusive of the weight of packaging.*

The exclusion of these factors means that the projected impacts are baseline estimates and that GHG emissions per kg, for example, may be marginally greater. Additional processes within the life cycle will require the outputs of these activities to be included in assessing environmental impacts, which would increase the extent of impacts associated with the functional unit (e.g. increase GHG emissions). However, the inclusion of processes that generate and use co/by-products would also result in an allocation of the impacts to those products, thereby reducing the extent of the impacts associated with the functional unit.

Additionally, several key data points were projected, notably the total live weight of harvested fish (700,000 kg total) and total quantity of feed used (1,624,000 kg).

Refrigerants have a high climate emission potential. It was indicated that refrigerants were not a part of on-farm operations at the time of assessment. Refrigerated transport is not used to transport harvested fish to the processor, with fish transported ‘on ice’. However, data associated with ice production, the volume and weight of fish transport, and additional transport materials (i.e. fish bins) was also not available at the time of assessment. A generic GHG emissions impact associated with freighting the full volume of fish produced at harvest (total live weight for cohort 4 of 700,000 kg) via a market sourced lorry with refrigeration to freezing was used. An estimate of the impact of chilled storage at the processing facility was also included. Other finfish LCAs suggest that freezing represents a negligible part of the energy use of processing plants, and that cold storage before and after processing uses most energy (e.g. Winther et al., 2020). Greater resolution of the nature and volume of fish transport from the offshore site to the processor, and then distributed to market, is needed. The use of refrigerants should be closely monitored, with this activity and its outputs incorporated into the analysis of GHG emissions if required.

3.6 Impact assessment and modelling

LCIA translates the way in which processes and activities identified in the LCI contribute to environmental impacts, to enable an assessment to be made of their environmental significance. Impact categories and classification for the LCIA results were identified by Forever Oceans’ interest in understanding their environmental footprint and spanned climate change, resource use, and environmental interactions. Categorization used for the interpretation of these impacts were: global warming impact (GHG emissions, kg CO_2 equivalent), fresh water use (deprivation), land and marine area use (spatial footprint, m^3), and biodiversity.

3.6.1 Global warming impact

To estimate GHG emissions, LCIA scores derived through the system model of “Allocation, cut-off by classification” and the IPCC 2013 Global Warming Potential 100a indicator for climate change (kg CO_2 eq) were applied to processes and activities throughout the life cycle.

With respect to several key factors known to be the major contributors to GHG emissions in finfish aquaculture, feed and transport (Bohnes et al., 2019), GHG emissions from feed production and transport were assessed by the feed supplier, calculated as global warming impact using the Environmental Footprint standard 3.0 methodology and the *PEFCR Feed for Food Producing Animals 2018*. A weighted average of 1.24 kg CO_2 eq per kg feed (1.18–1.98) across three products from the same range was estimated. Transport associated with delivery of the feed was described as occurring via two potential pathways, with the larger of three sizes of pellets being transported from Costa Rica to Forever Oceans facility in Panama (approximately 433 km by truck), and smaller pellets from France to Panama through Costa Rica (approximately 1,428 km by truck and 9,085 km by vessel). To provide a conservative estimate the highest GHG emissions impact of transport from France across the feed products was adopted.

At the time of assessment transport to market was solely by air freight. Two distribution points, Miami, Florida and Los Angeles, California, USA, to the point of entry (i.e. excluding distribution to wholesalers or restaurants), were assessed, with a 50:50 distribution of product assumed. Accurate data on yield post-processing was not available. As such, a conservative estimate of 50% was adopted, but the total quantity of edible product transported to market was doubled to provide some account for the weight associated with packaging in addition to the edible product.

To align global warming impact with production of a cohort of fish, and therefore the known quantity of fish produced and feed used, electricity usage in the hatchery was averaged over the 3-month period the cohort was in this facility, because energy consumption was lower at the start of this cycle and increased through to the end of the cycle. Diesel and electricity used in the hatchery and offshore was summed for the period these processes were employed and GHG emissions calculated for each. Because Forever Oceans is in the initial stages of implementing and scaling-up production data on diesel use in supporting infrastructure was available, but somewhat difficult to differentiate between test and development activities and those associated with day-to-day operations. An exact quantity of fuel used in the generators on barges tending the net pens was included, because fuel use was constant throughout the period assessed (450 L per month). But fuel used in vessels was more variable, including new infrastructure being added during the assessment. A total quantity of 20,000 L used in vessels across the 10 months to produce a cohort was included. This quantity should be closely monitored for any significant increases or decreases during the development phase.

To account for aquatic N_2O emissions the global average from Hu et al. (2012) was adopted. This global figure is widely used in assessing aquatic N_2O and established a generalized figure of 1.6 $gN_2O\text{-}N/kg$ fish farmed. The maximum biomass produced was used to establish the aquatic N_2O released from the farming of the cohort.

3.6.2 Fresh water use

The impact of freshwater use was calculated as the basic effect of deprivation, measured as water deprivation potential (WDP) in m^3 world equivalent. Data on the impact of fresh water use during the production of feed was provided by the feed supplier, because it was indicated that potable water only was used within the hatchery and data was not available to assess fresh water use during processing. It is likely that fresh water use during processing will constitute and notable portion of total use in on-farm and downstream processes. Further data on this activity should be collected, and fresh water use within the hatchery should be monitored for any notable use beyond potable water and day-to-day use.

→ **TNC RECOMMENDS** *that data is collected and assessed on the quantity of fresh water used during processing, including production of ice for transport of fish to the processor.*

3.6.3 Land and marine area use (spatial footprint)

Land use to produce feed was calculated by the feed supplier and confirmed (by the supplier) as being inclusive of land use change and conversion. The method for evaluating land use according to the EF 3.0 methodology and the *PEFCR Feed for Food Producing Animals 2018* was used. The land use impact category relates the use (occupation) and conversion (transformation) of land area by activities such as agriculture, forestry, roads, housing, and mining. Land occupation considers the effects of that land use, the amount of area involved and the duration of its occupation (changes in quality multiplied by area and duration). Land transformation considers the extent of changes in land properties and the area affected (changes in quality multiplied by the area)[3].

Broader 'land use' for Forever Oceans on-farm operations was calculated as the surface area—2D footprint—across land and marine areas. This footprint included assessment of land area used to develop the hatchery facilities (built facilities including pipelines), the area occupied by the net pen 'on pivot', inclusive of two net pens because both would be tethered to a single barge, and the maximum potential spatial distribution of excess nutrients via waste from the net pens to marine sediments.

3.6.4 Biodiversity

Accounting for impacts to biodiversity in LCA has been a longstanding challenge. A consistent approach and metrics to benchmark effects is not yet available, though there is widespread consensus that assessing impacts to biodiversity is an important consideration in production systems and progress is being made toward better defining key biodiversity variables for assessment and appropriate methods (Winter et al., 2017). Because of these challenges, biodiversity impacts, which can be broad and effect different parts of the ecosystem (e.g. physical variables, habitat, species, trophic interactions), remain rarely covered in LCA methodologies, including where positive environmental outcomes might occur (Vélez-Henao et al., 2021).

In fed finfish aquaculture negative effects on biodiversity in a production chain are often considered to be greatest in upstream processes, specifically feed production, because of the land use and conversion required to produce plant ingredients such as soy and wheat. Yet, fed finfish also farming presents a wide range of risks to biodiversity in the marine environment. To evaluate the potential biodiversity impacts of Forever Oceans on-farm operations, key biodiversity risks were considered. A qualitative and semi-quantitative assessment of the negative biodiversity effects was made using a conceptual model specifically developed for this work, intended to view the effects of Forever Oceans fed finfish aquaculture within the context of the current health of the local environment—the *reference situation*—and the opportunity for Forever Oceans to implement

---

[3] Information and confirmation provided by the feed supplier, 12 August 2022.

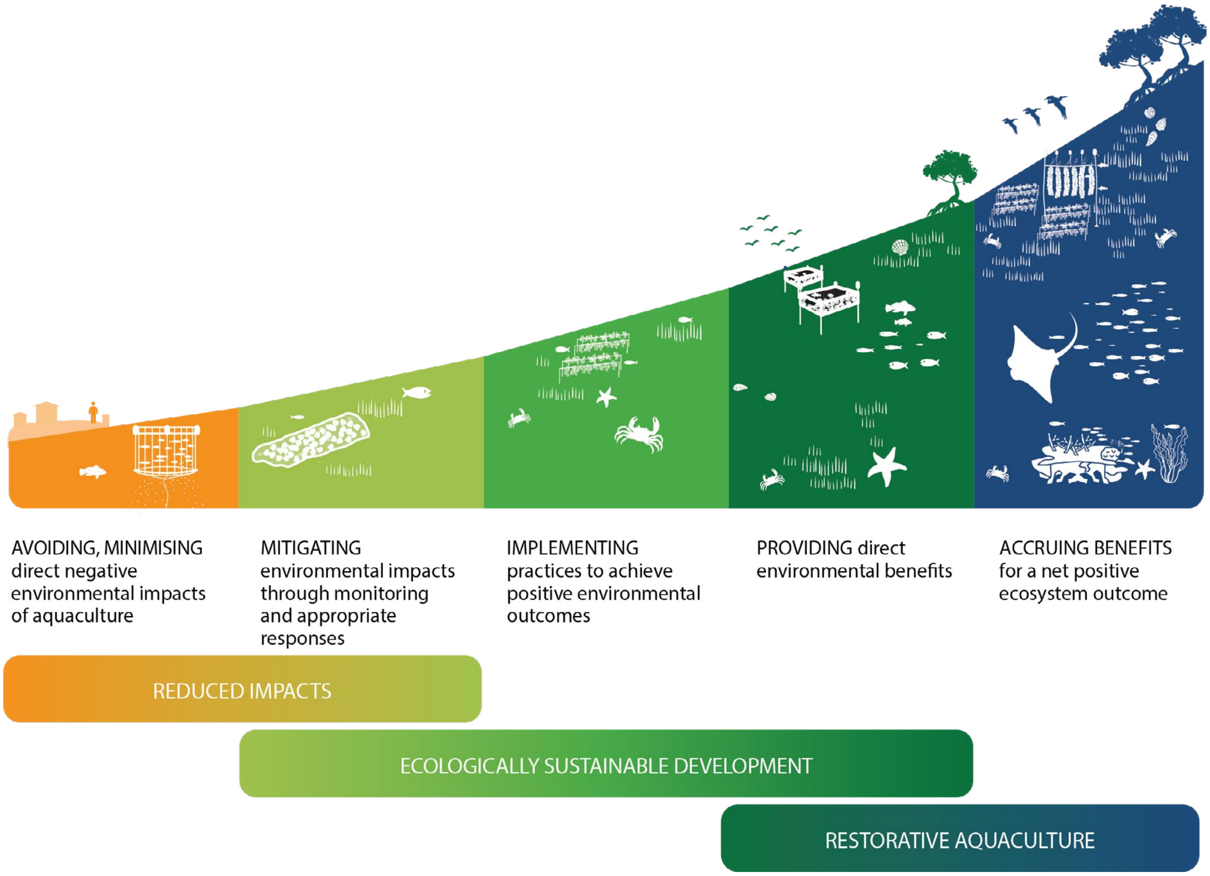


Figure 2. The restorative aquaculture pathway identifies how commercial and subsistence aquaculture can avoid, mitigate and then implement aquaculture practices (in all systems, species and environments) to provide environmental benefits, with the potential to accrue benefits for a net positive ecosystem outcome (The Nature Conservancy, 2021).

sustainability strategies and practices to have a positive effect on biodiversity—the *target reference situation* (Vrasdonk et al., 2019). The biodiversity-positive reference situation reflects Forever Oceans interests in restorative aquaculture. Restorative aquaculture occurs when commercial or subsistence aquaculture provides direct ecological benefits to the environment, with the potential to generate net positive environmental outcomes (Figure 2). Use of the model was paired with the results of the ESG assessment of the company's operations, which sought to assess the level of risk presented to a range of environmental factors, communities and species.

While use of this model provided a way to identify key biodiversity threats and specific strategies that could reduce or eliminate these risks, and then have the potential to provide a positive effect on biodiversity, further data on local ecosystem health and species conservation status in the Bay of Charco Azul is needed to generate to a more quantitative biodiversity assessment.

3.6.5 Sustainability indicators

As Forever Oceans works to increase its production in Panama and expand its operations to other geographies it may be advantageous to adopt a set of simplified sustainability metrics that can assist with tracking the efficacy of strategies across the company's operations quickly and consistently. These indicators should align with impact 'hot spots' in the life cycle.

The number and diversity of sustainability metrics now used in aquaculture is prompting discussion on the scope and complexity of accounting, with the suggestion that a smaller and more consistent set of sustainability metrics that can support frequent, repeated assessment would be valuable. Enabling regular monitoring and comparison within and across a company, sector and products will be critical to ensuring the seafood industry can achieve sustainability targets. Complex, often lengthy LCAs are valuable in generating a baseline but do not readily support ongoing monitoring. As such, a set of evidence informed metrics have been suggested to guide monitoring of progress in a timely way, in addition to LCAs when/where these are required (Ziegler et al., 2021).

In addition to assessing impacts in the life cycle the effect of resource use and activities was calculated according to two key fed finfish sustainability indicators:

1. Scope 1, 2 and 3 GHG emissions, aligning with the GHG Protocol Corporate Accounting and Reporting Standard[4]; and

2. economic FCR (eFCR), a metric that encompasses various mass balances that occur in the process of farming animals, including accounting for feed wastage and any animal production losses (e.g. mortalities) that occur. eFCR is considered especially important in relation to the GHG emissions footprint of farmed fish because the footprint of the feed typically dominates the overall footprint of the product (REFS). eFCR was calculated using the simplified formula of:

   eFCR = weight of feed fed / weight of fish produced

   for fish at harvest (live weight), 75% yield and 50% yield. Because losses during the production cycle are not often included in LCA's, eFCR has also been suggested as a scaling factor, applied to feed usage and production, to obtain a more representative estimate of total farmgate GHG emissions (Ziegler et al., 2021).

→ **TNC RECOMMENDS** *adopting and regularly reporting scope 1, 2 and 3 emissions and economic FCR, and progress made toward reducing both, in company materials as these are transparent and readily repeatable indicators of the sustainability of fed finfish aquaculture systems.*

3.6.6 Sensitivity analysis of key GHG emissions improvement strategies

Based on the results of estimating outputs from cohort 4 the effect of implementing two key strategies was evaluated, to assess the sensitivity of GHG emissions to these improvements and, therefore, their likely efficacy as sustainability strategies. These interventions were an improvement in FCR, with a proportional (per kg) reduction in feed use, and increasing the proportion of frozen product enabling fish to be freighted via sea rather than air.

To test the sensitivity of global warming impact to these strategies GHG emissions were modelled according to:

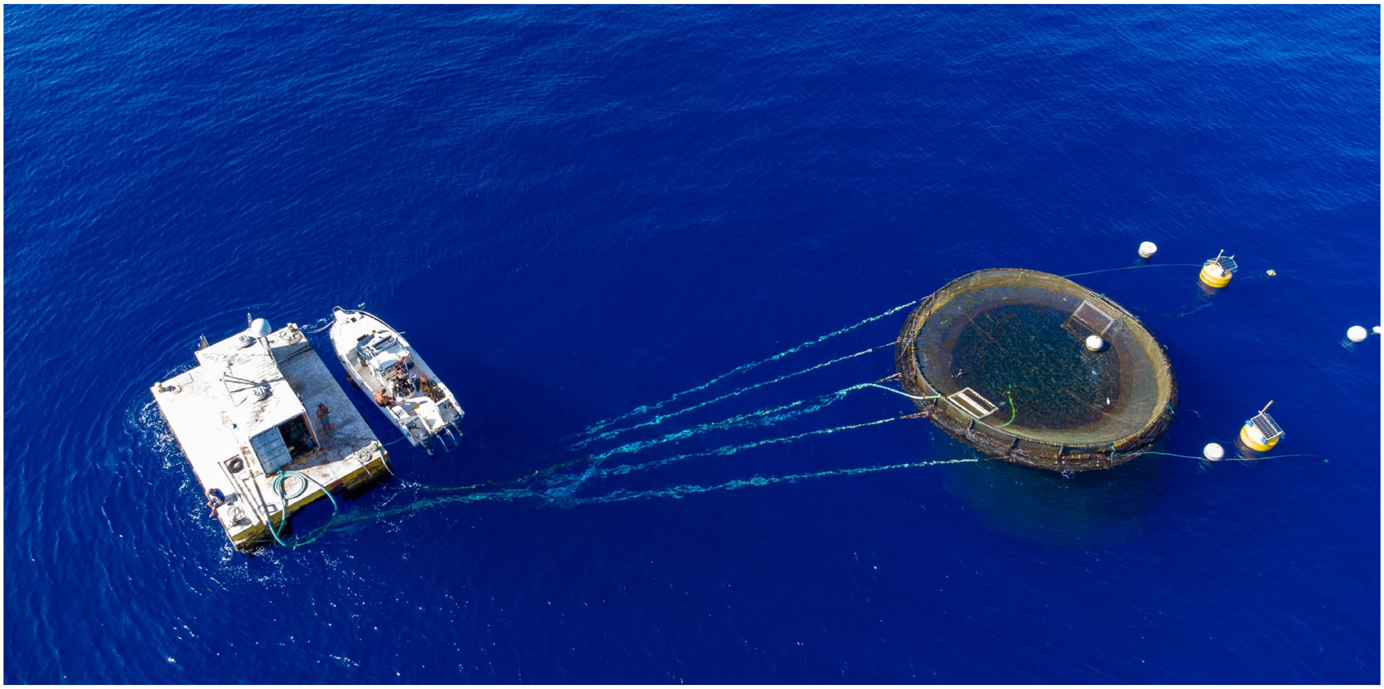
1. a reduction in FCR from 2.10 (the anticipated FCR at the end of 2022) to 1.42 in 2035; and

2. increasing the proportion of frozen product and ship freight from 0% in 2022 to 75% by 2026.

Year-on-year and the total cumulative effect on GHG emissions to 2035 were estimated, using Forever Oceans projections of a total farmed biomass of 26,000 tonnes per annum from its Panama operations by 2032 (continued through to 2035). Data on the projected changes in FCR and distribution of product were provided by Forever Oceans.

---

[4] The GHG Protocol Corporate Accounting and Reporting Standard provides requirements and guidance for companies and other organizations preparing a corporate-level GHG emissions inventory; https://ghgprotocol.org/corporate-standard



4. Life Cycle Impact Assessment

4.1 Global warming impact

The GHG emissions impact of Forever Oceans Panama operations are an estimated 7.13 kg CO$_2$ equivalent per kg fish, inclusive of GHG emissions to the farmgate and land use, basic processing, and distribution to international markets. Twelve per cent of this impact is associated with on-farm operations, with 48% generated by upstream activities, especially feed production, and 40% by downstream activities, largely because of the current production of fresh fish and use of air freight to markets (Figure 3). Excluding these downstream activities, which is representative of a 'farmgate' indicator of GHG emissions, Forever Oceans Panama operations' impact is an estimated 4.26 kg CO$_2$ equivalent per kg fish.

Scope 1 and 2 GHG emissions account for an estimated 0.38 kg CO$_2$ equivalent per kg fish (5.3% of total GHG emissions), with the significant majority of GHG emissions arising from scope 3 processes and activities (Figure 3).

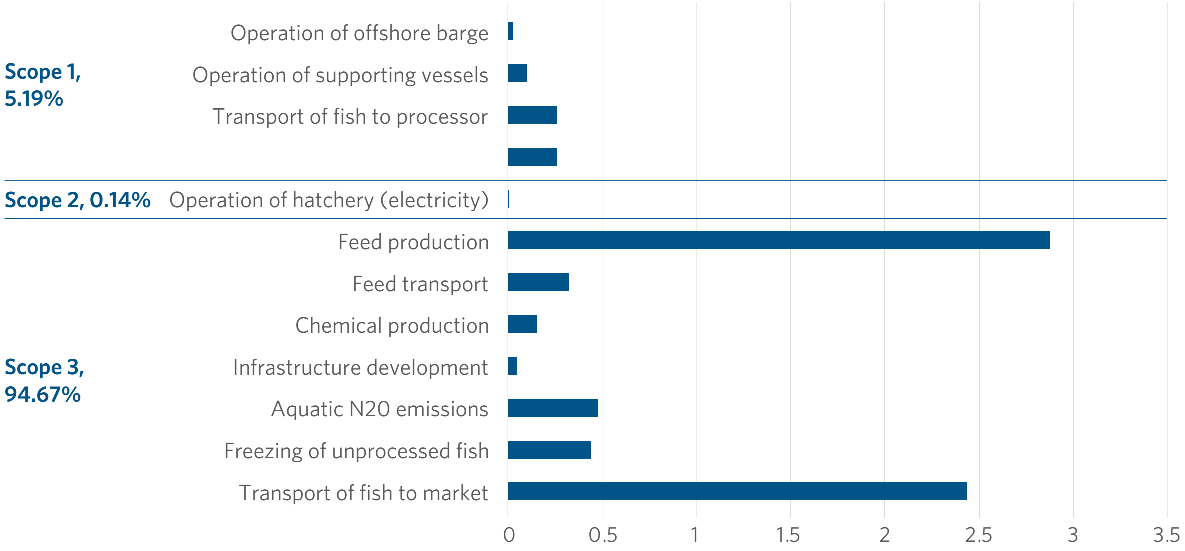


Figure 3. Estimated GHG emissions, kg CO$_2$ equivalent per kg fish, associated with Forever Oceans production of *S. rivoliana* in Panama.

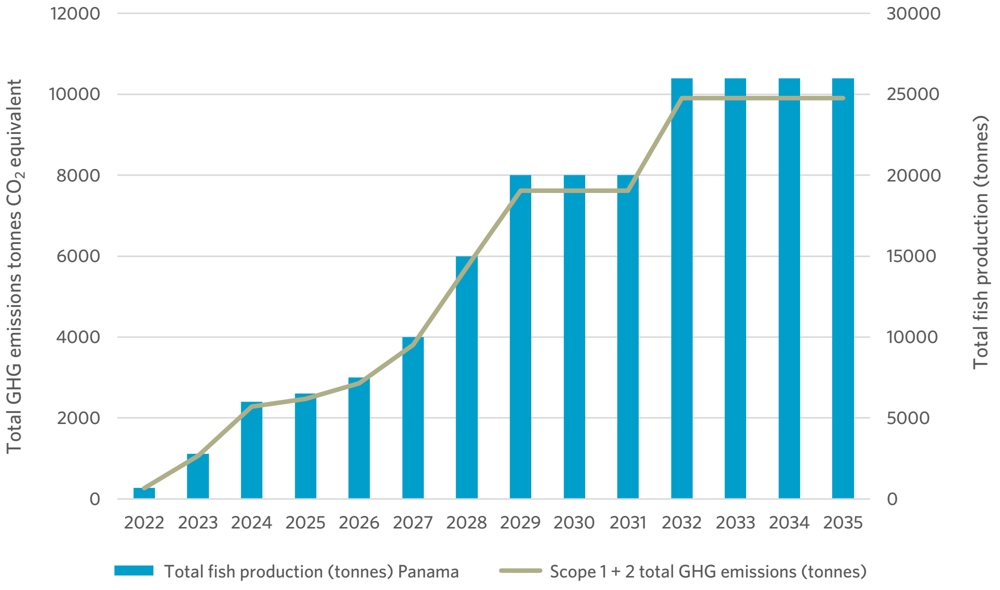


Figure 4. Total projected scope 1 and 2 GHG emissions (tonnes CO_2 equivalent) per annum associated with Forever Oceans production of *S. rivoliana* in Panama.

Data on projected annual production from Forever Oceans Panama operations indicate that total production per annum will increase over the next the 10 years, reaching 26,000 tonnes by 2032 with this output maintained thereafter. Under a 'business as usual' scenario, production at this scale would generate approximately 1,515,074 tonnes CO_2 equivalent per annum.

Based on the current assessment, with scope 1 and 2 GHG emissions representing 5.3% of the overall GHG emissions impact, this will create an estimated global warming impact of 9,905 tonnes CO_2 equivalent per annum at the maximum production of 26,000 tonnes (Figure 4). The estimated year-on-year impact of projected production to 2035, for scope 1 and 2 GHG emissions, is an estimated 80,955 tonnes CO_2 equivalent. This is the quantity of carbon that Forever Oceans will need to offset if they seek to achieve carbon neutrality in scope 1 and 2 GHG emissions (Table 1).

Given this total quantity GHG emissions, regardless of the per kg equivalent it must be a priority for the company to move decisively on mitigation strategies, including strategies they can directly implement to reduce scope 1 and 2 GHG emissions as well as strategies that will reduce GHG emissions associated with feed use and the transport phases of production (scope 3).

Table 1. Total projected scope 1 and 2 GHG emissions (tonnes CO_2 equivalent) per annum associated with Forever Oceans production of *S. rivoliana* in Panama.

Year	Per annum Scope 1 & 2 GHG emissions
2022	266.68
2023	1064.06
2024	2285.80
2025	2476.34
2026	2857.32
2027	3809.76
2028	5714.63
2029	7619.51
2030	7619.51
2031	7619.51
2032	9905.36
2033	9905.36
2034	9905.36
2035	9905.36
Total to 2035	**80954.59**

Although data on the quantity of packaging used was not available and this factor was therefore excluded from the LCA, the feed supplier provided information on the type of packaging used to transport their feed. Packaging used for feed is polypropylene and polyethylene. Polypropylene as a textile can have a global warming potential of 2.8 kg CO_2 equivalent per kg and low-density polyethylene packaging film 3.1 kg CO_2 equivalent per kg. While low volumes of these products may be used initially in the supply of feed to Forever Oceans Panama operations, they are GHG emissions intense materials. Appropriate waste recovery strategies should be put in place to adequately reduce the burden of their use, or lower carbon packaging alternatives could be explored with the feed supplier. This will be become particularly pertinent as Forever Oceans increases the scale of production.

→ **TNC RECOMMENDS** *Forever Oceans considers the impact of the packaging used in the supply of feed, either identifying appropriate recovery and recycling processes for these materials or exploring if low carbon alternatives are available with the feed supplier.*

4.1.1 Sensitivity of GHG emissions to mitigation strategies

From the LCIA two primary hot spots for GHG emissions were identified; the quantity of feed used and GHG emissions associated with feed production and transport, and the use of air freight to distribute fresh product to market. These are common hot spots in fed finfish aquaculture systems (Froehlich et al., 2018; MacLeod et al., 2020; Pelletier et al., 2009; Winther et al., 2020). To test the sensitivity of the global warming impact to strategies in these hotspots GHG emissions reduction were assessed.

Improving FCR, from 2.23 in 2022 to 1.42 in 2035, with subsequent proportional reductions in feed usage, was projected to reduce the GHG emissions impact associated with feed production and transport from 3.20 to 1.96 kg CO_2 equivalent per kg fish.

Increasing the proportion of product distributed frozen via ship freight, from 0% in 2022 to 75% by 2026, was projected to reduce the GHG emissions impact from 2.44 to 0.70 kg CO_2 equivalent per kg fish.

Combined, these two mitigation strategies alone would reduce GHG emissions from the 'business as usual' scenario by 2.99 kg CO_2 equivalent per kg fish, making the total projected global warming impact of one kg of fish 4.15 kg CO_2 equivalent (Figure 5). The effect of these improvement strategies would reduce total GHG emissions by 562,484 tonnes CO_2 equivalent; from 1,515,074 to 952,590 tonnes (Figure 6).

→ **TNC RECOMMENDS** *investing in strategies to reduce FCR and feed use and opportunities to use freight via sea rather than air, to immediately mitigate the most significant drivers of GHG emissions in its product life cycle.*

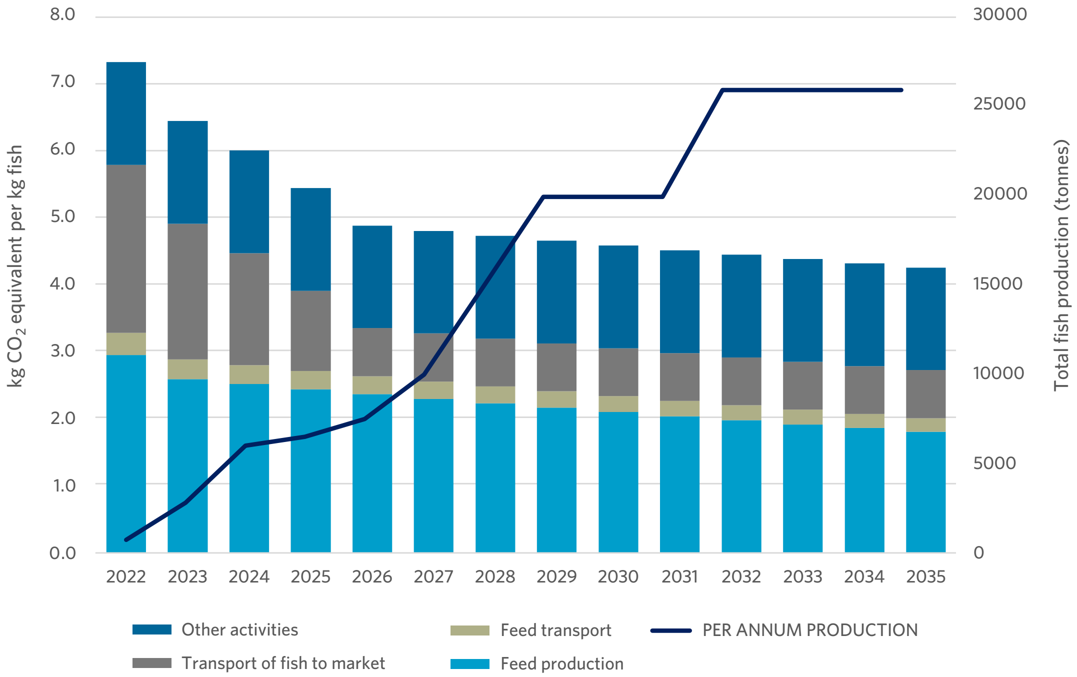


Figure 5. Per kg GHG emissions reductions arising from key mitigation strategies in FCR improvements and product distribution, with increasing production to 2035.

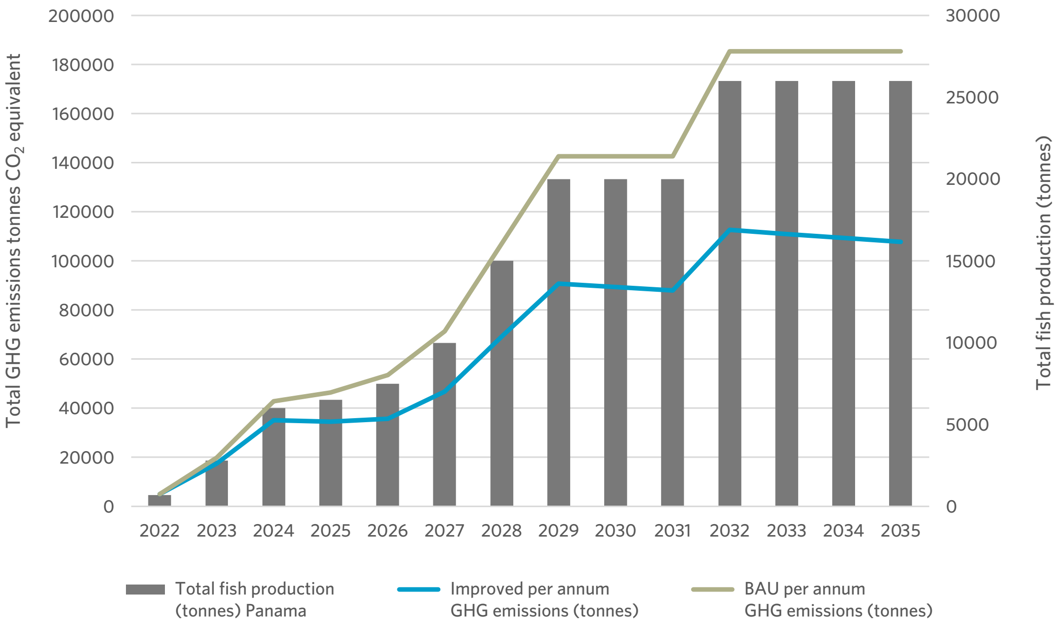


Figure 6. Total GHG emissions (tonnes) per annum under 'business as usual' and with the mitigation strategies implemented in feed and product distribution, with increasing production to 2035.

In addition to these key mitigation strategies a broader range of initiatives could be applied to Forever Oceans life cycle to reduce GHG emissions. These include the use of renewable energy (electricity and fuel, i.e. biofuel) in built facilities and supporting infrastructure. Electric vessels and vehicles are increasingly available. These forms of supporting infrastructure could present cost effective GHG emissions mitigation investments given the scale of production Forever Oceans is seeking to achieve in Panama.

Strategies with a longer time horizon include reducing FCR and achieving fish gains in fish productivity (e.g. improved growth rates) through selective breeding, and the use of Integrated Multi-Trophic Aquaculture to assist in offsetting emissions associated with aquatic N_2O, which in this assessment was estimated to be 0.48 kg CO_2 equivalent per kg fish.

To provide an indicative rating of the efficacy of these strategies to mitigating GHG emissions, the reduction of CO_2 that could be achieved was evaluated alongside a qualitative ranking of the cost of their implementation (from very low = 1 to very high = 5) over a 10-year period, with each of the strategies ranked by Forever Oceans (Figure 7). Strategies that will have a high impact on mitigating GHG emissions and may be comparatively lower in cost to implement include the development of products and distribution channels that use sea freight. Higher cost and higher impact strategies are those associated with achieving improvements in FCR through the development of specialized feeds (feeds that are lower emissions or can improve fish growth rates or FCR) or selective breeding.

Seaweed aquaculture may also present a strategy that could be used by Forever Oceans to progress an effective GHG emissions reduction strategy, and amplify this reduction value by providing additional ecological, social and economic co-benefits. Farming of seaweed in marine environments is gaining attention for its potential to support climate change mitigation, because seaweeds naturally cycle and remove inorganic nutrients—carbon, nitrogen and phosphorous—from the surrounding water for their growth. Opportunities for carbon sequestration via seaweed aquaculture can be broadly categorised in two ways: 1) the capacity of farmed seaweed to contribute to carbon sequestration in the marine environment, 'in situ', by cycling carbon and exporting it to long term sinks such as sediments and natural habitats; and 2) the opportunity to direct the carbon-rich farmed biomass toward sequestering or offsetting products, such as biofuels in replacement of fossil fuels or using seaweeds to reduce consumption of synthetic fertilizers in agriculture and actively restore soil health, thereby generating multiple benefits from production (offsetting GHG emissions at sea and on land).

In addition, seaweed aquaculture can provide a range of environmental benefits during farming, including reducing anthropogenic loading of nutrients in marine and coastal environments that can lead to eutrophication (Barrett et al., 2022), and providing additional habitat and a nutritional subsidy for fish and invertebrates (Corrigan et al., 2022; Theuerkauf et al., 2022). There is also evidence that seaweed aquaculture can increase the pH and oxygen content of marine waters, providing local refugia from ocean acidification (Duarte et al., 2017; Xiao et al., 2021).

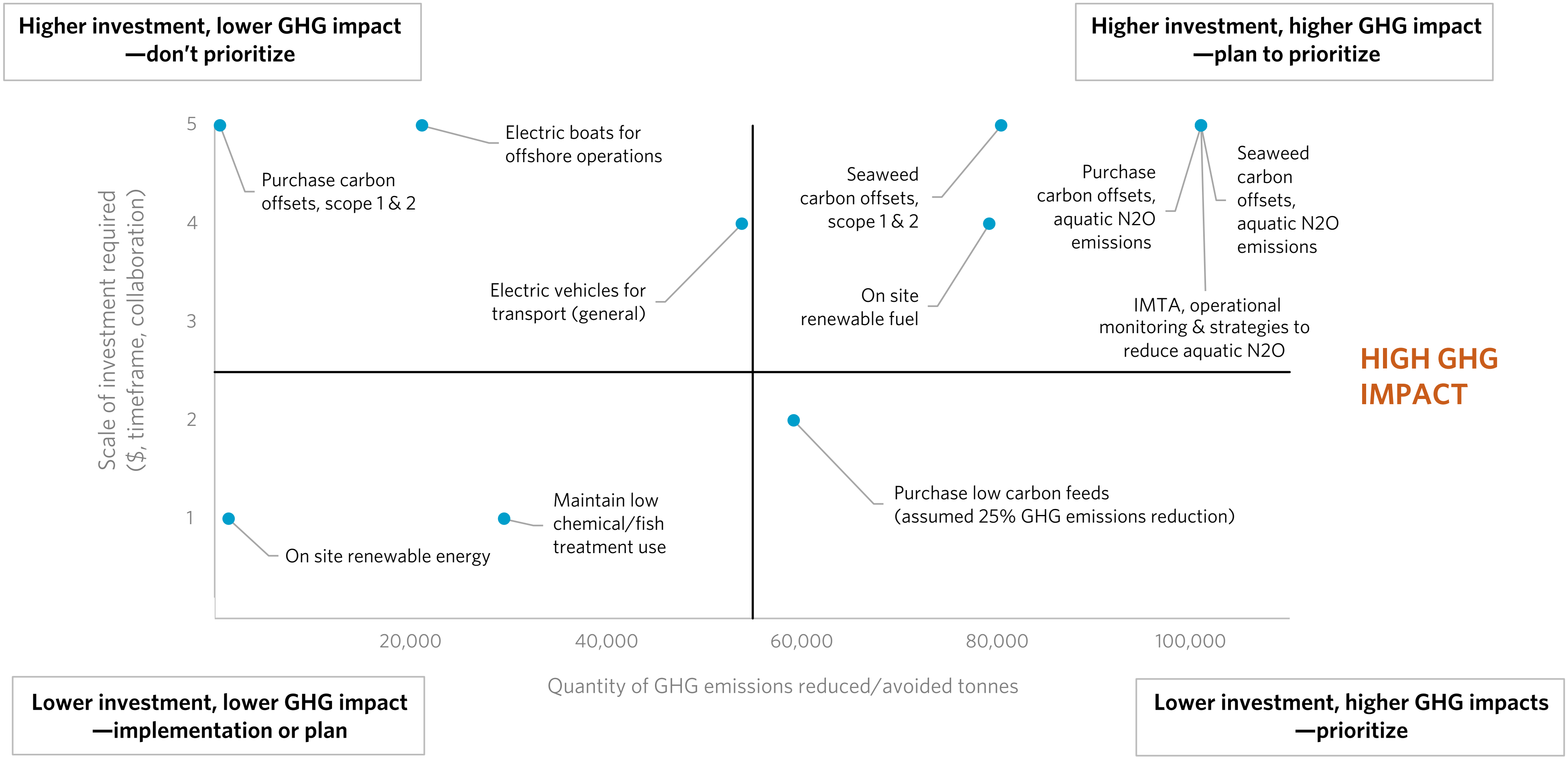


Figure 7. Comparative assessment of the benefits and likely costs associated with GHG emissions mitigation strategies appropriate for Forever Oceans life cycle. GHG emissions mitigation is a quantitative calculation of the total quantity of CO_2 that could be mitigated through to 2035, encompassing the company's projected scale up of production. Cost of implementation is a qualitative assessment of the likely monetary and resource costs (very low to very high; 1 to 5), scored by Forever Oceans

A range of viable seaweed species that are already cultivated via aquaculture have been identified in the wild along the Pacific coast of Panama, including *Ulva* and *Gracilaria* and to a lesser extent *Caulerpa* spp (Littler and Littler, 2010), however, these species are currently typically used for food rather than targeted carbon pathways; *Gracilaria* is mainly cultivated for agar, *Ulva* and *Caulerpa* for direct food consumption (Cai et al., 2021). *Asparagopsis taxiformis* is also reported to occur in the region (Littler and Littler, 2010). This genus and species have recently been shown to dramatically (>90%) reduce methane from livestock production when added to feed (Kinley et al., 2020).

→ **TNC RECOMMENDS** *Forever Oceans investigates and develops, as a priority, the feasibility of a wide range of climate change mitigation strategies, with a view to establish a roadmap for carbon neutrality consistent with global targets.*

4.1.2 Sustainability indicators

In addition to quantifying scope 1, 2 and 3 GHG emissions, monitoring eFCR as a proactive indicator of sustainability could be considered by Forever Oceans. This indicator provides an evidence-based metric that can be used to benchmark operations, and track progress against sustainability interventions relevant to maximizing output from the production chain, and decreasing the burden of excess GHG emissions.

At the time of assessment Forever Oceans eFCR was:

- 2.32 for fish at harvest (live weight);
- 3.09 with 75% yield from processing; and
- 4.64 with 50% yield from processing.

The global eFCR for total fed aquaculture is identified by the Marine Ingredients Organisation (IFFO), an international trade organisation that represents the marine ingredients industry including fishmeal, fish oil and other related industries, as being 0.732 in 2020. Salmonids are identified as being an average 1.27. Winther et al. (2020) identified eFCR in the Norwegian salmon aquaculture industry as varying from 0.9 and 1.6 kg feed/kg salmon, and an average of 1.32 kg feed/kg live weight salmon.

In Forever Oceans operations, a reduction in eFCR will be achieved through inherent reductions in FCR and feed usage, as operations improve (beyond the initial, early stages of production). However, the eFCR metric highlights that emphasis should also be placed on maximizing the saleable yield from the fish harvested. eFCR embodies the impact of losses during farming (e.g. mortalities and escapes) and the disposal of fish waste and offal during processing, as opposed to production of co-products or reuse of by-products. As such, attention should equally be given to minimizing mortalities and escapes, and maximizing the yield from the fish produced.

→ **TNC RECOMMENDS** *Forever Oceans closely monitor eFCR and implement strategies to accelerate maximum yield and 100% use of fish produced.*

4.2 Fresh water use

The use of fresh water in food production is of increasing interest due to growing, global impacts on this resource. As such, accounting of fresh water use and subsequent assessment of the efficiency of its use is commonly included in LCA-based methodologies. An understanding of fresh water consumption in an LCA can also assist in identifying potential 'hot spots' for other impacts, such as those that can arise through degraded water quality where local water sources are overused or water discharged from a facility is below that quality of the receiving water.

Common uses of fresh water in marine aquaculture production cycles include upstream in the production of feed ingredients and the feed milling process, on-farm in hatchery operations, downstream in processing facilities, and in transport where ice is used. However, fresh water consumption has been identified as been largely limited to feed production and evaporative losses in inland systems (Gephart et al., 2021). The rate of fresh water use for marine species and facilities is typically lower than land-based aquaculture systems, such as Recirculating Aquaculture Systems, flow-through systems, and ponds.

Data on water consumption in the production of feed for Forever Oceans operations was provided by the feed supplier. Based on the feed use for the cohort and projected production the weighted average WDP was 2.16 m^3. Plant dry matter ingredients accounted for 71% of the WDP.

Forever Oceans indicated that potable water only was used within the hatchery. Data on fresh water use for the production of ice for transport and in processing was not available at the time of assessment.

4.3 Land and marine area use (spatial footprint)

The way in which land is being used is of increasing interest in food sustainability targets and initiatives. Much of this interest centres on land use conversion, which in aquaculture is predominantly reflected in the production of feed. As a result, several LCA-based methodologies and standards now require land use to be accounted for in GHG assessment, e.g. the EU's PEF method and the GHG Protocol requires the land use climate impact to be reported in scope 3 accounts.

In this assessment the calculation provided by the feed supplier on land use impact for feed production was embodied in a dimensionless calculation including land occupation and transformation. The weighted average of the impact of land use for the feed range reported by the supplier was 43.04 (range 37.86–62.10) pt/kg.

In addition to this calculation, the spatial 'footprint' of Forever Oceans on-farm activities was considered. Bugnot et al. (2021) estimate marine aquaculture infrastructure to cover 2.3 million ha of ocean area. Forever Oceans concession in Panama is 46,000 ha, representing 2% of that global distri-bution. Forever Oceans has indicated that a maximum of 10% of the concession will be used for farming, equivalent to 0.2% of the area estimated to be occupied by marine aquaculture infrastructure, with net pens in the area sparsely distributed, approximately 2 km apart to maintain effective biosecurity to reduce the risk of cumulative impacts from waste.

Because of the significant size of the concession, however, a more detailed understanding of the way in which the marine area as well as land area is being used is important. Forever Oceans on-farm operations, which include operation of the hatchery on land and associated infrastructure (e.g. pipelines), the operation of two net pens on a single mooring in the offshore marine environment, and the maximum potential effect to water quality (and sediment deposition) through eutrophication, occupies a total surface area (2D spatial footprint) of 28.12 ha (Figure 8). Seventy-four per cent (20.7 ha) of this area is that identified as being within the area that may experience the effects of eutrophication because of fish faeces and waste feed. This potential affect represents less than 1% of the total lease area, and has been calculated using conservative estimates for sediment loading to align with global expectations for minimal impact on benthic habitats. As Forever Oceans adds additional sites to the concession this footprint could be scaled linearly to estimate the maximum area of use.

4.4 Eutrophication and impacts to benthic marine habitats

Offshore, open ocean environments typically provide faster-moving currents, and deeper water sites for production. This can result in a higher dispersal rate, and lower concentration of solid waste on the benthos surrounding a net pen. Open ocean environments are also generally less subject to excess nutrients than coastal environments, which are often subjected to runoff and are more susceptible to eutrophication. As such, the capacity for assimilation of soluble waste from open ocean aquaculture into the water column and trophic system can be higher than coastal net pen aquaculture (Welch et. al, 2018). Additionally, siting operations in deep water facilitates the ability to raise and lower net pens in the water column. This can aid in avoiding damage to infrastructure during significant weather events, lowering the risk of large escapes of farmed fish and habitat damage associated with large pieces of equipment breaking free of mooring systems.

The results of farm waste and nutrient modelling suggest that under the modelled conditions, Forever Oceans operations will not have a significant impact on the marine aquatic environment (water and sediment). Three environmental footprint scenarios were modelled using current speeds of 3.75, 7.5 and 15 centimetres per second (cm/s). International research recognises that 2.43 grams of carbon per meter squared per day (gC m-2 d-1) benthic nutrient enrichment effects are not a cause for concern (Hargrave et al., 1997). At the lower current speeds modelled (3.5 to 7.5 cm/s) a loading at or above this level may be possible. Deposition of nutrients to the benthos indicated an impact area ranging from 18 to 24 ha in one area, depending on the current speed, and between 21 to 24 ha in a second area. This impact area was driven by effects from eutrophication at low current speeds. With loading estimated to be between 1.5 and 2.05 gC m^{-2} d^{-1} at current speeds of 15 cm/s and between 2.26 and 2.49 gC m^{-2} d^{-1} at current speeds of 7.5 cm/s Forever Oceans environmental footprint from eutrophication was considered negligible and low impact. The findings of this modelling also highlighted that further data on current speed and direction is warranted, to increase the model accuracy under a range of environmental conditions, alongside fast-tracked environmental monitoring of water quality parameters to ensure compliance with the highest environmental standards.

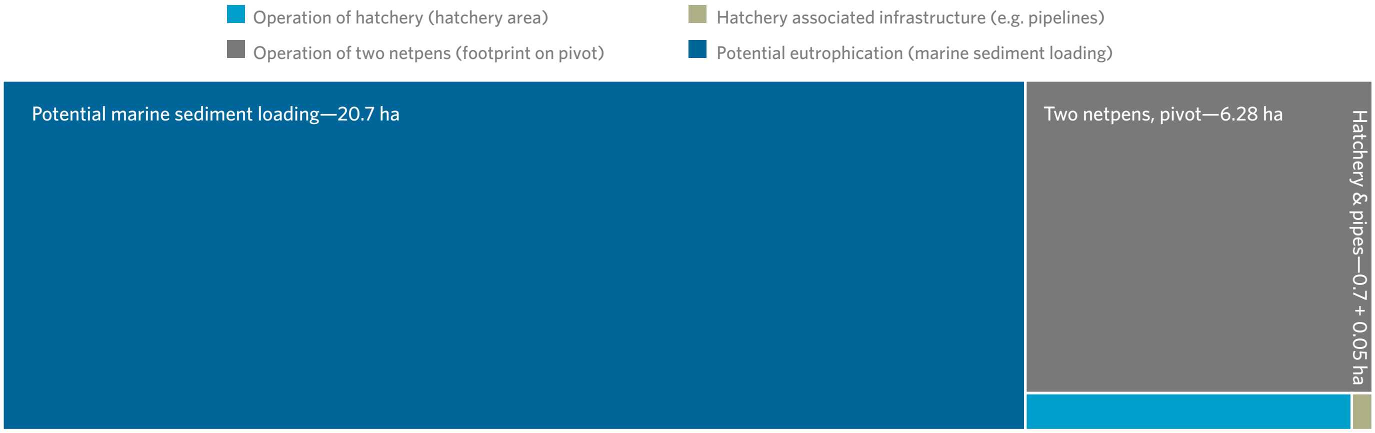


Figure 8. Surface area (2D spatial footprint) of Forever oceans on-farm operations, including operation of a land-based hatchery and in the marine environment a single mooring, two net pens and the maximum potential effect of eutrophication.

It is likely the net pen system adopted by Forever Oceans, which pivots on a single mooring will further reduce the impact of eutrophication, by dispersing nutrients over a larger area and reducing the likelihood of accumulation. This effect, however, has not yet been assessed and will require more comprehensive monitoring, including detailed measurement of current speeds across successive seasons and years.

In international standards (e.g. the Environmental Product Declaration) environmental impacts are often quantified as eutrophication potential for aquatic freshwater (kg P eq), aquatic marine (kg N eq), and aquatic terrestrial (mol N eq) environments. Should Forever Oceans seek to build further alignment and accreditation via international standards, collecting data that can build a more comprehensive understanding of eutrophication potential from all operations (i.e. encompassing feed production, operation of the hatchery, operation of the offshore site, processing) will be useful.

→ **TNC RECOMMENDS** *that data on environmental parameters, especially those associated with water quality, be collected through a comprehensive environmental monitoring program, and in a way that will enable early detection for any cumulative impacts in the region from aquaculture and any other uses.*

4.5 Biodiversity

As food production systems work to identify approaches that can not just meeting the challenge the achieving sustainability but meet the demands of a growing population at the same time as restoring degraded environments and lost biodiversity, ecological solutions that can achieve multiple social and ecological outcomes are becoming especially important. The most developed knowledge base for environmental benefits from aquaculture is associated with bivalve and seaweed aquaculture, with studies indicating that positive ecosystem outcomes can be provided through water quality improvements, climate mitigation, and the provision of habitat (Gentry *et al.*, 2020). But less is known about fed finfish aquaculture systems, especially marine finfish aquaculture.

To bridge this knowledge gap, this assessment applied a novel model that identifies practices specific to fed finfish aquaculture and qualitatively sizes their negative effects on biodiversity, and the potential size of the positive effect that could be achieved through certain management measures. This model aims to calibrate the current status of the local environment—the *reference situation*—and the opportunity for Forever Oceans to implement sustainability strategies and practices to have a positive effect on biodiversity—the *target reference situation* (Vrasdonk et al., 2019). An initial six strategies were identified as having the potential to generate both a negative impact to biodiversity, and a positive impact, if specific, identifiable strategies are put in place (Figure 9).

A range of known and potential negative impacts stand out as realistically reparable, including restoration of habitat disturbed to develop land-based facilities, which should be restored to at least two time the original area given that ecosystem services in restored habitat can be lower than that of natural habitat. For example, restored mangroves often return lower ecosystem functions, especially carbon storage and sequestration, and have lower ability to deliver different functions, and lower levels of biogeochemical functions with the response ratio an average -0.20 across all functions (Su et al., 2021). Further biodiversity impacts that may occur and could be mitigated through appropriate practices to ensure there is no decline of the reference situation, are the risks of marine ecotoxicity as a result of the use of chemical treatments for parasites or disease and eutrophication (Figure 9).

With respect to biodiversity impacts that could be influenced to create a positive effect, once any negative effects have been mitigated, were identified for the operation of offshore net pens. It is well known that wild fish populations can be attracted to aquaculture infrastructure, and on average, farms are associated with much higher density and diversity of wild fish that natural habitats (Barrett et al., 2019). The extent to which fish aggregate around a net pen can be influenced by a range of species-specific and local environmental conditions and the way in which they use the area (e.g. transiently or permanently, for foraging or shelter), and can have both negative and positive effects. Negative effects include the risk of changing fish behaviour, which can make them easier to catch or increase natural rates of mortality, and the risk of disease or parasites in farmed stock being transferred to wild populations.

→ **TNC RECOMMENDS** *that a site-specific risk assessment identifying the degree of risk of disease transfer from farmed to wild populations is conducted, accounting for the likelihood of farming infrastructure attracting wild fish, and that a surveillance program for disease is implemented for potentially vulnerable wild populations.*

If these risks are mitigated, however, the aggregation of fish around a net pen could provide a novel opportunity to protect fish stocks, including fish stocks that would benefit from sanctuary or an enhancement to the size of fishable biomass. The size of Forever Oceans concession might also provide a unique opportunity to use the area for proactive management of fish stocks, or for conservation, reflecting an approach referred to as 'effective area-based conservation measures', OECMs (Gurney et al., 2021). The positive effect of this interaction, however, will be dependent on effective and equitable representation of this value within regional fisheries management agreements or regulations.

A range of Vulnerable, Threatened and Endangered species have been identified as being present in the area. Twenty-four marine species in the Gulf of Chiriquí are registered on the IUCN

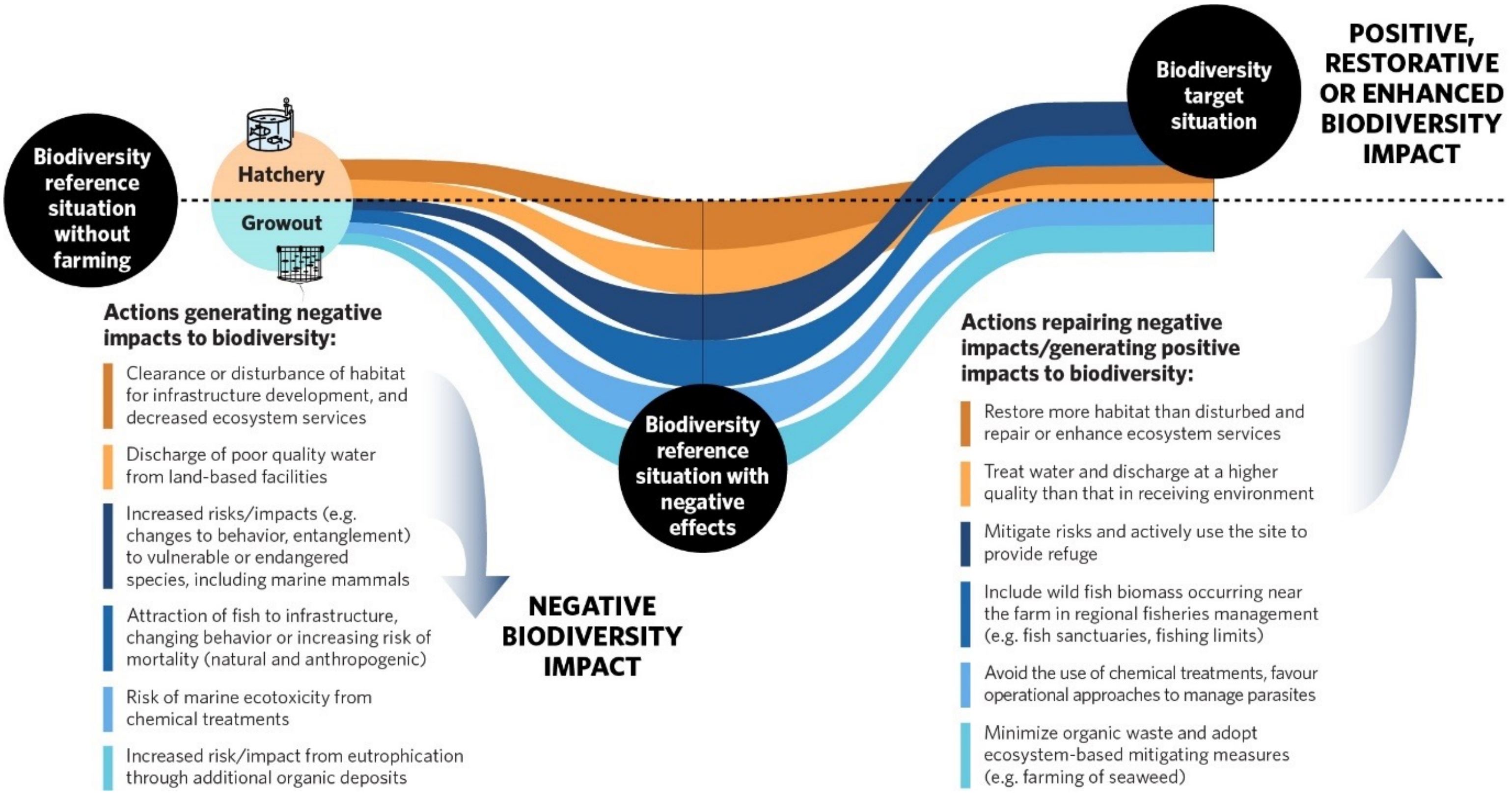


Figure 9. Model of biodiversity intersections associated with fed finfish aquaculture that could generate a negative impact, or a positive impact, depending on the practices implemented.

Red List as Vulnerable, with an additional three Endangered, and two Critically Endangered. Endangered species include the Great hammerhead shark (*Sphyrna mokarran*), Scalloped hammerhead shark (*Sphyrna lewini*), and the Grandparent's clingfish (*Tomicodon abuelorum*). Critically Endangered species include the Largetooth sawfish (*Pristis pristis),* and the Fin-joined goby (*Gobulus birdsongi*). Of the 14 marine mammal species present in the area, 12 are considered Threatened by the IUCN, including the blue whale (*Balaenoptera musculus*), sperm whale (*Physeter macrocephalus*), and fin whale (*Balaenoptera physalus*). A gear simulation has been conducted by Forever Oceans to understand the risks of entanglement. However, this modelling was done for potentially significant weather events and abiotic conditions at the site and the assessment has identified that the potential for wildlife entanglements in net pen structures, mooring lines, or other associated lines under general (day-to-day) operations remains unknown.

→ **TNC RECOMMENDS** *that a risk assessment and further modelling is used to identify potential impacts to species listed as Vulnerable, Threatened, Endangered or otherwise, and using the outcomes of these studies, strategies to mitigate any unforeseen impacts to wildlife populations are implemented.*

If appropriate actions to mitigate the risks of interaction and changes to the behaviour of these species (e.g. changes in foraging behaviour, avoiding the area) can be implemented it is possible that the size of Forever Oceans concession (46,000 ha) could provide a positive biodiversity benefit by acting as an area of refuge for Vulnerable, Threatened and Endangered species. The positive effects of this benefit would be contingent on species occupying the concession area in an abundance that is commensurate with protection (i.e. not just travelling through the concession), and potentially excluding other harmful activities from the area.

In addition to these potential biodiversity benefits the value of Forever Oceans offshore infrastructure was considered. Operators farming in deeper waters can position net pens at a depth that presents the most favourable conditions for the species, improving their health, welfare, and survival and maximizing economic returns (Kim and Lipton, 2011). Submerging net pens may reduce the type and/or frequency of interactions between net pens and marine macrofauna and gives operators the ability to shift the depth of the cages to lower exposure to parasites and/or pathogens. This, in turn, can improve survival rates of the farmed population and lower the potential for disease amplification and retransmission to vulnerable wild populations, and decrease the need for chemical treatment (O'Shea et al., 2019).

→ **TNC RECOMMENDS** *Forever Oceans utilizes the advantages of its deeper, open water sites by maintaining operational strategies that can reduce the incidence of parasites and need for chemical treatments.*

5. Comparison to other proteins

In comparison to other many terrestrial and marine foods, Forever Oceans *S. rivoliana* product offers a potentially low impact source of protein. GHG emissions, per kg of food product, are currently projected to be below the average emissions for similar seafood products, including wild caught tuna, and marginally higher than farmed trout and salmon (Figure 10). For salmon aquaculture, it should be noted that 5.10 kg CO_2 equivalent per kg represents a farmgate figure, excluding distribution to market. A comprehensive assessment of salmon aquaculture in Norway in 2017 (Winther et al., 2020) estimated GHG emissions to the farmgate for salmon of 5.3 kg CO_2 equivalent per kg live weight, of which 1.6 was due to land use conversion (i.e. 4.2 without land use conversion). Forever Oceans estimated GHG emissions impact to the farmgate, of 4.26 kg CO_2 equivalent per kg fish, compares favourably. Also, when distribution of processed product is taken into account the overall GHG emissions profile of salmon aquaculture varies markedly. Winther et al., (2020) assessed a range of salmon products, proportion of by-product use in the market and distribution locations and modes resulted in a range of 6.5 to 19.4 kg CO_2 equivalent per kg edible product delivered to the wholesaler, where product shipping includes air freight, and 6.5 to 8.4 4 kg CO_2 equivalent per kg where freight occurs by road and ship only.

This assessment identified that Forever Oceans may be able to maintain an operational advantage in comparison to some finfish operations, including salmon aquaculture, through lower GHG emissions intensity in the hatchery, maintenance requirements associated with remote handling, including treatment for lice and parasites, which increase mortalities and requirements for fish handling associated with treatment but can also result in increased feed use due to poor fish health (Figure 11). Enabling the requirements for treatment of lice, parasites and diseases to remain nominal (e.g. through operational approaches such as positioning in the water column) may present a unique competitive but also ecological advantage. Winther et al. (2020) concluded for salmon aquaculture that GHG emissions at slaughter (to the farmgate) are dominated by three factors: the eFCR, the composition of feed (major feed ingredients), and service and well boat activity. That study calculated that these three parameters account for almost 94% of the farmgate salmon GHG emissions; feed alone accounting for 85% (Winther et al., 2020).

Accounting for the projected reductions that could be achieved by the GHG mitigation strategies assessed, of improvements in FCR and reductions in feed use, and increasing the proportion of the frozen product distributed by ship (as opposed to fresh product distributed by air freight), the projected Forever Oceans per kg GHG emissions impact of 4.15 kg CO_2 equivalent per kg would be lower than the average GHG emissions produced by salmon aquaculture, marginally higher than some of the lowest wild caught fishery offering of herring/sardines at 3.88 kg CO_2 equivalent per kg one of the lowest seafoods produced via marine aquaculture excluding bivalve and seaweed production (Figure 10).

Jones et al. (2022) also examined the major GHG sources and carbon sinks associated with the fed finfish aquaculture sector more broadly, as well as bivalve and seaweed mariculture, and the factors influencing variability across these sectors with a focus on their distribution across production streams. The median estimate of the fed finfish species assessed was a total GHG emissions across the supply chain of 3.27 kg CO_2 equivalent per kg, excluding post-farm transport, but with large variability in these estimates (1.38 to 44.4 kg of CO_2 equivalent). In that assessment on-farm operations were identified as being the largest source of GHG emissions, with a median value of 1.04 kg CO_2 equivalent per kg. Forever Oceans on-farm operations, which in this assessment also included operation of the hatchery and transport of the fish to the processor, which in other assessments is often classified in upstream and downstream activities, represented a total GHG emissions impact of 0.86 kg of CO_2 equivalent per kg fish. This comparison suggests that Forever Oceans may be able to maintain several operational strategies that could enable their on-farm GHG emissions to be consistently lower than other current approaches to fed finfish aquaculture.

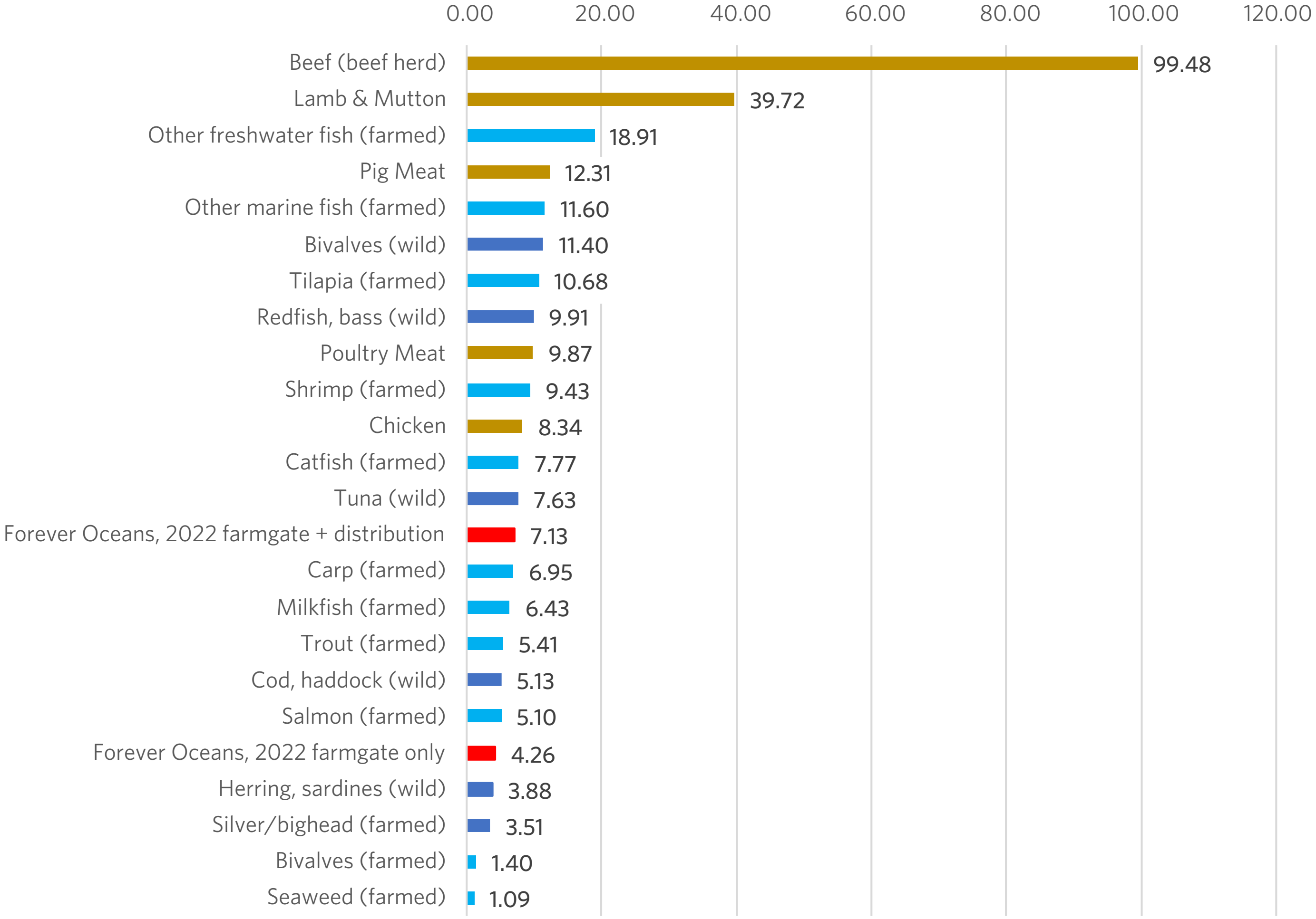


Figure 10. GHG emissions (kg CO_2 equivalent) per kg edible weight of key terrestrial animal and seafoods. Terrestrial and seafood GHG estimates based on open source data from Gephart et al., (2021; Poore and Nemecek, (2018) and Our World in Data, Environmental Impacts of Food Production, https://ourworldindata.org/environmental-impacts-of-food.

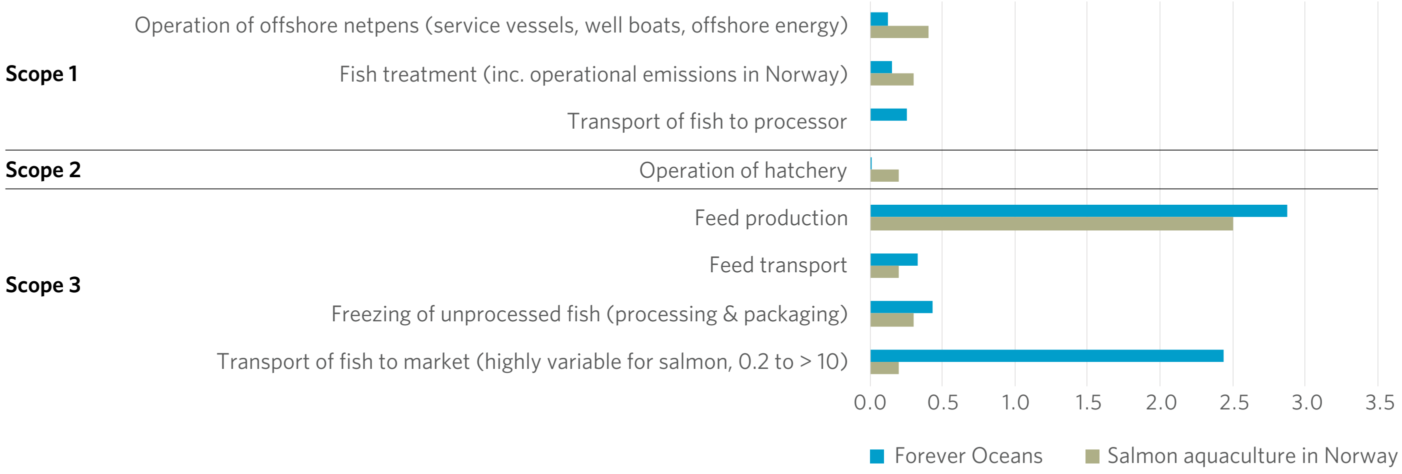
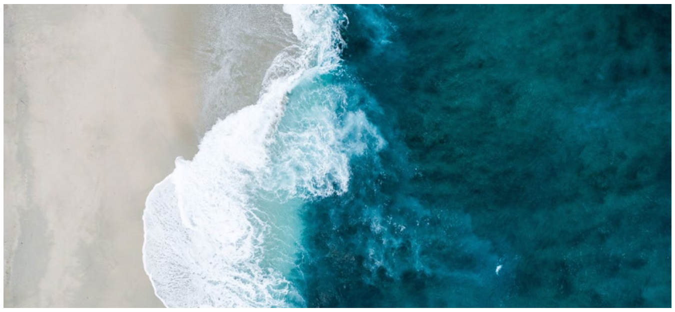


Figure 11. Comparison of Forever Oceans activity- and scope-based GHG emissions (kg CO_2 per kg fish) to salmon aquaculture operations in Norway. Data for salmon activities from Winther et al., (2020).

6. Summary and Recommendations

This assessment has identified that if Forever Oceans in Panama can implement an environmental sustainability plan that ensures GHG emissions per kg of fish can be reduced during the scale-up of production, uses the offshore operating environment to eliminate impacts to benthic habitats and maintain a high standard of fish health, and uses the extent of its concession (i.e. lease) to implement restorative aquaculture approaches, the company could be influential in sustainable seafood production and the transformation needed to overcome growing threats from the environmental burden of food production. Given the significant increase in total GHG emissions during scale-up and for full production, the company must act decisively to mitigate impacts, especially those associated with feed use and the transport phases of production.



Understanding the GHG emissions footprint generated by production processes across Forever Oceans life cycle provided the opportunity to clearly identify 'hot spots' and operational strategies that will be most effective in enabling emissions and other impact reductions. Critical opportunities to improve operations and achieve reductions in environmental impacts include:

- improving feed efficiency;
- ensuring full by-product utilization along the entire supply chain; and
- finding alternatives to air freight and shifting to low GHG transport modes throughout the life cycle.

In addition to these climate change focused approaches a range of supporting sustainability strategies have been identified, including strategies that could ensure risks to biodiversity are allayed, and positive impacts potentially created. To support Forever Oceans in identifying these strategies and establishing effective monitoring approaches to track their efficacy, TNC has identified 13 recommendations that could be adopted and implemented, and their priority (Table 2).

Table 2. Summary of recommendations associated with sustainability and monitoring strategies arising from the assessment of the environmental footprint of Forever Oceans operations in Panama

Recommendation	Suggested priority for development	Issue Linkage
Recommendations to Reduce Environmental Footprint		
Invest in strategies to reduce FCR and feed use and immediate opportunities to use freight via sea rather than air, to immediately mitigate the most significant drivers of GHG emissions in its product life cycle.	High	GHG emissions
Closely monitor eFCR and implement strategies to accelerate maximum yield and 100% use of fish produced.	High	GHG emissions
Maintain operational strategies that can reduce the incidence of parasites and need for chemical treatments.	High	GHG emissions, Biodiversity
Further investigate and develop, as a priority, the feasibility of a wide range of climate change mitigation strategies, with a view to establish a roadmap for carbon neutrality consistent with global targets.	High	GHG emissions
Consider the impact of the packaging used in the supply of feed, either identifying appropriate recovery and recycling processes for these materials or exploring if low carbon alternatives are available with the feed supplier.	Low	GHG emission
Data on environmental parameters, especially those associated with water quality, be collected through a comprehensive environmental monitoring program, and in a way that will enable early detection for any cumulative impacts in the region from aquaculture and any other uses.	Moderate	Eutrophication
Conduct a site-specific risk assessment identifying the degree of risk of disease transfer from farmed to wild populations, accounting for the likelihood of farming infrastructure attracting wild fish, and that a surveillance program for disease is implemented for potentially vulnerable wild populations.	High	Biodiversity
A risk assessment and further modelling is used to identify potential impacts to species listed as Vulnerable, Threatened, Endangered or otherwise, and using the outcomes of these studies, strategies to mitigate any unforeseen impacts to wildlife populations are implemented.	High	Biodiversity
Recommendations on Monitoring, Data Collection, and Data Quality		
Data on the processes and activities identified in the LCI should continue to be collected through a standardized data collection and monitoring program, to support future updates to the LCA and inclusion of sensitivity analyses to generate more robust results for comparison.	High	All
Adopt and regularly report scope 1, 2 and 3 emissions and economic FCR, and progress made toward reducing both, in company materials as these are transparent and readily repeatable indicators of the sustainability of fed finfish aquaculture systems.	High	GHG Emissions
Activities associated with on-farm operations should be closely monitored during the scale-up of production and compared to the benchmarks established in this assessment, to identify any unforeseen disproportional increases in energy requirements. The results of the LCA should be updated if significant differences are identified.	High	GHG emissions
Begin data collection process to gather foreground data on processing activities, yield from processing, and weight/volume of product transport, inclusive of the weight of packaging.	Moderate	GHG emissions
Data is collected and assessed on the quantity of fresh water used during processing, including production of ice for transport of fish to the processor.	Moderate	GHG emissions

7. References

Barrett, L.T., Swearer, S.E., Dempster, T., 2019. Impacts of marine and freshwater aquaculture on wildlife: a global meta-analysis. Reviews in Aquaculture 11, 1022–1044. https://doi.org/10.1111/raq.12277

Barrett, L.T., Theuerkauf, S.J., Rose, J.M., Alleway, H.K., Bricker, S.B., Parker, M., Petrolia, D.R., Jones, R.C., 2022. Sustainable growth of non-fed aquaculture can generate valuable ecosystem benefits. Ecosystem Services 53, 101396. https://doi.org/10.1016/j.ecoser.2021.101396

Bohnes, F.A., Hauschild, M.Z., Schlundt, J., Laurent, A., 2019. Life cycle assessments of aquaculture systems: a critical review of reported findings with recommendations for policy and system development. Rev Aquacult 11, 1061–1079. https://doi.org/10.1111/raq.12280

BSI Standards Limited, 2012. PAS 2050-2:2012. Assessment of life cycle greenhouse gas emissions: Supplementary requirements for the application of PAS 2050:2011 to seafood and other aquatic food products. British Standards Institution.

Bugnot, A.B., Mayer-Pinto, M., Airoldi, L., Heery, E.C., Johnston, E.L., Critchley, L.P., Strain, E.M.A., Morris, R.L., Loke, L.H.L., Bishop, M.J., Sheehan, E.V., Coleman, R.A., Dafforn, K.A., 2021. Current and projected global extent of marine built structures. Nat Sustain 4, 33–41. https://doi.org/10.1038/s41893-020-00595-1

Cai, J., Lovatelli, A., Aguilar-Manjarrez, J., Cornish, L., Dabbadie, L., Desrochers, A., Diffey, S., Garrido Gamarro, E., Geehan, J., Hurtado, A., Lucente, D., Mair, G., Miao, W., Potin, P., Przybyla, C., Reantaso, M., Roubach, R., Tauati, M., Yuan, X., 2021. Seaweeds and microalgae: an overview for unlocking their potential in global aquaculture development (No. FAO Fisheries and Aquaculture Circular No. 1229). FAO, Rome.

Corrigan, S., Brown, A.R., Ashton, I.G.C., Smale, D.A., Tyler, C.R., 2022. Quantifying habitat provisioning at macroalgal cultivation sites. Reviews in Aquaculture n/a. https://doi.org/10.1111/raq.12669

Duarte, C.M., Wu, J., Xiao, X., Bruhn, A., Krause-Jensen, D., 2017. Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? Front. Mar. Sci. 4. https://doi.org/10.3389/fmars.2017.00100

European Commission, 2022. Marine Fish PEFCR DRAFT v5 for Supporting Studies.

FAO, 2022a. The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. FAO, Rome.

FAO, 2022b. FishStatJ—Software for Fishery and Aquaculture Statistical Time Series 1950-2020.

FOLU, 2019. Growing Better: Ten Critical Transitions to Transform Food and Land Use. The Global Consultation Report of the Food and Land Use Coalition.

Froehlich, H.E., Jacobsen, N.S., Essington, T.E., Clavelle, T., Halpern, B.S., 2018. Avoiding the ecological limits of forage fish for fed aquaculture. Nat Sustain 1, 298–303. https://doi.org/10.1038/s41893-018-0077-1

Gentry, R.R., Alleway, H.K., Bishop, M.J., Gillies, C.L., Waters, T., Jones, R., 2020. Exploring the potential for marine aquaculture to contribute to ecosystem services. Reviews in Aquaculture 12, 499–512. https://doi.org/10.1111/raq.12328

Gephart, J.A., Henriksson, P.J.G., Parker, R.W.R., Shepon, A., Gorospe, K.D., Bergman, K., Eshel, G., Golden, C.D., Halpern, B.S., Hornborg, S., Jonell, M., Metian, M., Mifflin, K., Newton, R., Tyedmers, P., Zhang, W., Ziegler, F., Troell, M., 2021. Environmental performance of blue foods. Nature 597, 360–365. https://doi.org/10.1038/s41586-021-03889-2

Gurney, G.G. et al., 2021. Biodiversity needs every tool in the box: use OECMs. Nature 595, 646–649. https://doi.org/10.1038/d41586-021-02041-4

Hargrave, B.T., Phillips, G.A., Doucette, L.I., White, M.J., Milligan, T.G., Wildish, D.J., Cranston, R.E., 1997. Assessing Benthic Impacts of Organic Enrichment from Marine Aquaculture. Water, Air, and Soil Pollution 99, 641–650. https://doi.org/10.1023/A:1018332632372

Hoegh-Guldberg, O., Caldeira, K., Chopin, T., Gaines, S., Haugan, P., Hemer, M., Howard, J., Konar, M., Krause-Jensen, D., Lindstad, E., Lovelock, C., Michelin, M., Gunnar Nielsen, F., Northrop, E., Parker, R., Roy, J., Smith, T., Some, S., Tyedmers, P., 2019. The Ocean as a Solution to Climate Change: Five Opportunities for Action. World Resources Institute, Washington, D.C.

International Organization for Standardization, 2006. ISO 14044 Environmental management—Life cycle assessment—Requirements and guidelines. ISO 14044:2006. International Organization for Standardization, Geneva, Switzerland.

Jones, A.R., Alleway, H.K., McAfee, D., Reis-Santos, P., Theuerkauf, S.J., Jones, R.C., 2022. Climate-Friendly Seafood: The Potential for Emissions Reduction and Carbon Capture in Marine Aquaculture. BioScience biab126. https://doi.org/10.1093/biosci/biab126

Kim, D., Lipton, D., 2011. A COMPARISON OF THE ECONOMIC PERFORMANCE OF OFFSHORE AND INSHORE AQUACULTURE PRODUCTION SYSTEMS IN KOREA. Aquaculture Economics & Management 15, 103–117. https://doi.org/10.1080/13657305.2010.549165

Kinley, R.D., Martinez-Fernandez, G., Matthews, M.K., de Nys, R., Magnusson, M., Tomkins, N.W., 2020. Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed. Journal of Cleaner Production 259, 120836. https://doi.org/10.1016/j.jclepro.2020.120836

Lester, S.E., Gentry, R.R., Kappel, C.V., White, C., Gaines, S.D., 2018. Offshore aquaculture in the United States: Untapped potential in need of smart policy. Proceedings of the National Academy of Sciences 115, 7162–7165. https://doi.org/10.1073/pnas.1808737115

Littler, D.S., Littler, M.M., 2010. Marine Plants of Pacific Panama. Smithsonian Tropical Research Institute, Smithsonian Institution.

MacLeod, M.J., Hasan, M.R., Robb, D.H.F., Mamun-Ur-Rashid, M., 2020. Quantifying greenhouse gas emissions from global aquaculture. Scientific Reports 10, 11679. https://doi.org/10.1038/s41598-020-68231-8

Matthews, N.E., Stamford, L., Shapira, P., 2019. Aligning sustainability assessment with responsible research and innovation: Towards a framework for Constructive Sustainability Assessment. Sustainable Production and Consumption 5–73. https://doi.org/doi:10.1016/j.spc.2019.05.002

Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., Mooney, H., Troell, M., 2000. Effect of aquaculture on world fish supplies. Nature 405, 1017–1024. https://doi.org/10.1038/35016500

Naylor, R.L., Hardy, R.W., Buschmann, A.H., Bush, S.R., Cao, L., Klinger, D.H., Little, D.C., Lubchenco, J., Shumway, S.E., Troell, M., 2021. A 20-year retrospective review of global aquaculture. Nature 591, 551–563. https://doi.org/10.1038/s41586-021-03308-6

O'Shea, T., Jones, R., Markham, A., Norell, E., Scott, J., Theuerkauf, S., Waters, T., 2019. Towards a Blue Revolution: Catalyzing Private Investment in Sustainable Aquaculture Production Systems. The Nature Conservancy and Encourage Capital, Arlington, VA, USA.

Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjo, A., Kruse, S., Cancino, B., Silverman, H., 2009. Not All Salmon Are Created Equal: Life Cycle Assessment (LCA) of Global Salmon Farming Systems. Environ. Sci. Technol. 43, 8730–8736. https://doi.org/10.1021/es9010114

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992. https://doi.org/10.1126/science.aaq0216

Su, J., Friess, D.A., Gasparatos, A., 2021. A meta-analysis of the ecological and economic outcomes of mangrove restoration. Nature Communications 12, 5050. https://doi.org/10.1038/s41467-021-25349-1

The Nature Conservancy, 2021. Global Principles of Restorative Aquaculture. Arlington, VA.

Theuerkauf, S.J., Barrett, L.T., Alleway, H.K., Costa-Pierce, B.A., St. Gelais, A., Jones, R.C., 2022. Habitat value of bivalve shellfish and seaweed aquaculture for fish and invertebrates: Pathways, synthesis and next steps. Reviews in Aquaculture 14, 54–72. https://doi.org/10.1111/raq.12584

Vélez-Henao, J.A., Weinland, F., Reintjes, N., 2021. Life cycle assessment of aquaculture bivalve shellfish production — a critical review of methodological trends. The International Journal of Life Cycle Assessment 26, 1943–1958. https://doi.org/10.1007/s11367-021-01978-y

Vrasdonk, E., Palme, U., Lennartsson, T., 2019. Reference situations for biodiversity in life cycle assessments: conceptual bridging between LCA and conservation biology. The International Journal of Life Cycle Assessment 24, 1631–1642. https://doi.org/10.1007/s11367-019-01594-x

Winter, L., Lehmann, A., Finogenova, N., Finkbeiner, M., 2017. Including biodiversity in life cycle assessment—State of the art, gaps and research needs. Environmental Impact Assessment Review 67, 88–100. https://doi.org/10.1016/j.eiar.2017.08.006

Winther, U., Skontrop Hognes, E., Jafarzadeh, S., Ziegler, F., 2020. Greenhouse gas emissions of Norwegian seafood products in 2017 (No. 2020- 06- 04). SINTEF Ocean AS, Trondheim, Norway.

Xiao, X., Agustí, S., Yu, Y., Huang, Y., Chen, W., Hu, J., Li, C., Li, K., Wei, F., Lu, Y., Xu, C., Chen, Z., Liu, S., Zeng, J., Wu, J., Duarte, C.M., 2021. Seaweed farms provide refugia from ocean acidification. Science of The Total Environment 776, 145192. https://doi.org/10.1016/j.scitotenv.2021.145192

Ziegler, F., Jafarzadeh, S., Skontorp Hognes, E., Winther, U., 2021. Greenhouse gas emissions of Norwegian seafoods: From comprehensive to simplified assessment. Journal of Industrial Ecology 1–12. https://doi.org/10.1111/jiec.13150