Marine Mussels

Mytilus spp*, Perna* spp*.*

Worldwide

On and Off Bottom Culture

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Disclaimer
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About Seafood Watch

Monterey Bay Aquarium's Seafood Watch program evaluates the ecological sustainability of wild-caught and farmed seafood commonly found in the United States marketplace. Seafood Watch defines sustainable seafood as originating from sources, whether wild-caught or farmed, which can maintain or increase production in the long-term without jeopardizing the structure or function of affected ecosystems. Seafood Watch makes its science-based recommendations available to the public in the form of regional pocket guides that can be downloaded from www.seafoodwatch.org. The program's goals are to raise awareness of important ocean conservation issues and empower seafood consumers and businesses to make choices for healthy oceans.

Each sustainability recommendation on the regional pocket guides is supported by a Seafood Watch Assessment. Each assessment synthesizes and analyzes the most current ecological, fisheries and ecosystem science on a species, then evaluates this information against the program's conservation ethic to arrive at a recommendation of "Best Choices," "Good Alternatives" or "Avoid." This ethic is operationalized in the Seafood Watch standards, available on our website here. In producing the assessments, Seafood Watch seeks out research published in academic, peer-reviewed journals whenever possible. Other sources of information include government technical publications, fishery management plans and supporting documents, and other scientific reviews of ecological sustainability. Seafood Watch Research Analysts also communicate regularly with ecologists, fisheries and aquaculture scientists, and members of industry and conservation organizations when evaluating fisheries and aquaculture practices. Capture fisheries and aquaculture practices are highly dynamic; as the scientific information on each species changes, Seafood Watch's sustainability recommendations and the underlying assessments will be updated to reflect these changes.

Parties interested in capture fisheries, aquaculture practices and the sustainability of ocean ecosystems are welcome to use Seafood Watch assessments in any way they find useful.

Guiding Principles

Seafood Watch defines sustainable seafood as originating from sources, whether fished[1] or farmed that can maintain or increase production in the long-term without jeopardizing the structure or function of affected ecosystems.

The following guiding principles illustrate the qualities that aquaculture farms must possess to be considered sustainable by the Seafood Watch program. Sustainable aquaculture farms and collective industries, by design, management and/or regulation, address the impacts of individual farms and the cumulative impacts of multiple farms at the local or regional scale by:

1. **Having robust and up-to-date information on production practices and their impacts available for analysis;**
   Poor data quality or availability limits the ability to understand and assess the environmental impacts of aquaculture production and subsequently for seafood purchasers to make informed choices. Robust and up-to-date information on production practices and their impacts should be available for analysis.
2. **Not allowing effluent discharges to exceed, or contribute to exceeding, the carrying capacity of receiving waters at the local or regional level;**
   Aquaculture farms minimize or avoid the production and discharge of wastes at the farm level in combination with an effective management or regulatory system to control the location, scale and cumulative impacts of the industry's waste discharges.
3. **Being located at sites, scales and intensities that maintain the functionality of ecologically valuable habitats;**
   The siting of aquaculture farms does not result in the loss of critical ecosystem services at the local, regional, or ecosystem level.
4. **Limiting the type, frequency of use, total use, or discharge of chemicals to levels representing a low risk of impact to non-target organisms;**
   Aquaculture farms avoid the discharge of chemicals toxic to aquatic life or limit the type, frequency or total volume of use to ensure a low risk of impact to non-target organisms.
5. **Sourcing sustainable feed ingredients and converting them efficiently with net edible nutrition gains;**
   Producing feeds and their constituent ingredients has complex global ecological impacts, and the efficiency of conversion can result in net food gains or dramatic net losses of nutrients. Aquaculture operations source only sustainable feed ingredients or those of low value for human consumption (e.g. by-products of other food production), and convert them efficiently and responsibly.
6. **Preventing population-level impacts to wild species or other ecosystem-level impacts from farm escapes;**
   Aquaculture farms, by limiting escapes or the nature of escapees, prevent competition, reductions in genetic fitness, predation, habitat damage, spawning disruption, and other impacts on wild fish and ecosystems that may result from the escape of native, non-native and/or genetically distinct farmed species.

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1 "Fish" is used throughout this document to refer to finfish, shellfish and other invertebrates.

7. **Preventing population-level impacts to wild species through the amplification and retransmission, or increased virulence of pathogens or parasites;**
   Aquaculture farms pose no substantial risk of deleterious effects to wild populations through the amplification and retransmission of pathogens or parasites, or the increased virulence of naturally occurring pathogens.
8. **Using eggs, larvae, or juvenile fish produced from farm-raised broodstocks thereby avoiding the need for wild capture;**
   Aquaculture farms use eggs, larvae, or juvenile fish produced from farm-raised broodstocks thereby avoiding the need for wild capture, or where farm-raised broodstocks are not yet available, ensure that the harvest of wild broodstock does not have population-level impacts on affected species. Wild-caught juveniles may be used from passive inflow, or natural settlement.
9. **Preventing population-level impacts to predators or other species of wildlife attracted to farm sites;**
   Aquaculture operations use non-lethal exclusion devices or deterrents, prevent accidental mortality of wildlife, and use lethal control only as a last resort, thereby ensuring any mortalities do not have population-level impacts on affected species.
10. **Avoiding the potential for the accidental introduction of secondary species or pathogens resulting from the shipment of animals;**
    Aquaculture farms avoid the international or trans-waterbody movements of live animals, or ensure that either the source or destination of movements is biosecure in order to avoid the introduction of unintended pathogens, parasites and invasive species to the natural environment.

Once a score and rating has been assigned to each criterion, an overall seafood recommendation is developed on additional evaluation guidelines. Criteria ratings and the overall recommendation are color-coded to correspond to the categories on the Seafood Watch pocket guide:

Best Choices/Green: Are well managed and caught or farmed in environmentally friendly ways.

Good Alternatives/Yellow: Buy, but be aware there are concerns with how they're caught or farmed.

Avoid/Red: Take a pass on these. These items are overfished or caught or farmed in ways that harm other marine life or the environment.

Final Seafood Recommendation

Marine mussels - worldwide

Criterion	Score	Rank	Critical?
C1 Data	7.05	GREEN	
C2 Effluent	10.00	GREEN	NO
C3 Habitat	6.53	YELLOW	NO
C4 Chemicals	8.00	GREEN	NO
C5 Feed	10.00	GREEN	NO
C6 Escapes	4.00	YELLOW	NO
C7 Disease	8.00	GREEN	NO
C8X Source	0.00	GREEN	NO
C9X Wildlife mortalities	-5.00	YELLOW	NO
C10X Introduced species escape	-1.80	GREEN	
Total	**46.78**		
Final score (0-10)	**6.68**		

OVERALL RANKING

Final Score	6.68
Initial rank	GREEN
Red criteria	0
Interim rank	GREEN
Critical Criteria?	NO

FINAL RANK
GREEN

Scoring note – scores range from 0 to 10, where 0 indicates very poor performance and 10 indicates the aquaculture operations have no significant impact. Criteria 8X, 9X, and 10X are exceptional criteria, where 0 indicates no impact and a deduction of -10 reflects a very significant impact. Two or more Red criteria result in a Red final result.

Summary

The final numerical score for marine mussels farmed globally is 6.68 out of 10 which is in the Green range and with no Red criteria; the final recommendation is a Green “Best Choice”.

Executive Summary

The scope of this global report is farmed marine mussels of the *Mytilus* and *Perna* species. This includes farming of the: Chilean blue mussel (*Mytilus chilensis*), blue mussel (*M. edulis*), Mediterranean mussel (*M. galloprovincialis*), New Zealand Greenshell® mussel (*Perna canaliculus*), Korean mussel (*M. unguiculatus* Valenciennes, also referred to as *M. coruscus*), Green mussel (*P. viridis*), and hybrids.

Global aquaculture production for all marine mussel species in 2017 was 2,163,784 metric tons (mt) or approximately 94% of all commercial global mussel production, including fisheries. China is the largest producer of farmed mussels, with production exceeding 900,000 mt in 2017. In 2018, the US imported 30,889 mt of mussels, primarily from Canada (13,647 mt), Chile (9,667 mt), and New Zealand (6,519mt). US aquaculture only produced 406 mt of mussels in 2016. Since China is by far the largest producer of farmed mussels globally and the US market is dominated by imports from Prince Edward Island (PEI) in Canada, Chile, and New Zealand, this report focuses on production in these four regions.

Globally, mussel farming uses a range of production systems, including on bottom and suspended culture systems. However, the main production systems in the regions this report focuses on are suspension systems, primarily using longlines or rafts. These systems are located in shallow coastal waters and mainly stocked with wild seed collected using passive collectors. Mussels feed on natural seston in the water column rather than commercial feeds. Chemicals are used to control biofouling in some regions but there is little evidence that environmentally impactful chemicals are applied. Production cycles usually take around two years until harvest depending on final size of mussels at harvest.

This Seafood Watch assessment involves a number of different criteria covering impacts associated with: effluent, habitats, wildlife and predator interactions, chemical use, feed production, escapes, introduction of non-native organisms (other than the farmed species), disease, the source stock, and general data availability.

Overall, available data are relatively detailed for Chile, PEI and New Zealand but very limited for China. With a relatively straightforward production system and well-established industries, some aspects (e.g. feed and effluent) are robustly understood and drive high data scores here. In contrast, many data scores represent an "averaging" factor with regard to scoring the individual categories across the various regions. The final score for Criterion 1 – Data is 7 out of 10.

Mussel farming is entirely reliant on naturally available food, including organic matter and phytoplankton, in the water column. Filter feeding by mussels may improve regional water quality by reducing nitrogen and phosphorus levels in the water column, and promoting the deposition of phosphate and silicate in seafloor sediments. Mussel farming may also replace ecosystem services lost from wild mussel beds. Evidence from New Zealand suggests benefits at reducing suspended solids in the water column may not materialize, as material encapsulated in pseudofeces may be re-suspended from the seabed as these degrade over a period of days. There is evidence of localized depletion of phytoplankton due to mussel grazing in some mussel farming locations, which are overstocked. The ecosystem consequences of such depletions are not well understood, but such depletions are usually avoided by mussel farming as it results in decreased farm production. Using the evidence-based assessment with no evidence of potential impacts associated with effluents, the final score was 10 out of 10 for Criterion 2 – Effluent.

Mussel farms, particularly longline operations, may alter benthic habitats through organic enrichment via pseudofeces and feces, and by an influx of live and dead mussels. This can change the physical, chemical and biological conditions beneath farming systems. Some of these changes can be positive, such as by restoring the ecosystem services and habitat lost from the removal of filter-feeding communities associated with wild mussel beds, while others maybe negative, such as by increasing biomass of pest biofouling organisms or attracting predator species, such as sea stars. Changes to benthic habitats could be compounded by the reduction of currents through the farm structures. Case studies have found that habitat impacts caused by mussel farming can range from excessive impact through to no detectable changes, and influenced by water depth, mussel stocking density, and currents. The vast majority of mussel farms occupy shallow coastal waters with soft-sediment seabeds, with low biodiversity relative to reefs structures and are occupied by detrital feeding organisms with capabilities for utilizing mussel farm deposits. These habitats are considered by Seafood Watch to be of moderate value, and the evidence suggests that habitat impacts could be case specific, depending on conditions at the farm. Since the organic enrichment from mussels is a natural product, the removal of mussel farms from sites, usually results in a rapid return of the seafloor to an undisturbed state. For these reasons, the habitat impacts are considered to be "minor-moderate" and the score for Habitat Conversion and Function is 8 out of 10.

Evidence of habitat management measures and enforcement are available for Chile, PEI and New Zealand but limited for China. Information available suggests that globally the potential habitat impacts caused by individual farms are likely to be considered in regulation but not cumulative impacts. However, this maybe expected where deposition habitat impacts are likely limited to the local environment to the farm sites. When all these factors are considered, the score for management content is 3 out of 5 and the score for management enforcement is also 3 out of 5. When combined the, the final score for management effectiveness (aggregated globally) is 3.6 out of 10. The final Criterion 3 – Habitat score is 6.53 out of 10.

Biofouling is a major challenge to mussel farming by competing with mussels for food, damaging shells, and increasing the risk of gear failure. A number of control techniques exist, but many are impractical, costly, or have negative consequences to the mussels. In this context, the use of chemical controls is considered to be limited because the mussels may uptake and concentrate them in their tissues. Known chemicals used in industry, such as hydrated lime, have extremely short-term localized impacts in the water column, which are unlikely to cause negative impacts on non-target populations. As such, the final score for Criterion 4 – Chemical Use is 8 out of 10.

External feed is not provided to farmed mussels; therefore, the final score for Criterion 5 – Feed is 10 out of 10.

Mussels are farmed in open-systems and are likely to spawn during production. Planktonic larvae are widely dispersed and impossible to recapture. This resulted in an Escape Risk Score of 0 out of 10. The majority (> 80%) of the global mussel aquaculture industry is thought to use wild-caught seed from long since established local populations (of either native or non-native species) that are unlikely to cause significant and ongoing environmental impacts when they "escape" from the farm during spawning. However, some species of mussels can be highly invasive, including *M. galloprovincialis* and *P. viridis*. Should new introductions occur, both intentionally or accidentally (such as in ballast water), significant risks to both farmed and wild mussel populations could occur, including genetic impacts resulting from hybridization and introduced susceptibility to pathogens. Additional risks could result from the increased use of hatchery seed in the industry, such as ineffective species identification in broodstock collection that could result in the accidental forming of new hybrids in regions where natural barriers prevented this occurring in the wild. Selective breeding, which may result in reduced genetic diversity in farmed stocks as well as differences between farmed and wild populations, could also create impacts associated with interbreeding between farmed and wild mussels. These risks could be mitigated by using sterile seed (e.g., triploids) but in New Zealand, where mussel seed from selective breeding programs now accounts for between 5-10% of industry demand, triploids are not used.

When considered at the global level, the current concern of competitive and genetic interactions from escapes is considered low, scoring 8 out of 10, while noting that fringe elements of the industry may have a high risk of impacts and that risks to aquaculture from new accidental introductions from other industries, such as shipping, are still present. The escape factors combine to give a final score of 4 out of 10 for Criterion 6 – Escapes.

Mussels, like any animal, are susceptible to a range of pathogens and parasites, but there is little evidence of impactful disease outbreaks in either farmed or wild mussel populations. It is acknowledged that "no evidence of impacts" is not the same as "evidence of no impacts", and the mussel farming system remain open to the potential transfer of pathogens and parasites between wild and farmed populations. A potential example are parasitic pea crab (*Pinnotheres novaezelandiae*) populations in New Zealand, but this would be challenging to measure. Nevertheless, it is considered that any amplification of pathogen and parasite numbers resulting from farmed mussels is not currently having any detectible impact on wild populations, and the final score for Criterion 7 – Disease is 8 out of 10.

Worldwide mussel culture is primarily dependent on wild seed. The use of passive longline seed collectors increases overall larval settlement, but there is no evidence of a significant reduction in wild populations as a result of seed collection. Hatchery production is possible but not generally price competitive with highly abundant wild seed; however, the benefits of consistent seed supplies and selective breeding may change this in the future, particularly as evidence from New Zealand is showing that production cycles for selected seed are significantly shorter than wild seed. Some industries, particularly in Europe, remain reliant on wild seed that is collected using dredging, but these represent a minor component of global mussel production. For this report, it is assumed that less than 10% of farmed stock is dependent on active (dredged) wild seed fisheries, as such the final score for Criterion 8X – Source of Stock is a deduction of 0 out of -10.

Mussel farming is associated with several potential impacts on wildlife, including entanglement with farm structures and litter, changing prey abundance in and around the farm, and causing partial habitat exclusion by disturbance caused by the presence of the farm. Examples of beneficial impacts include increasing food availability for some species, such as seals, or providing roosting for some birds or haul-outs for seals in New Zealand. Several examples of negative impacts were also found, including very rare but significant examples of entanglements of endangered whales and sea turtles. Many of these species face cumulative threats, including fisheries bycatch, to which mussel farming may contribute additional risk. Mussel farming currently occurs mainly in shallow coastal waters, where fewer interactions with endangered whale species would be expected, however, these risks may increase as mussel farming moves further offshore. For these reasons, the precautionary final score for Criterion 9X – Wildlife Mortalities is -5 out of -10.

Marine mussel introductions have mainly occurred by accident, primarily through ship ballast waters, and most of these introductions occurred decades ago. Nevertheless, ongoing mussel seed transportation between water bodies does occur. In some regions, this can account for the majority of seed supply, particularly for on-bottom culture in Europe, as well as the New Zealand industry. It also occurs to a limited degree in China and Spain. At the global level, it is estimated that between 10-20% of mussel production is associated with mussel seed transportation across waterbodies. The rest of global production is considered to be reliant on seed collected from the same water body as the farms. Controls to prevent the introduction of secondary species vary but include prohibitions of movements or monitoring of seed from one area or another. Nevertheless, where movements are permitted, both the seed source and farms receiving them are completely open systems that are vulnerable to the entry or subsequent escape of secondary species during movements. Despite few examples of pathogen introductions associated with mussel farming, significant and ongoing concerns exist with the role that mussel farming can play in increasing both the spread and impact of invasive biofouling species, which can impact the health of both farmed and wild bivalve populations. With only a low percentage of the industry reliant on movements, the final score for Criterion 10X – Escape of Unintentionally Introduced Species is -1.8 out of -10.

Mussel farming can provide important and beneficial environmental services; particularly filter feeding that has the potential to improve regional water quality by reducing nitrogen and phosphorus levels in the water column. The industry does not use additional feed or fertilizers, and chemical use is minimal and unlikely to have significant impacts. There is also little current evidence that mussel farming contributes to impactful pathogen outbreaks on farmed or wild species. Potential environmental impacts, such as those on benthic habitats from mussel feces and pseudo-feces are well understood and have the potential to be effectively managed through regulation. Wild seed collection, which is used by the majority of the global industry, does not represent a major concern, even when mussels spawn during the production cycle, since most seed is of local origins and most non-native mussel species were introduced many decades ago. These are significant strengths, particularly when compared to many types of intensive aquaculture for marine finfish species.

However, biofouling represents a significant and ongoing challenge to the industry, with some mussel farms potentially playing a role in the further spread and impact of invasive biofouling species. Concerns over negative interactions with wildlife are an additional concern, with very rare examples of entanglements or other negative effects on marine mammals, including endangered species, but positive interactions also occur, such as by increasing food availability for some species, such as seals. The increasing use of fertile, selectively bred seed in New Zealand, as opposed to sterile triploid seed, is also a potential concern given that mussels may spawn during production cycles and interbred with wild populations. Finally, in China, a concern over the collection and poor species identification of broodstock may have significant concerns over introducing hybrid mussels that may have been inhibited by natural barriers in the wild.

Overall, the concerns are generally minor or affect only a small part of the global industry assessed here. As such, the final numerical score for global mussels farming is 6.68 out of 10 which is in the Green range and with no Red criteria; the final recommendation is a Green “Best Choice”.

Introduction

Scope of the analysis and ensuing recommendation

Species
Marine Mussels (including Chilean blue mussel (*Mytilus chilensis*), blue mussel (*M. edulis*), Mediterranean mussel (*M. galloprovincialis*), and New Zealand Greenshell® mussel (*Perna canaliculus*), Korean mussel (*M. coruscus*), Green mussel (*P. viridis*), and hybrids)).

Geographic Coverage
Worldwide.

Production Method(s)
On-bottom and suspended (off-bottom) culture

Species Overview

Brief overview of the species
Mussels are bivalve molluscs from the family Mytilidae, which includes 20 different mussel genera including *Perna* and *Mytilus* (CABI 2018a). Globally, mussels have a wide distribution, with species found in freshwater and marine environments (CABI 2018a). This report focuses on marine mussels, as freshwater mussels are not normally consumed as seafood. Mussels are highly robust and able to withstand a wide range of environmental fluctuations in temperature, salinity, desiccation, and water movement; and as such, they can be found in a wide range of conditions from intertidal, estuarine, oceanic environments (CABI 2018a).

Adult mussels are sedentary; using byssal threads to attach to substrate or one another and filtering plankton and other small particles from the water column. Mussels are highly fecund broadcast spawners and release eggs and sperm into water, where fertilization takes place. The planktonic larvae go through a range of developmental phases before developing into a highly mobile larval phase called a veliger. The veliger larva may swim for 15-30 days, depending on the species, before actively seeking a substrate to settle on. The larvae attach to substrate using a mucous thread, which then undergo a metamorphosis before developing a shell, where they become known as a plantigrade or “spat”. The spat are often highly mobile, being able to detach their byssal threads and crawl along surfaces, or drift in the water column using buoyant mucus threads, in a process known as secondary settlement (A. Jeffs 2020, personal communication). Juvenile mussels larger than about 10 mm in length lose the ability to relocate by mucous drifting, but remain able to relocate over short distances by crawling (A. Jeffs 2020, personal communication).

Production system
Mussel farming dates back to 13th century France, with the development of the bouchot method (Goulletquer 2004; described below), which is still practiced today. Figure 1 shows the

general production method for mussel farming. Depending on the species, stocking densities used, and grow-out method, mussels may take around two years reach market size (Island Institute, 1999).

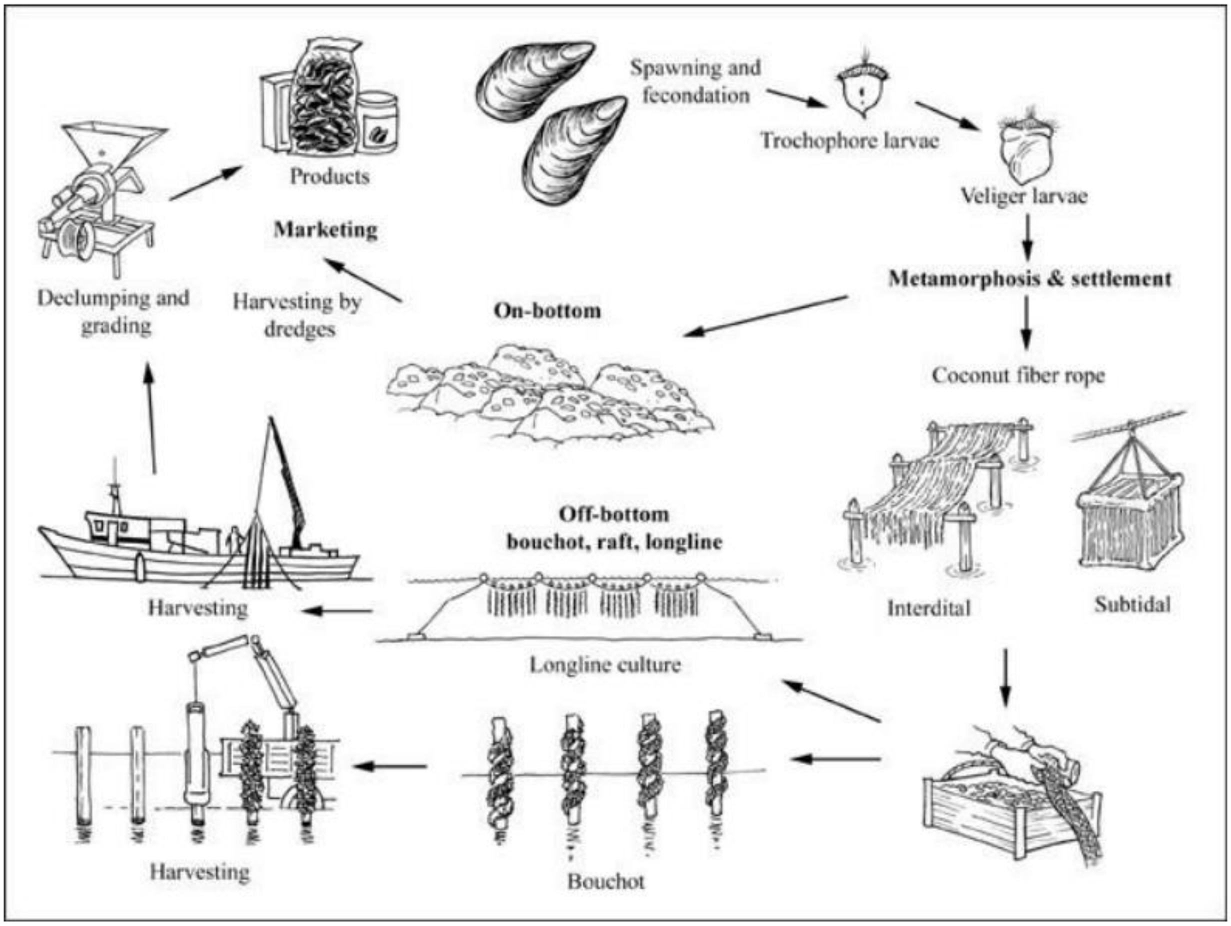

Figure 1. Production cycle of blue mussel aquaculture. (Copied from Goulletquer, 2004)

<u>Seed Collection:</u>

Marine mussels are highly fecund, producing large quantities of free drifting larvae, which actively seek suitable substrate on which to settle (Goulletquer 2004). The lifecycle of marine mussels frequently involves a secondary settlement phase when early juvenile mussels move from settlement habitat, into nearby adult mussel beds (A. Jeffs 2020, personal communication). According to Kamermans and Capelle (2019), there are three approaches to collecting seed; fishing for recently settled individuals, the use of collectors suspended in the water column or hatchery raised seed. Seed are usually available in sufficient quantities from the wild but hatchery production maybe employed to supplement wild seed in times of shortage or to supply specialized seed, such as part of a selective breeding program, hybrid mussels, or polyploids (e.g., triploid) (Goulletquer 2004). In terms of cost, hatchery seed is the most expensive, followed by passively collected seed from the water column, and fishing seed (either by subtidal dredging or intertidal collection), but the latter is both the most susceptible to overexploitation and unreliable (Kamermans and Capelle 2019). The cost and effort associated with seed collection is usually reflected in the grow-out system, such that wild harvested seed is used for on-bottom culture but hatchery seed is used exclusively with longline systems (Kamermans and Capelle 2019).

Fishing for mussel seed employs dredging for mussels on mussel beds or in areas with ephemeral mussel settlement (Davenport et al. 2009). The type of fishing gear varies depending on the size of mussels being harvested and the type of seafloor (Baer et al. 2017). For example, in the Wadden Sea, mussels are collected using a metallic net, around 1.9 m wide, with 4 cm steel bar, that is dragged along the sea bottom (Baer et al. 2017). In New Zealand, mussel seed is harvested from the intertidal zone by hand gathering and modified tractors when it washes ashore in large quantities attached to drift seaweed and other debris (Jeffs et al. 1999, 2018).

Passive suspended seed collecting gear usually employs materials that provide a large area of suitable substrate (Filgueira et al. 2007), such as fuzzy polypropylene ropes, plastic mesh strip, artificial seaweed (Go Deep 2019), or natural material such as coconut fibers (Goulletquer 2004). These lines are deployed on longline systems, an example of which is shown in Figure 2.

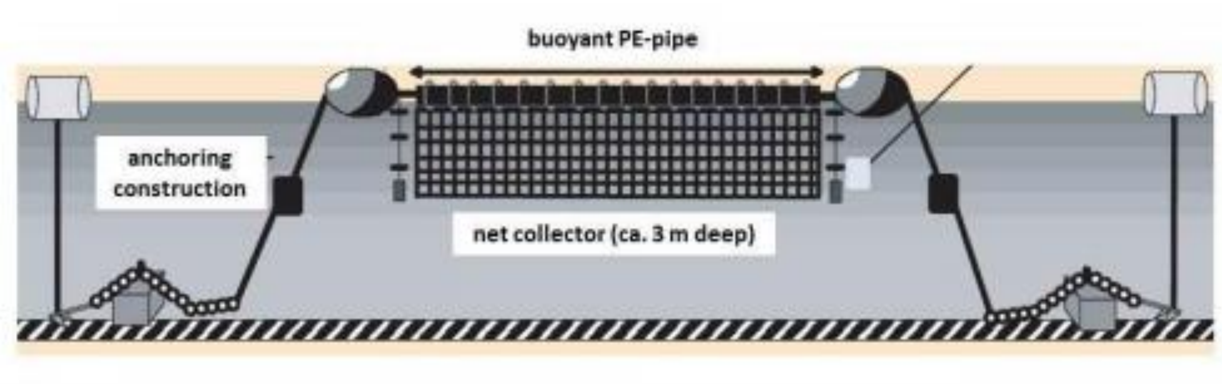

Figure 2. Example of suspended mussel seed collection gear. Copied from Baer et al. 2017.

A study by Filgueira et al. (2007) compared different materials to assess their spat settlement of *M. galloprovincialis* and found that ropes with loops had higher recruitment than ropes without loops, potentially due to loops protecting spat from predators.

The scale of suspended seed collection can be significant relative to the area used for grow-out, for example an area of 339 hectares (ha) were used for seed collection to supply 5,400 ha of grow-out in the Wadden Sea in 2015 (Baer et al. 2017). Seed collectors can be negatively impacted by biofouling and low larval abundance (Kamermans and Capelle 2019).

Hatchery seed is not commonly used in mussel culture due to the cost compared to wild resources, which are often abundant (Kamermans and Capelle 2019). Zhang (1984) described an artificial breeding system in China as collectors placed in tanks. In New Zealand, a selective breeding program for the Greenshell™ mussel (*P. canaliculus*) is now used in commercial hatchery production of mussel seed (A. Jeffs 2020, personal communication). Various industries are testing triploid mussels (which grow year around as they do not spawn) for commercial viability (Kamermans and Capelle 2019), however this is not currently occurring in New Zealand (A. Jeffs 2020, personal communication). Where hatchery seed are used, care must be taken at the hatchery to protect from genetic problems, such as genetic drift, where alleles are lost from the population (Kamermans and Capelle 2019).

Once collected, mussel seed may go through a nursery stage. For example, in China mussel seed may be put in suspended net bags until they reach 0.5-1 cm in length (Mao et al. 2019). Mussels destined for suspended culture techniques may be placed in socks along with a 5 mm diameter polyethylene rope that the mussels will attach to using their byssal threads.

<u>Grow Out:</u>
Grow-out techniques include direct bottom culture, bouchot culture and suspended, off-bottom systems using longlines or rafts in coastal or offshore environments (Kamermans and Capelle 2019).

On-bottom culture
On-bottom culture is most common in the Netherlands, Germany, UK, and Ireland for blue mussels (*M. edulis*) and is primarily supplied by fished seed (Kamermans and Capelle 2019). Seed mussels are transported from collection sites to leased shallow mudflats (Kamermans and Capelle 2019), areas with large food availability and limited competition from wild filter feeding species (Calderwood et al. 2016). Mussels may be seeded from 25-75 mt of seed/ha (Calderwood et al. 2016). Increased prey abundance in these new sites may attract predators, such as crabs and, especially starfish (Calderwood et al. 2016). Losses to predators can be significant, for example in UK waters, it was estimated that starfish at densities of 4 m^{-2} could remove 200,000 mussels/ha/day (McQuaid et al. 2007 in Calderwood et al. 2016). Where predator numbers become excessive, they may be actively removed using crab pots and various dredges, including starfish mops which use frayed or noted ropes to entangle starfish (see references in Calderwood et al. 2016). Mussels are harvested using dredges. *P. viridis* is also cultivated in this manner in some locations (A. Jeffs 2020, personal communication, Kripa and Mohamed 2008).

Bouchot culture
This is the original mussel aquaculture system developed in France (Kamermans and Capelle 2019). Seed for this method is collected on ropes that are then placed on racks over the seabed (Kamermans and Capelle 2019). Once seeded, the ropes are wrapped around poles driven into intertidal mudflats to grow until harvest (Kamermans and Capelle 2019). Harvest is performed using mechanical means, stripping the mussels off the lines (Kamermans and Capelle 2019). Species cultivated using the bouchot technique include *P. viridis* and *M. edulis* (Goulletquer 2004), including in Asia (A. Jeffs 2020, personal communication).

Raft and longline culture:
Both systems use suspended grow-out lines that hanging vertically from either a raft at the surface or a horizontal longline suspended in the water column using floating buoys that maybe submerged or at the surface (see Figure 3) (Kamermans and Capelle 2019). Seed for grow-out is

commonly supplied from the wild using collecting systems (Kamermans and Capelle 2019), sometimes also utilizing the same rafts or floating bouys used for grow-out to facilitate deployment of seed collectors (A. Jeffs 2020, personal communication). Biofouling is a significant concern, and can cause mussel mortalities, while also reducing both mussel growth and quality (Kamermans and Capelle 2019). Biofouling controls include covering all exposed surfaces will mussels, mechanical removal, periods of aerial exposure and antifoulant treatments (Kamermans and Capelle 2019). Species cultivated on longlines include *P. canaliculus* (Kaspar 2005), *M. galloprovincialis* (Figueras 2004), *P. viridis* (Koedprang 2013), *M. edulis* (Goulletquer 2004) and *M. coruscus* (Lee et al. 2016).

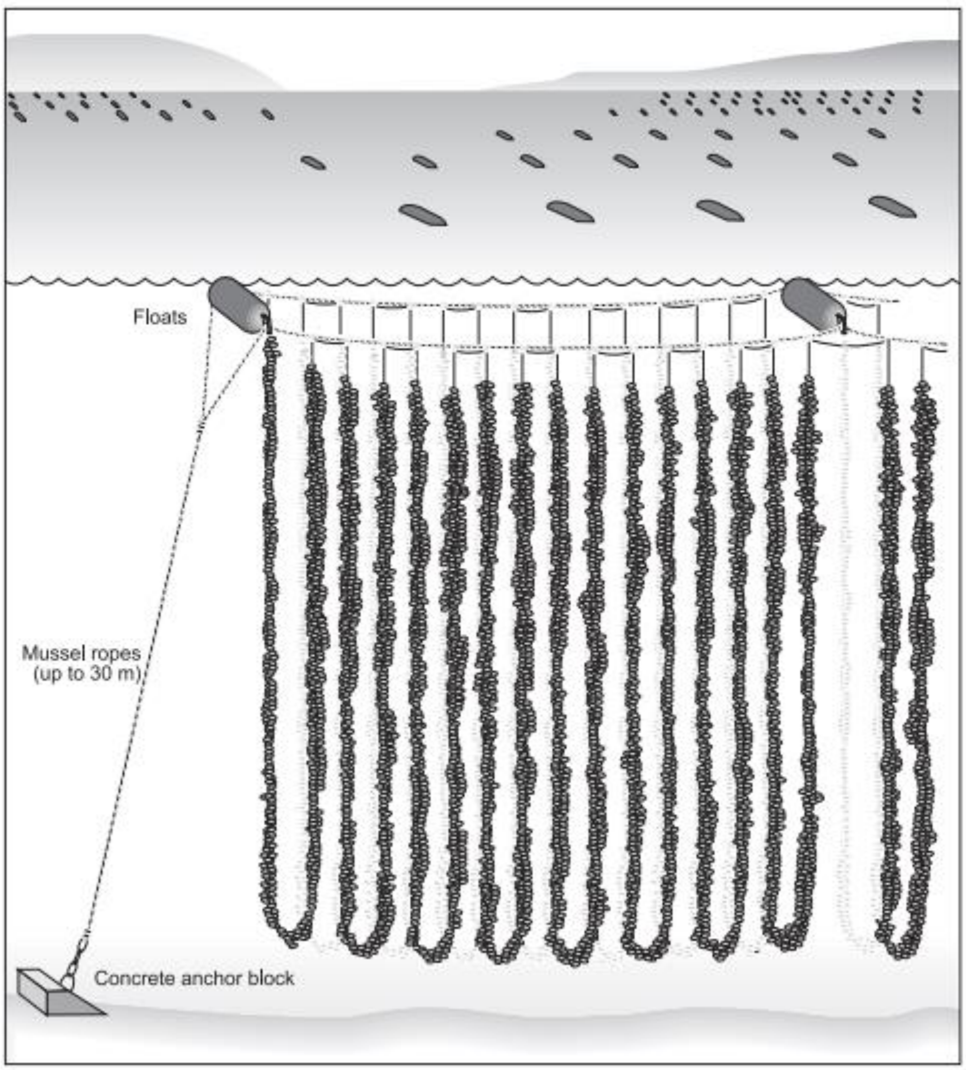

Figure 3. Example of a longline mussel aquaculture farm in New Zealand. (Copied from Lloyd, 2003).

Offshore mussel culture:

Currently, the vast majority of mussel farming occurs in shallow coastal waters near shore, however, suitable locations for shellfish aquaculture in these regions may have significant user conflicts (such as recreational and commercial fisheries) and stakeholder objections (due to visual concerns, etc.), which makes further industry expansion difficult (Mizuta et al. 2019). This has led to interest in moving offshore, which in the US means Federal waters (three miles from shore) until water depths around 100 m, beyond which mussel farms would not be feasible to maintain from shore (Mizuata et al. 2019). In New Zealand, several offshore mussel farms have been in operation for a number of years (A. Jeffs 2020, personal communication). In addition to greatly increased potential space for aquaculture, additional benefits in these environments are expected (and being observed in New Zealand (A. Jeffs 2020, personal communication)), such as less polluted water, fewer food safety concerns, fewer mussel parasites, and reduced competition for the plankton that the mussels feed on (see references in Mizuta et al. 2019). Farms in these areas are exposed to much higher energy than coastal farms (Mizuta et al. 2019) and require stronger engineering, such as line breaking strength. In addition, mussels are suspended around 15-20' below the water surface on longlines to both minimize the forces placed on them and to keep them at the peak depth for feed particles (Mizuata et al. 2019). Figure 4 shows the proposed design for an individual longline used for offshore mussel aquaculture.

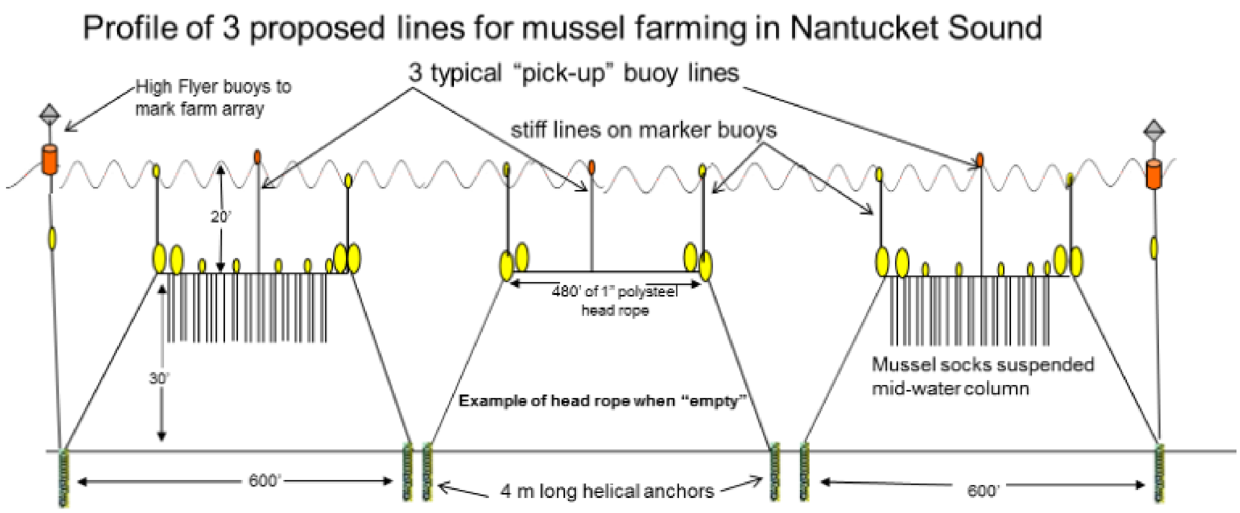

Figure 4. Design of a proposed offshore mussel longline. (Copied from GARFO 2019).

As described in the Production Statistics section below, the top three producers of mussels globally are China, followed by Chile and Spain. Longlines are the main grow out system used in China (Mao et al. 2019) and Chile (Rivera et al. 2017), while in Spain "Bateas mussel rafts" are the preferred culture system (Wijsman et al. 2018). Bottom culture is the main farming system used in the Netherlands, Germany, Ireland and the UK (Wijsman et al. 2018), but the combined production of these countries was 100,000 metric tons in 2017, just 5% of global farmed mussel production (FIGIS, 2019). This would suggest that suspended culture systems are the predominant culture system for mussel farming globally.

Production Statistics

According to FAO's FIGIS database, global aquaculture production for all mussel species in 2017 was 2,163,784 metric tons (mt). NOAA (2018) reported that wild mussel fisheries globally produced 128,453 mt. As such, aquaculture accounts for approximately 94% of all global mussel production.

Figures 5 and 6 show the breakdown of global aquaculture production by country and species respectively. China does not differentiate between the species in the data it reports to the FAO, however this production includes three species, *M. galloprovincialis*, *M. coruscus* and *P. viridis* (Tuathail personal communication 2019). According to Zhang et al. (2019), production of *M. coruscus* accounts for around 8% of Chinese production, with the vast majority focused on *M. galloprovincialis*, which was first used for farming in the early 1970's. For this reason, it is expected that the largest production by species shown in Figure 6, labeled "Sea Mussels, nei" (nei = not elsewhere included in FAO statistics), is almost entirely *M. galloprovincialis.* This would make it the most commonly farmed species in the world by a significant margin. The most recent data available for US mussel production data showed that in 2017, 1,603 mt of mussels were wild harvested almost entirely from State waters (0 to 3 miles from shore), while aquaculture production in 2016 was 406 mt (NOAA, 2018).

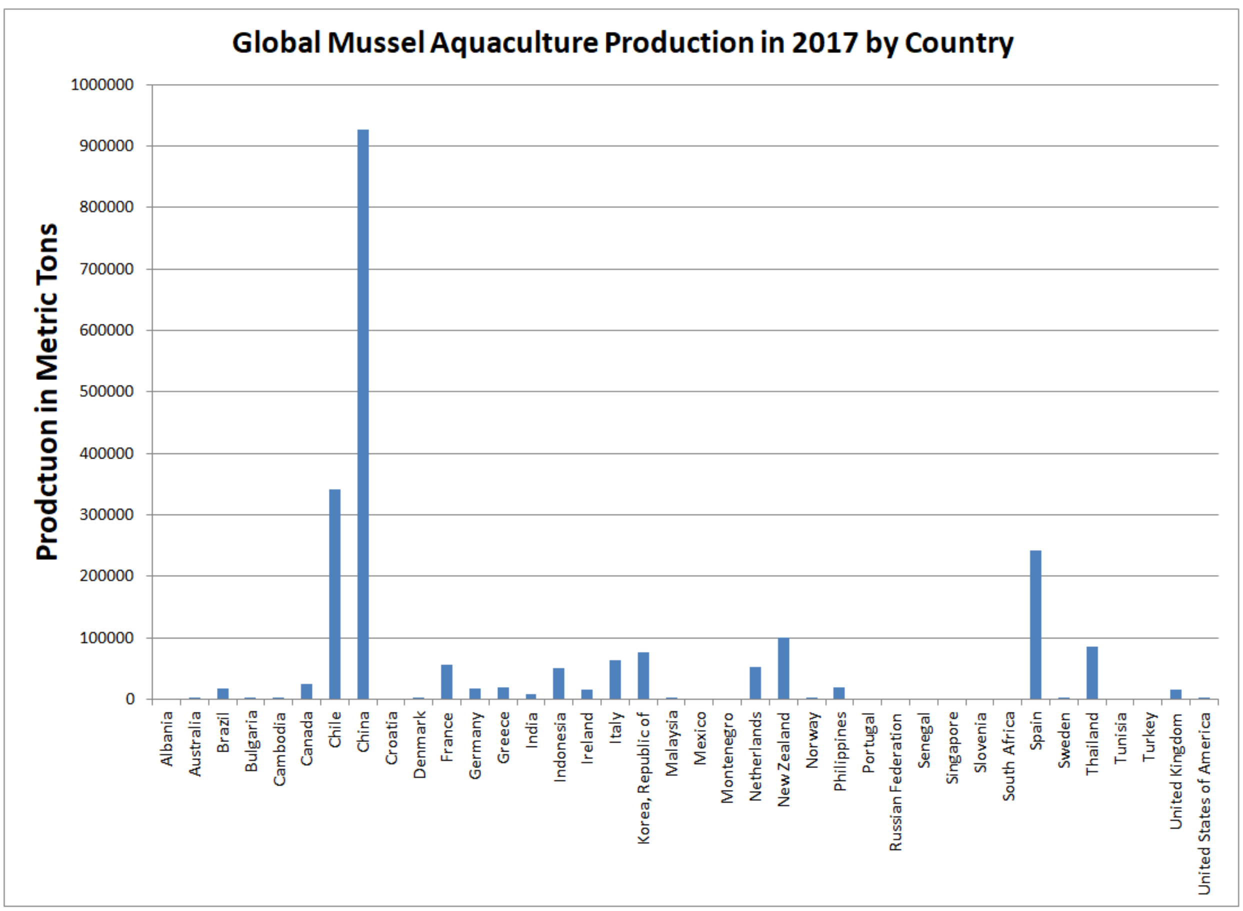

Figure 5. Global Mussel Aquaculture Production in 2017 by Country. (From FIGIS, 2019).

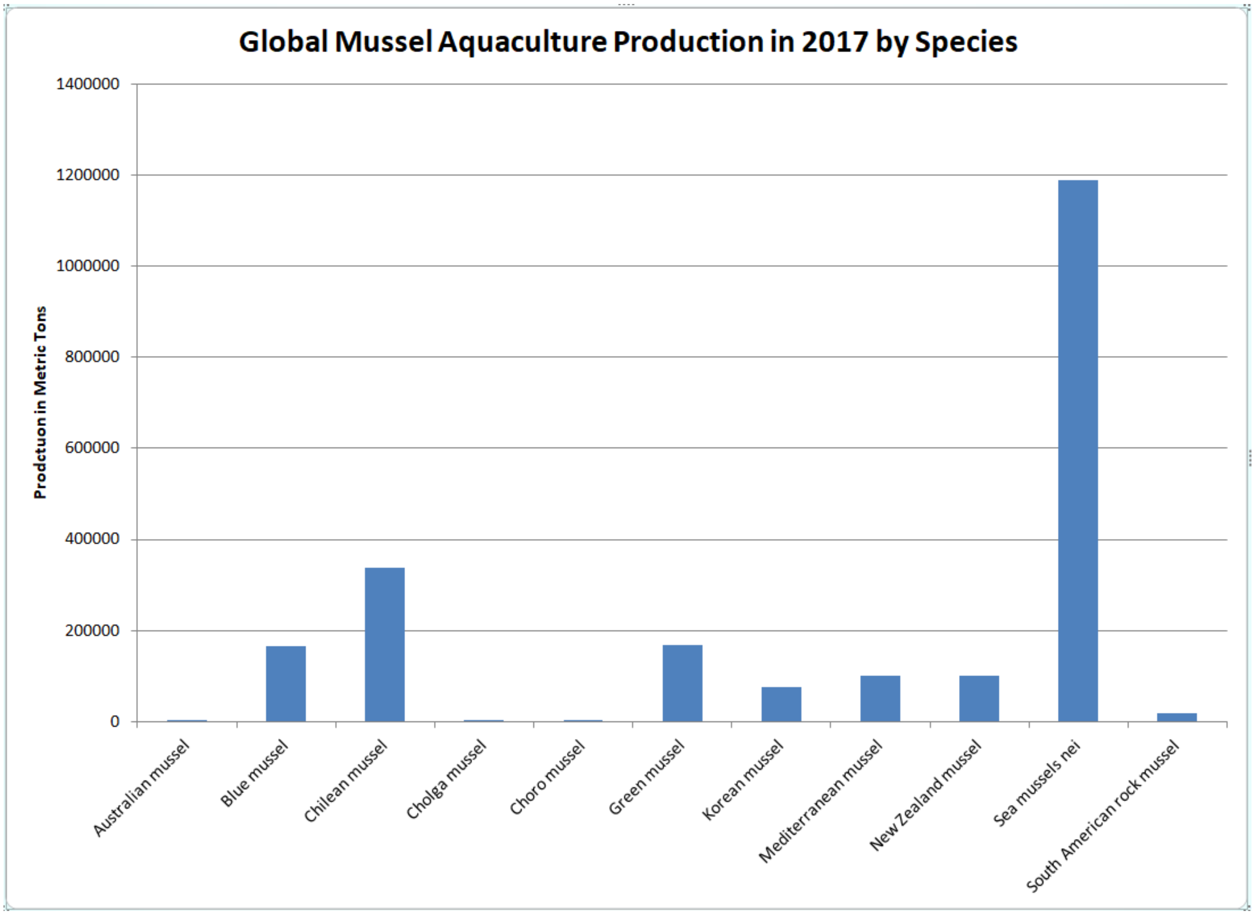

Figure 6. Global Mussel Aquaculture Production in 2017 by Species. (From FIGIS, 2019). It is expected that most of sea mussels nei is the Mediterranean mussel (*M. galloprovincialis*) farmed in China.

Import and Export Sources and Statistics

In 2018, the US imported 30,889 mt of mussels and exported 600 mt (USDA, 2019). Table 1 shows countries exporting over 100 mt of mussels to the US in that same year, as well as the weight of mussels imported and their main product forms.

Table 1. Imports of farmed mussels into the US in 2018 by Country. (From USDA, 2019).

Country	Imports to US in metric tons	Major product forms (in order of import amounts)
Canada	13,647	Live
Chile	9,667	Prepared, dried, frozen
New Zealand	6,519	Frozen, dried
China	598	Prepared, frozen, dried
Spain	133	Prepared meals
Thailand	119	Prepared
All others	207	
Total	30,889	

While China is by far the largest producer of farmed mussels globally, very little production from currently enters the US market, which is instead dominated by imports from Canada, Chile, and New Zealand. As such, this report focuses on these four countries as the most relevant to both global production and seafood available in the US market. Since Prince Edward Island (PEI) accounts for 80% of Canadian production (FOC, 2017), this Province will be the primary focus of the research into mussel farming in this country. The main characteristics of these countries are summarized in Table 2.

Table 2. Key Mussel Farming Characteristics of China, Chile, Canada and New Zealand (From Canada: CABI 2018a, CABI 2018b, FOC 2017, White et al. 2014. China: Mao et al. 2019, Zhang 1984. Chile: Carrasco et al. 2014. New Zealand: Anon 2015, SLH 2019).

Country	Species	Seed Source	Production System	Locations
Canada	Eastern Blue mussel (Mytilus edulis) native East Coast. West Coast hybrid species complex (native *M. trossolus with M. edulis and M. galloprovincialis (introduced in the 1980-90s for aquaculture).*	Wild/longline East Coast, Hatcheries West Coast	Mussel socks on longlines or rafts.	British Columbia, Newfoundland and Labrador, Nova Scotia, Prince Edward Island (PEI accounts for 80% of production) and Quebec.
Chile	*M. chilensis* (native)	Wild/longline	Mussel socks on longlines	Concentrated in the Lakes Region.
China	*M. galloprovincialis (Introduced/established 1970's), M. coruscus* (native) and *P. viridis* (native).	Unclear; Wild/hatchery for *M. galloprovincialis.* Hatchery and wild *M. coruscus*	Primarily longlines with additional raft production.	*M. galloprovincialis* and *M. coruscus* overlap in the Yellow Sea and the East China Sea. *P. viridis* only in South China Sea.
New Zealand	*P. canaliculus (native)*	Collected from seaweed washed onto Ninety Nine Mile Beach	Mussel socks on longlines.	North Island coastline, top of the South Island and Stewart Island. Marlborough Sounds and the

				Coromandel/ Hauraki Gulf

Common and Market Names

According to the 2019 FDA Seafood List, the acceptable market name for all species sold in the US is "mussel", with the exception of the Pen Shell mussel (*Atrina pectinata*), which can be called "Pen Shell" (FDAa, 2019). The New Zealand Government has trademarked the name Greenshell™ mussels to identify *P. canaliculus* raised in New Zealand in the global market (NZG, 2011).

Product forms

Farmed mussels are found in a variety of product forms including live, dried, frozen, canned, and value-added products, such as prepared dinners.

Criterion 1: Data quality and availability

Impact, unit of sustainability and principle

- Impact: poor data quality and availability limits the ability to assess and understand the impacts of aquaculture production. It also does not enable informed choices for seafood purchasers, nor enable businesses to be held accountable for their impacts.
- Sustainability unit: the ability to make a robust sustainability assessment
- Principle: having robust and up-to-date information on production practices and their impacts available for analysis.

Criterion 1 Summary

Data Category	Data Quality	Score (0-10)
Industry or production statistics	5	7.5
Management	5	10
Effluent	10	7.5
Habitat	7.5	7.5
Chemical use	7.5	7.5
Feed	10	5
Escapes	7.5	7.5
Disease	7.5	7.5
Source of stock	5	10
Predators and wildlife	5	7.5
Escape of secondary species	7.5	5
Other – (e.g. GHG emissions)	Not Applicable	n/a
Total		**77.5**

C1 Data Final Score (0-10)	**Total (0-10)**	**7.0**

Brief Summary

Overall, available data are relatively detailed for Chile, PEI and New Zealand but very limited for China. With a relatively straightforward production system and well-established industries, some aspects (e.g. feed and effluent) are robustly understood and drive high data scores here. In contrast, many data scores represent an “averaging” factor with regard to scoring the individual categories across the various regions. The final numerical score for Criterion 1 – Data is 7 out of 10.

Justification of Rating

Industry and Production Statistics:

High quality data are available for Chile, PEI and New Zealand, with locations of farms, species, and general production methods being relatively easily available from a range of regulatory bodies, industry associations, and peer-reviewed journal articles. Data on China, the largest producer of farmed mussels globally, were not readily available or were incomplete. This report relied on relatively recent overviews, such as Wijsman et al. (2018), but this still left questions about the sources of seed and locations of farms etc., which were potentially more consistent with a low-moderate score. For these reasons, the data score for Industry or Production Statistics was moderate and 5 out of 10.

Management and Regulations:
Data on management and regulations for Canada were available for all provinces, including PEI, and also from New Zealand and Chile. Data on environmental enforcement agencies and activities were detailed for Chile and available for Canada and New Zealand. Management and regulation overviews were available for China but enforcement data were not readily available. As such, this report relied on the slightly dated and brief summaries provided by the FAO's National Aquaculture Legislation Overviews. This disparity in detail was the reason behind a moderate data score of 5 out of 10 for the Management and Regulation category.

Effluent:
Mussels do not require feed or fertilizer inputs, and these production characteristics mean the effluent characteristics and potential impacts (or lack thereof) are fully understood. This resulted in a data score of 10 out of 10 for this category.

Habitat:
The impact of mussel farming on benthic habitats is relatively well known, as was shown in Gallardi's (2014) review of the environmental impacts of this type of industry. A literature review of ecosystem services supplied by mussel farms in New Zealand by Stenton-Dozey and Broakhuizen (2019) was also useful at identifying positive attributes. However, the score also needs to reflect the limited data availability for both habitat regulations and enforcement in China. As such, the data score is a moderate high 7.5 out of 10 for the Habitat category.

Chemicals:
Mussel farming can be severely challenged by biofouling organisms and has limited effective options to combat them. The Fitridge et al. (2012) study was important to understand the current status of options available to farmers. Examples of chemical use were limited, but data on the environmental impacts of more common treatments, such as hydrated lime, were useful, including the Burridge and Comeau (2016) study. Available data, while limited, is consistent and results in high confidence and a score of 10 out of 10 for this category.

Feed:
Mussels do not require feed or fertilizer inputs and as such, the feed characteristics are fully understood. This resulted in a data score of 10 out of 10 for this category.

Escapes:

Mussels are likely to spawn during the production cycle and, since their biology is well understood, this information was able to provide a reliable view of the industry. Details on the transportation of mussel seed could be improved, particularly for Chinese production. The Zhang et al. (2019) report was useful understanding that new and ongoing impacts may still occur in the global industry. This resulted in a moderate-high data score of 7.5 out of 10 for this category.

Disease:
Mussel aquaculture is well established and there is sufficient information in the literature and the World Organisation for Animal Health (OIE) disease profiles to have confidence that the state of disease outbreaks and impacts in farmed and wild mussel populations are reasonably well understood. This results in a data score of 7.5 out of 10 for the Disease category.

Source of Stock:
With exception of China, the source of seed is well understood from industry reports, government sources, and the literature. However, as China is the most significant industry in terms of production, the data score for Source of Stock category is 5 out of 10 or moderate.

Predators and Wildlife:
Information on predators and wildlife interactions with mussel aquaculture gear includes case studies from PEI, New Zealand, and Chile, including entanglement events summarized in Price et al. (2017) and Young (2015), and partial habitat disturbance in Kemper et al. (2013). Information on China came from personal communication from regional aquaculture experts. Gaps in data (including unreported interactions) have the potential to skew perceptions of impact. Overall, data is considered moderate and scores of 5 out of 10, for the Predators and Wildlife category.

Escape of Secondary Species:
Gallardi (2014) and McKindsey et al. (2007) summarized a large number of examples of introductions of hitchhiker species associated with shellfish aquaculture, highlighting that most were associated with the movement of oysters rather than mussels for aquaculture. Fitridge et al. (2012) focused on the specific challenges associated with invasive biofouling species and mussel aquaculture, including details of challenges in PEI, while Stenton-Dozey and Broakhuizen (2019) provided both positive and negative issues associated with biofouling. Data on introduced species, specifically on invasive biofouling species during mussel seed movements, are considered scarce but representative, resulting in a moderate-high score of 7.5 out of 10 for this category.

Conclusions and Final Score
Overall, available data are relatively detailed for Chile, PEI and New Zealand but very limited for China. With a relatively straightforward production system and well-established industries, some aspects (e.g. feed and effluent) are robustly understood and drive high data scores here. In contrast, many data scores represent an “averaging” factor with regard to scoring the

individual categories across the various regions. The final numerical score for Criterion 1 – Data is 7 out of 10.

Criterion 2: Effluent

Impact, unit of sustainability and principle

- Impact: aquaculture species, production systems and management methods vary in the amount of waste produced and discharged per unit of production. The combined discharge of farms, groups of farms or industries contributes to local and regional nutrient loads.
- Sustainability unit: the carrying or assimilative capacity of the local and regional receiving waters beyond the farm or its allowable zone of effect.
- Principle: not allowing effluent discharges to exceed, or contribute to exceeding, the carrying capacity of receiving waters at the local or regional level.

Criterion 2 Summary

Effluent Evidence-Based Assessment

C2 Effluent Final Score (0-10)	**10**	**GREEN**

Brief Summary

Mussel farming is entirely reliant on naturally available food, including organic matter and phytoplankton, in the water column. Filter feeding by mussels may improve regional water quality by reducing nitrogen and phosphorus levels in the water column, and promoting the deposition of phosphate and silicate in seafloor sediments. Mussel farming may also replace ecosystem services lost from wild mussel beds. Evidence from New Zealand suggests potential benefits of reduced suspended solids in the water column may not materialize, as material encapsulated in pseudofeces may be re-suspended from the seabed as these degrade over a period of days. Using the evidence-based assessment with no evidence of potential impacts associated with effluents, the final score was 10 out of 10 for Criterion 2 – Effluent.

Justification of Rating

Evidence-Based Assessment:

Farmed mussels feed on naturally available food in the water column, and do not rely on additional feed or fertilizers. As this is robustly understood, the Evidence-based assessment was utilized.

Mussels pump water at around 2-3 liters per hour, which means a 200 mt mussel farm is cable of filtering around 5.6 m^3 of seawater every second (Lindahl et al. 2005). Mussels feed by filtering seston, consisting of organic matter and phytoplankton, out of the water column (Lindahl et al. 2005). This filtering feeding action reduces turbidity and increases light penetration, which in combination with the ammonium excreted by the mussels, further stimulates phytoplankton growth (Gallardi 2014). Mussels remove phosphate and silicate from the water column and, through the creation pseudofeces and feces, transfer these into the sediments. This results in net loss of nutrients in the region and has the combined benefits of improving regional water quality, while producing nutritious food for human consumption (Lindahl et al. 2005). Overall, the removal of nutrients from the water column each year by mussels is estimated to be approximately 1% of their wet weight of nitrogen (Lindahl et al. 2005) and 0.08% phosphorus (Gren, 2019). Perhaps surprisingly, a literature review into the ecosystem benefits of mussel farming in New Zealand was unable to show localized reductions in suspended solids (Stenton-Dozey and Broakhuizen 2019). Stenton-Dozey and Broakhuizen (2019) suggested that although particles were being collected and bound in pseudofeces, these large particles may degrade over a number of days on the seabed and result in a resuspension of small particles. The contribution to benthic environments from mussel farming includes a flux of both live and dead mussels, which can creates new habitat, which are dominated by filter-feeding organisms and may replace ecosystem services lost from wild mussel beds (Stenton-Dozey and Broakhuizen 2019).

There is evidence of localized depletion of phytoplankton due to mussel grazing in some mussel farming locations, which are overstocked. The ecosystem consequences of such depletions are not well understood, but such depletions are usually avoided by mussel farming as it results in decreased farm production (A. Jeffs 2020, personal communication).

Another concern is the potential for mussel farming to contribute to plastic pollution, since suspended longline gear utilize a large number of plastic components (including ropes, socking materials, floats etc.) which shed plastic particles into the marine environment (A. Jeffs 2020, personal communication). In New Zealand, mussel farm debris is common component of material washed up on beaches (A. Jeffs 2020, personal communication).

Conclusions and Final Score

Mussel farming is entirely reliant on naturally available food, including organic matter and phytoplankton, in the water column. Filter feeding by mussels may improve regional water quality by reducing nitrogen and phosphorus levels in the water column, and promoting the deposition of phosphate and silicate in seafloor sediments. Mussel farming may also replace ecosystem services lost from wild mussel beds. Evidence from New Zealand suggests potential benefits of reduced suspended solids may not materialize, as material encapsulated in pseudofeces may be re-suspended from the seabed as these degrade over a period of days. Using the evidence-based assessment with no evidence of potential impacts associated with effluents, the final score was 10 out of 10 for Criterion 2 – Effluent.

Criterion 3: Habitat

Impact, unit of sustainability and principle

- Impact: Aquaculture farms can be located in a wide variety of aquatic and terrestrial habitat types and have greatly varying levels of impact to both pristine and previously modified habitats and to the critical “ecosystem services” they provide.
- Sustainability unit: The ability to maintain the critical ecosystem services relevant to the habitat type.
- Principle: being located at sites, scales and intensities that maintain the functionality of ecologically valuable habitats.

Criterion 3 Summary

Habitat parameters	Value	Score
F3.1 Habitat conversion and function		8
F3.2a Content of habitat regulations	3	
F3.2b Enforcement of habitat regulations	3	
F3.2 Regulatory or management effectiveness score		3.6
C3 Habitat Final Score (0-10)		**6.53**
Critical?	NO	**YELLOW**

Brief Summary

Mussel farms, particularly longline operations, may alter benthic habitats through organic enrichment via pseudofeces and feces, and by an influx of live and dead mussels. This can change the physical, chemical and biological conditions beneath farming systems. Some of these changes can be positive, such as by restoring the ecosystem services and habitat lost from the removal of filter-feeding communities associated with wild mussel beds, while others maybe negative, such as by increasing biomass of pest biofouling organisms or attracting predator species, such as sea stars. Changes to benthic habitats could be compounded by the reduction of currents through the farm structures. Case studies have found that habitat impacts caused by mussel farming can range from excessive impact through to no detectable changes, and influenced by water depth, mussel stocking density, and currents. The vast majority of mussel farms occupy shallow coastal waters with soft-sediment seabeds, with low biodiversity relative to reefs structures and are occupied by detrital feeding organisms with capabilities for utilizing mussel farm deposits, which Seafood Watch considers to be of moderate value, and the summary above suggests that habitat impacts could be case specific, depending on conditions at the farm. Since the organic enrichment from mussels is a natural product, the removal of mussel farms from sites, usually results in a rapid return of the seafloor to an undisturbed state. For these reasons, the habitat impacts are considered to be "minor-moderate" and the score for Factor 3.1 is 8 out of 10.

Evidence of habitat management measures and enforcement are available for Chile, PEI and New Zealand but limited for China. Information available suggests that globally the potential habitat impacts caused by individual farms are likely to be considered in regulation but not cumulative impacts. However, this maybe expected where deposition habitat impacts are likely limited to the local environment to the farm sites. When all these factors are considered, the score for Factor 3.2a is 3 out of 5 and the score for Factor 3.2b is 3 out of 5. When combined the, the final Factor 3.2 score for management effectiveness is 3.6 out of 10.

Factors 3.1 and 3.2 combine to give a final Criterion 3 – Habitat score of 6.53 out of 10.

Justification of Rating

Factor 3.1. Habitat conversion and function

Habitat impacts associated with dredging for seed are possible but are not considered in this report as the primary regions that his occurs in, such as the Netherlands, are not significant producers or exporters to the U.S. The primary production systems used in China, Chile, PEI, and New Zealand are suspension systems, including longline culture or rafts, as such these are the focus of this report.

Gallardi (2014) conducted a review of the effects of bivalve aquaculture on the environment. Many of these impacts are summarized in Figure 7, created by New Zealand's Ministry of Primary Industries (MPI) (MPI 2013a).

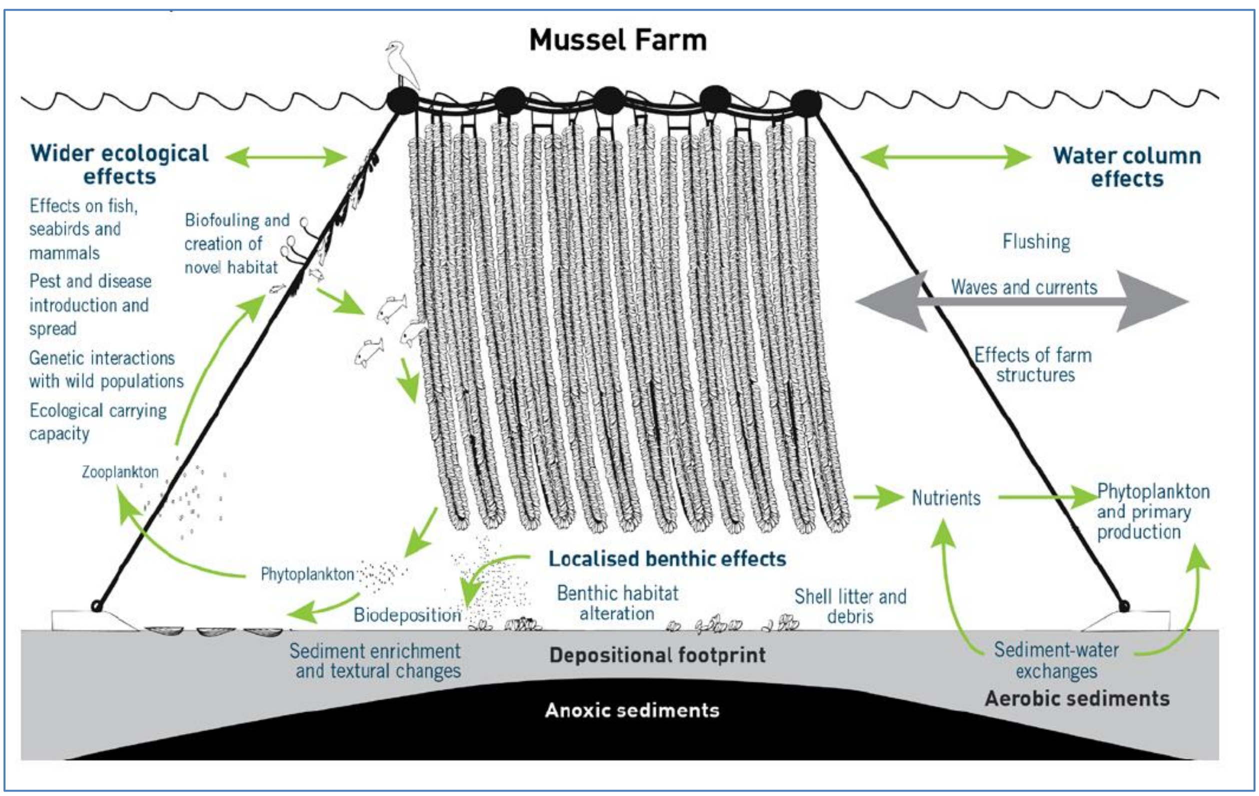

Figure 7. Ecological impact of longline mussel farming in New Zealand (Copied from MPI 2013a).

Gallardi (2014) identified mussels, as well as oysters, as the bivalves with the most significant potential to affect the environment, principally due to their significant water filtering abilities and because they reject the most particles as pseudofeces. According to a Shellfish Association of Great Britain report (SAGB 2008) "*The main concern with suspended culture is a predicted increase in sedimentation beneath the rafts and longlines, caused by reduced flow because of the suspension structure, and increased levels of faeces and pseudofaeces from the mussels and associated epibiota*." Mussels remove particles, including phytoplankton and zooplankton, from the water column, some of which are ingested, while others are incorporated into pseudofeces (Davenport et al. 2000, Lehane and Davenport 2002), which can form relatively large (500-3000 µm) pellets (Gallardi 2014). These organic matter rich pellets rapidly settle on the seabed beneath the mussel farm, particularly where water flow is reduced (Gallardi 2014). In addition to the mussels themselves, organic waste is also produced by biofouling organisms (e.g., tunicates), which can account for as much as 86% of the organic waste entering the sediments (Giles et al. 2006).

The impacts of organic enrichment in sediments were summarized in Gallardi (2014) and include an increase in oxygen demand, which at high levels may create anaerobic conditions. This may change sediment chemistry and drive faunal communities away from macrofaunal populations (i.e., bivalves, crustaceans etc.) towards smaller opportunistic meiofauna and bacteria rich populations

Several factors may influence the risks of accumulation and impact of pseudofeces on the sediment, including the stocking density of mussels, the water depth, the currents at depth, sediment type (erosional or depositional) and their associated benthic communities (Gallardi, 2014). According to Gallardi (2014) the impacts of increased organic matter sedimentation as a result of mussel farming have been well studied; ranging from little to no impacts on benthic infauna to strong, long-lasting impacts. Gallardi (2014) highlights that the impact of mussel farming are generally less than those of bottom dredging.

In addition to impacts of organic enrichment, Gallardi (2014) described a number of concerns associated with mussel shells, including creating novel habitats for unwanted epifauna, including tunicates. Suspended mussel farming can increase the flux of shells to the seabed, which in low energy conditions can be significant; Gallardi (2014) highlighted an example where shells added an additional 10 cm in sediment depth within one year. These additional concerns can be significant; for example, mussel farming in PEI is challenged by a number of invasive tunicate species (MacNair, 2005). Stenton-Dozey and Broakhuizen (2019) also found that in New Zealand, mussel farms attracted greater numbers of predatory species, such as sea stars to the benthic environment below the farms.

Stenton-Dozey and Broakhuizen (2019) highlighted several positives associated with habitat changes associated with mussel farming, claiming that "*to some degree mussel farms compensate for the loss of both wild mussel beds and biogenic reefs by providing renewable mussel stocks and habitats that increase the abundance of organisms that once that would have been plentiful among the now-destroyed benthic habitats*." In particular, their literature review "*recorded a total of 139 taxa associated with suspended farm structures from the literature, of which most were suspension feeders (ca. 61%) followed by scavengers, predators and detritivores.*" These filter-feeding organisms would increase the benefits identified in Criterion 2 – Effluents. Additionally, "*mussel-culture derived reefs form three-dimensional heterogenous habitats that provide EcolS* [ecological services] *of food, shelter and protection for other marine flora and fauna and help to stabilise bottom sediments*."

Currently, the vast majority of mussel farming occurs in shallow coastal waters, near shore (Mizuta et al. 2019). These areas are commonly soft-sediment seabeds, with low biodiversity relative to reefs structures and are occupied by detrital feeding organisms with capabilities for utilizing mussel farm deposits (A. Jeffs 2020, personal communication). Seafood Watch considers these environments to be of moderate habitat value and the summary above suggests that mussel farming impacts on benthic habitats and communities could range from very little impact though to long-lasting impacts, depending on currents, depth, farming intensity, and normal benthic conditions. For these reasons, habitat impacts associated with global mussel farming are considered to be "minor-moderate" and the score for Factor 3.1 is 8 out of 10.

Factor 3.2. Farm siting regulation and management

<u>Factor 3.2a: Content of habitat management measures</u>
The scope of this report covers marine mussels farmed anywhere in the world. Habitat management measures are likely to differ in specifics from one country to another, thus this factor will be scored by focusing on China, as the leading global producer, and the three main exporting regions to the US; PEI, Chile, and New Zealand.

Under its overarching Fisheries Law, China has established a number of regulations, at both the state and local levels, focused on marine bivalve aquaculture, including 12 regional shellfish mariculture zones (Wijsman et al 2018). However, these zones are primarily defined on food safety criteria, such as the content of bacteria in shellfish meat and juice, rather than environmental or biosecurity purposes (Wijsman et al 2018). According to the FAO's National Aquaculture Legislation Overview (NALO) report on China "*natural spawning, breeding and feeding grounds of fish, shrimp, crab, shellfish and algae in state owned water surfaces and tidal flats as well as their major migration passages must be protected and cannot be used as aquaculture grounds*" and that under the Sea Area Use Management Law (2002) prospective businesses must apply for permits from the Ministry of Land and Natural Resources to build new farms (NALO 2004). Environmental Impact Assessments (EIA)'s would likely only be required for large construction (NALO 2004), which would probably exclude mussel aquaculture. It is believed that China has highly knowledgeable aquaculture managers within its research agencies but that these managers are mainly focused on increasing production rather than limiting environmental impacts (DLPF 2016). This may indicate that regulations are not necessarily focused on protecting benthic habitats. Information on enforcement organizations responsible for shellfish aquaculture or penalties for infringements could not be found.

Fisheries and Oceans Canada (FOC) has a detailed website, which includes aquaculture regulations and policies across the three principal regulatory regimes for aquaculture in Canada, as well as the responsible enforcement agencies. According to FOC (2019) "*in Prince Edward Island, a management board with members from DFO, the province, and industry, issues a lease which has a licence attached. Fisheries and Oceans Canada is responsible for issuing shellfish licences to farmers in British Columbia. The administration of aquaculture tenures in British Columbia is the responsibility of the provincial government. In other provinces where mussels are farmed, there are provincial regulations and legislation for the administration of aquaculture site leases, licences, and permits*." PEI is the main region of production and has operated an Aquaculture Zoning System since the 1980's (FOC, 2019). This is primarily a tool to address user conflicts in the region. Conditions to obtaining a lease, including proposed site assessment criteria, specifically address environmental issues and impacts on fish habitat, as well as carrying capacity "*based on scientific information as it becomes available*" (FOC, 2019). Additionally, conditions for cancelling a lease are spelled out in regulation; however, these do not reference excessive habitat impacts (FOC, 2019).

According to the FAO's National Aquaculture Legislation Overview (NALO) report on Chile, aquaculture is regulated under the General Fisheries and Aquaculture Law, and new farms must obtain a concession or authorization to use marine areas (NALO 2012). Concessions are granted by the Ministry of Defense, where their jurisdiction applies, otherwise authorizations are issued by the Sub-Secretariat for Fisheries (NALO, 2012). Authorizations are issued with respect to the Environmental Regulation on Aquaculture, which requires a study of the proposed area with respect to physical, biological, and chemical parameters, as well as potential impacts on the carrying capacity of the water body (i.e., an Environmental Impact Assessment (EIA)) (NALO, 2012). In addition, under the Environmental Regulation for Aquaculture (RAMA), material and substances that may affect the seabed should be addressed by the farms (NALO 2012). RAMA also sets on environmental quality standards (EQS) for the level of benthic quality in Chilean aquaculture and requires that conditions remain aerobic. An environmental assessment is carried out every two years for extensive (unfed) aquaculture, such as mussel farming (Subpesca 2019). Chilean EQS values include organic matter (≤9%), pH (≥7.1), redox potential (≥50 mV), granulometry (absence of bacteria mats or outgassing), and dissolved oxygen (≥2.5 mg/l) (Subpesca 2019).

In New Zealand, MPI has published a guide on how the establish and operate a mussel farm (MPI 2013b). According to MPI (2013b) "*the Resource Management Act 1991 (RMA) is the primary legislation which governs the establishment of marine farms. Any person wishing to establish a marine farm must apply and obtain a resource consent from the appropriate regional council or unitary authority, in addition to passing the subsequent undue adverse effects on fishing test undertaken by the Ministry for Primary Industries (MPI)*." MPI is responsible for issuing an "aquaculture decision" based on the Undue Adverse Effects Test, which must show no adverse impacts on "*recreational, customary, or commercial fishing*" due to displacement of those activities (MPI 2013b). Regional councils require the completion of an Assessment of Environmental Effects (AEE) and any proposed activities must be consistent with relevant regional coastal planning. "*The AEE looks at the effects of the proposed activity and* *considers those effects against the purpose of the RMA to promote the sustainable management of natural and physical resources*" (MPI 2013a). Evidence that benthic conditions are considered in the AEE is demonstrated by Marlborough District Council, a key mussel farming region of New Zealand, which underwent a study by Banta and Gibbs (2006) of marine farm consent refusals prior to 2006. The study found that "*potentially adverse effects on benthic or marine communities were one of the reasons for refusal in 35 % of the applications studied, and 5 % reported concern for the unknown adverse effects on natural communities from the reduction in chlorophyll and phytoplankton levels. 27 % acknowledged the possibility of negative effects on particular species such as King Shags and other nesting seabirds, brachiopods, Hectors dolphins, orca, and tubeworms.*"

Evaluating habitat content measures for mussel farming globally is challenging, because often attention is focused on marine finfish aquaculture in the available data. Secondly, regulatory documentation is typically complex and voluminous, and often difficult to translate into English. In places where mussel farming is relatively more important, such as PEI and New Zealand, it's generally easier to find information specific to mussel farming compared to other forms of aquaculture, such as finfish culture, but reviews such as FAO's NALO are important resources of general information. Chile publishes mussel aquaculture data along with other types of aquaculture, including Atlantic salmon, into some environmental reports, which is positive. Since the habitat impacts associated with mussel farming are likely well known, it is also likely that the issue would receive consideration in regulatory decisions globally; however, it is not common in aquaculture that cumulative habitat impacts are considered. For this reason, the content of Habitat Management Measures is considered moderate for the global marine mussel farming industry and the score for Factor 3.2a is 3 out of 5

Factor 3.2b: Enforcement of habitat management measures

Information on enforcement measures, beyond food safety, in global mussel aquaculture is limited. In Chile, under RAMA, the results of environmental monitoring of mussel farms conducted by Supesca are published online in an annual report (in Spanish only). The 2018 report showed that of 137 mussel farms monitored, only five had anaerobic benthic conditions (Subpesca 2019). Enforcement bodies and controls in PEI and New Zealand, including permitting processes, are well defined and regionally based. Banta and Gibbs (2006), while dated, provided evidence of enforcement in New Zealand. However, little information was available for China. This may not mean that effective enforcement does not exist, it may simply not be reported or well-studied in the literature. Most of the information in Factor 3.2a points to the presence of regulation addressing habitat impacts at the individual farm rather than at the cumulative level.

When all these factors are considered, enforcement bodies and some evidence of enforcement measures appear to be present in Chile, PEI, and New Zealand, but information is limited from China. As such, a Moderate score for Factor 3.2b, 3 out of 5, is appropriate when considering the global industry. When combined with the Factor 3.2a score of 3 out of 5, the final Factor 3.2 score (aggregated globally) is 3.6 out of 10.

Conclusions and Final Score

Mussel farms, particularly longline operations, may alter benthic habitats through organic enrichment via pseudofeces and feces, and by an influx of live and dead mussels. This can change the physical, chemical and biological conditions beneath farming systems. Some of these changes can be positive, such as by restoring the ecosystem services and habitat lost from the removal of filter-feeding communities associated with wild mussel beds, while others maybe negative, such as by increasing biomass of pest biofouling organisms or attracting predator species, such as sea stars. Changes to benthic habitats could be compounded by the reduction of currents through the farm structures. Case studies have found that habitat impacts caused by mussel farming can range from excessive impact through to no detectable changes, and influenced by water depth, mussel stocking density, and currents. The vast majority of mussel farms occupy shallow coastal waters with soft-sediment seabeds, with low biodiversity relative to reefs structures and are occupied by detrital feeding organisms with capabilities for utilizing mussel farm deposits, which Seafood Watch considers to be of moderate value, and the summary above suggests that habitat impacts could be case specific, depending on conditions at the farm. Since the organic enrichment from mussels is a natural product, the removal of mussel farms from sites, usually results in a rapid return of the seafloor to an undisturbed state. For these reasons, the habitat impacts are considered to be "minor-moderate" and the score for Factor 3.1 is 8 out of 10.

Evidence of habitat management measures and enforcement are available for Chile, PEI and New Zealand but limited for China. Information available suggests that globally the potential habitat impacts caused by individual farms are likely to be considered in regulation but not cumulative impacts. However, this maybe expected where deposition habitat impacts are likely limited to the local environment to the farm sites. When all these factors are considered, the score for Factor 3.2a is 3 out of 5 and the score for Factor 3.2b is 3 out of 5. When combined the, the final Factor 3.2 score for management effectiveness is 3.6 out of 10.

Factors 3.1 and 3.2 combine to give a final Criterion 3 – Habitat score of 6.53 out of 10.

Criterion 4: Evidence or Risk of Chemical Use

Impact, unit of sustainability and principle

- Impact: Improper use of chemical treatments impacts non-target organisms and leads to production losses and human health concerns due to the development of chemical-resistant organisms.
- Sustainability unit: non-target organisms in the local or regional environment, presence of pathogens or parasites resistant to important treatments
- Principle: limiting the type, frequency of use, total use, or discharge of chemicals to levels representing a low risk of impact to non-target organisms.

Criterion 4 Summary

Chemical Use parameters	Score	
C4 Chemical Use Score (0-10)	**8**	
Critical?	NO	**GREEN**

Brief Summary

Biofouling is a major challenge to mussel farming by competing with mussels for food, damaging shells, and increasing the risk of gear failure. A number of control techniques exist, but many are impractical, costly, or have negative consequences to the mussels. In this context, the use of chemical controls is considered to be limited because the mussels may uptake and concentrate them in their tissues. Known chemicals used in industry, such as hydrated lime, have extremely short-term localized impacts in the water column, which are unlikely to cause negative impacts on non-target populations. As such, the final numerical score for Criterion 4 – Chemical Use is 8 out of 10.

Justification of Rating

Examples of chemical use in mussel aquaculture are generally associated with the control of biofouling. Biofouling organisms compete with mussels for natural feeds, cause physical damage to shells or impede shell function, decrease oxygen availability in the water, and add significant additional weight and drag stress on farming gear (Fitridge et al. 2012).

Fitridge et al. (2012) summarized the following five strategies to control biofouling and their potential for mussel aquaculture:

- **Avoidance of natural recruitment to prevent settlement and growth of biofouling:** By removing or moving gear away from peak points of settlement (e.g., favored water depths or times of the year), or reducing available space by increasing mussel stocking density. These approaches offer limited success.
- **Physical removal ranging from scrubbing and brushing to chemical dips and sprays:** This is the dominant approach at present. Depending on the biofouling species, this can include air

exposure, power washing, freshwater immersion, brine immersion, heated water immersion, low-concentration acid or alkaline sprays/immersion (including acetic acid, lime, hydrated lime), and chlorine bleach. These approaches maybe useful for some biofouling species but not others, may damage mussels, and may lead to great coverage of fouling as displaced organisms resettle.

- **Biological control using natural predator species:** This is challenging in suspended mussel culture due to the need to keep predator species on the gear.
- **Coatings on shells:** No relevant mussel examples, but has been used in oyster culture.
- **Control and protection for equipment using antifouling coatings and organic biocides:** These have included the use of heavy metals, such as copper, on ropes, floats, and other equipment. However, these are often highly toxic to marine invertebrates, such as mussels.

A limiting factor to chemical control of biofouling on mussel farms is the likely uptake by the mussels during feeding, which may affect their health and could be concentrated in the sediments via pseudofeces (Gallardi 2014). Examples of chemical use for biofouling control in mussel aquaculture include rafts in Spain being painted in situ with tars or waterproof paints (Towers 2015), the use of hydrated lime in PEI (CBC, 2009) and New England, "*dilute bleach dips*" in New Zealand and the use of white vinegar (Carman et al. 2016). The most common forms of control used in PEI and East Coast of the US are hydrated lime and power washing (Davidson et al. 2016). The cost of biofouling controls compared to the value of the mussel crop is another limiting factor to their use (A. Jeffs 2020, personal communication).

Burridge and Comeau (2016) researched the potential environmental impact of hydrated lime use in PEI, finding that "*treatment with hydrated lime results in a significant, yet short-lived, increase in pH and the conversion of Ca(OH)2 to carbonate which may precipitate into the environment. Lab-based studies have characterised the hazard associated with elevated pH and the presence of particulate carbonate. Field studies have shown that exposure to hazardous pH or particulate carbonate is unlikely to last more than several minutes and elevated pH is only observed for distances of several metres from the treatment operation. These data lead us to conclude that under current operating conditions lethal effects on non-target organisms resulting from use of hydrated lime are unlikely to occur*."

Both Fitridge et al. (2012) and Carman et al. (2016) agree that biofouling as an ongoing and critical issue for mussel aquaculture, with Fitridge et al. (2012) suggesting that effective, non-leaching biocides or non-toxic coatings might offer potential for future use.

As an indirect indicator of chemical use, between January 2014 and September 2019, there have been 32 cases of mussels being rejected for import by the U.S. FDA, however, none of these have been caused by chemical residues (FDA 2019b).

Conclusions and Final Score

Biofouling is a major challenge to mussel farming by competing with mussels for food, damaging shells, and increasing the risk of gear failure. A number of control techniques exist, but many are impractical, costly, or have negative consequences to the mussels. In this context, the use of chemical controls is considered to be limited because the mussels may uptake and concentrate them in their tissues. Known chemicals used in industry, such as hydrated lime, have extremely short-term localized impacts in the water column, which are unlikely to cause negative impacts on non-target populations. As such, the final numerical score for Criterion 4 – Chemical Use is 8 out of 10.

Criterion 5: Feed

Impact, unit of sustainability and principle

- Impact: feed consumption, feed type, ingredients used and the net nutritional gains or losses vary dramatically between farmed species and production systems. Producing feeds and their ingredients has complex global ecological impacts, and their efficiency of conversion can result in net food gains, or dramatic net losses of nutrients. Feed use is considered to be one of the defining factors of aquaculture sustainability.
- Sustainability unit: the amount and sustainability of wild fish caught for feeding to farmed fish, the global impacts of harvesting or cultivating feed ingredients, and the net nutritional gains or losses from the farming operation.
- Principle: sourcing sustainable feed ingredients and converting them efficiently with net edible nutrition gains.

Criterion 5 Summary

C5 Feed Final Score (0-10)		10
Critical?	NO	GREEN

Brief Summary

External feed is not provided to farmed mussels. Therefore, the final score for Criterion 5 – Feed is 10 out of 10.

Justification of Rating

Farmed mussels feed on naturally available food in the water column, and do not rely on additional feed or fertilizers. Therefore, the final score for Criterion 5 – Feed is 10 out of 10.

Criterion 6: Escapes

Impact, unit of sustainability and principle

- Impact: competition, genetic loss, predation, habitat damage , spawning disruption, and other impacts on wild fish and ecosystems resulting from the escape of native, non-native and/or genetically distinct fish or other unintended species from aquaculture operations
- Sustainability unit: affected ecosystems and/or associated wild populations.
- Principle: preventing population-level impacts to wild species or other ecosystem-level impacts from farm escapes.

Criterion 6 Summary

Escape parameters	Value	Score
F6.1 System escape risk	0	
F6.1 Recapture adjustment	0	
F6.1 Final escape risk score		0
F6.2 Competitive and genetic interactions		8
C6 Escape Final Score (0-10)		**4**
Critical?	No	**YELLOW**

Brief Summary

Mussels are farmed in open-systems and are likely to spawn during production. Planktonic larvae are widely dispersed and impossible to recapture. This resulted in an Escape Risk Score for Factor 6.1 of 0 out of 10. The majority (> 80%) of the global mussel aquaculture industry is thought to use wild-caught seed from long since established local populations (of either native or non-native species) that are unlikely to cause significant and ongoing environmental impacts when they “escape” from the farm during spawning. However, some species of mussels can be highly invasive, including *M. galloprovincialis* and *P. viridis*. Should new introductions occur, both intentionally or accidentally (such as in ballast water), significant risks to both farmed and wild mussel populations could occur, including genetic impacts resulting from hybridization and introduced susceptibility to pathogens. Additional risks could result from the increased use of hatchery seed in the industry, such as ineffective species identification in broodstock collection that could result in the accidental forming of new hybrids in regions where natural barriers prevented this occurring in the wild. Selective breeding, which may result in reduced genetic diversity in farmed stocks as well as differences between farmed and wild populations, could also create impacts associated with interbreeding between farmed and wild mussels. These risks could be mitigated by using sterile seed (e.g., triploids) but in New Zealand, where mussel seed from selective breeding programs now accounts for between 5-10% of industry demand, triploids are not used.

When considered at the global level, the current concern of competitive and genetic interactions from escapes is considered low, scoring 8 out of 10 for Factor 6.2, while noting that fringe elements of the industry may have a high risk of impacts and that risks to aquaculture from new accidental introductions from other industries, such as shipping, are still present. Factors 6.1 and 6.2 combine to give a final numerical score of 4 out of 10 for Criterion 6 – Escapes.

Justification of Rating

Factor 6.1. Escape risk

The primary culture system in the global marine mussel farming industry is suspension culture using longlines and production cycles may last from 1-2 years. Mussels may reach sexual maturity in the same period (e.g. Seed, 1969; Ceccherelli and Rossi,1984; Alfaro et al. 2008), meaning that it is very likely that mussels will spawn during the culture period. Mussels are broadcast spawners and free-living larval phases are likely to create significant dispersion of a large number of larvae.

In addition to broadcast spawning, mussels can also fall off onto the seabed. Farms may use socking material to minimize these losses (Go Deep, 2019), however, as Gallardi (2014) highlighted, mussel farms can deposit around 10 cm depth sediment in one year in shells, and this would be expected to include both live and dead mussels. Kamermans and Capelle (2019) claim that over stocking on ropes or nets can increase mussel drop off rates due to "self-thinning", when space or food becomes limiting.

Since mussels are farmed in open systems, are likely to spawn during production, and have free-living larval phases that are not possible to recapture, the score for Factor 6.1 is 0 out of 10.

Factor 6.2. Competitive and genetic interactions

Most initial mussel introductions appear to have been accidental, primarily via ballast water or biofouling on vessels used for shipping; however, the movement of broodstock due to species misidentification is also possible (Branch and Stefani 2006). In terms of the main mussel farming countries that use non-native species, it is common that these introductions occurred long ago (before the 1970's) (Castinel et al. 2019, Zhang et al. 2019).

These initial introductions may have been highly impactful. For example, *M. galloprovincialis* has been profiled in the Invasive Species Compendium by the Centre for Agriculture and Bioscience International (CABI). According to CABI (2018b) "*M. galloprovincialis is considered highly invasive due to its quick rate of spread and its ability to displace and outcompete native mussels*." CABI (2018b) highlight several examples of impacts on native species resulting from *M. galloprovincialis'* introduction, including the displacement of several species of mussels and polychaetes in South Africa, and also displacing native mussels and forming hybrid populations on the Pacific coast of North America. Of the marine mussels, *P. viridis* is also considered by CABI (2018c) to be an invasive species, with impacts associated with biofouling, as it can form large, dense colonies very quickly, e.g., Gulf of Mexico (Rajagopal et al. 2006). In Korea, native *M. coruscus* populations are thought to be in rapid decline due, in part, to habitat competition with invasive *M. galloprovincialis* (Kang et al. 2013). While the latter species was thought to have been accidentally introduced to Korea in ballast waters around the 1960’s, its natural competitiveness has made it the dominant mussel species in the wild (Kang et al. 2013). Interestingly, Kang et al. (2013) found no evidence of hybridization between the two species in Korea, speculating that there might be a difference in habitat preference between the two, with *M. coruscus* preferring deeper and colder waters than *M. galloprovincialis*.

While initial introductions may have occurred long ago, as Castinel et al. (2019) highlights in New Zealand, concerns that new introductions of mussel species, along with hitchhiker pathogens, still continue today. Where mussel species are genetically similar (particularly *Mytilus* species) or have similar environmental niches, it’s possible that hybridization between native and introduced mussel species may occur and introduce susceptibility to pathogens that native populations, both farmed and wild, were tolerant to (Castinel et al. 2019). It should be noted that these risks would largely be introduced to aquaculture from other industries (e.g., shipping), although as highlighted below in China, the transportation of broodstock and seed could also result in these issues.

Global mussel farming primarily sources wild seed passively collected from the wild, then moved onto grow-out farms. It is estimated in Criterion 10X of this asessment that between 10-20% of mussel seed is transported between waterbodies, with the remainder likely to be collected and farmed in the same waterbody. This is region dependent, but broadly means that escapes from the large majority of mussel farms (i.e. the 80% to 90% of farms that use seed collected from the same waterbody) would be considered low risk and score 10 out of 10 for Factor 6.2. However, there are examples of potentially significant concerns with some elements of the industry.

In China, mussel farming is dominated by *M. galloprovincialis*, a native species to the Mediterranean, which was first farmed in China before the early 1970's (Zhang et al. 2019) and is now likely well established. According to Mao et al. (2019) production of *M. galloprovincialis* and *M. coruscus* (a native species) overlap in the Yellow Sea and the East China Sea, while *P. viridis* (also native) is only found in the South China Sea. All of these industries are supplied primarily by wild seed collection, with a small amount supplemented by hatchery production (Mao et al. 2019). However, Zhang et al. (2019) identified that increasing market demand in China for *M. coruscus* is driving hatchery production and the trade of juvenile mussels is increasing. Broodstock for these hatcheries are collected from the wild, but species identification is a problem, and mussel species are known to form hybrids (Zhang et al. 2019). While using genetic tests on hatchery seed, Zhang et al. (2019) detected two farms unknowingly using hybrids of *M. galloprovincialis* and *M*. coruscus, which may have been the result of a broodstock mix up at a hatchery or that the wild populations were already hybrids. Zhang et al. (2019) raised the potential economic interest in the potential for hybrid vigor (where hybrids outperform the pure species) but also highlighted concerns over their escape/release into the environment to backcross with native species, with potential impacts to their genetic fitness and pathogen susceptibility. In this example, the potential concern for impacts on native *M. coruscus* populations in China could be considered high, scoring 0 out of 10 for factor 6.2.

In New Zealand, there is significant movement of wild seed between locations and there are clear genetic differences in the wild population (A. Jeffs 2020, personal communication). It should also be noted that in New Zealand, a selective breeding program for the Greenshell™ mussel (*P. canaliculus*) has been initiated (called the SPATnz programme) and now accounts for between 5-10% of the seed used by industry, with the aim of increasing this to 30% (O'Connell 2019). The program is developing multiple lines of broodstock for the selection program and the resultant seed has been shown to have significantly faster growth rates than wild seed (O'Connell 2019). Where hatchery seed is used, care must be taken to protect from genetic problems, such as genetic drift, where alleles are lost from the population (Kamermans and Capelle 2019). These risks may be mitigated by using sterile, triploid mussels (which grow year around as they do not spawn) (Kamermans and Capelle 2019). However, New Zealand is not using triploid mussels (A. Jeffs 2020, personal communication).

In summary, mussel farming using locally wild-caught seed from either native or non-native but long since established populations are unlikely to cause significant and ongoing environmental impacts when they "escape" from the farm during spawning. This is the case with the majority (between 80 to-90%) of the global industry. However, when new introductions occur, or if appropriate safeguards are not applied when hatchery seed is used (e.g., effective species identification in hatcheries and/or using sterile seed stocks) and aquaculture practices disrupt natural barriers to hybridization, significant risks to both farmed and wild mussel populations could occur, including genetic impacts and introduced susceptibility to pathogens. When considered at the global level, the concern of competitive and genetic interactions from escapes is considered low, scoring 8 out of 10 for Factor 6.2, while noting that fringe elements of the industry may have a high risk of impacts and that risks to aquaculture from new accidental introductions from other industries, such as shipping, are still present.

Conclusions and Final Score

Mussels are farmed in open-systems and are likely to spawn during production. Planktonic larvae are widely dispersed and impossible to recapture. This resulted in an Escape Risk Score for Factor 6.1 of 0 out of 10. The majority (> 80%) of the global mussel aquaculture industry is thought to use wild-caught seed from long since established local populations (of either native or non-native species) that are unlikely to cause significant and ongoing environmental impacts when they "escape" from the farm during spawning. However, some species of mussels can be highly invasive, including *M. galloprovincialis* and *P. viridis*. Should new introductions occur, both intentionally or accidentally (such as in ballast water), significant risks to both farmed and wild mussel populations could occur, including genetic impacts resulting from hybridization and introduced susceptibility to pathogens. Additional risks could result from the increased use of hatchery seed in the industry, such as ineffective species identification in broodstock collection that could result in the accidental forming of new hybrids in regions where natural barriers prevented this occurring in the wild. Selective breeding, which may result in reduced genetic diversity in farmed stocks as well as differences between farmed and wild populations, could also create impacts associated with interbreeding between farmed and wild mussels. These risks could be mitigated by using sterile seed (e.g., triploids) but in New Zealand, where mussel seed from selective breeding programs now accounts for between 5-10% of industry demand, triploids are not used.

When considered at the global level, the current concern of competitive and genetic interactions from escapes is considered low, scoring 8 out of 10 for Factor 6.2, while noting that fringe elements of the industry may have a high risk of impacts and that risks to aquaculture from new accidental introductions from other industries, such as shipping, are still present. Factors 6.1 and 6.2 combine to give a final numerical score of 4 out of 10 for Criterion 6 – Escapes.

Criterion 7: Disease; pathogen and parasite interactions

Impact, unit of sustainability and principle

- Impact: amplification of local pathogens and parasites on fish farms and their retransmission to local wild species that share the same water body
- Sustainability unit: wild populations susceptible to elevated levels of pathogens and parasites.
- Principle: preventing population-level impacts to wild species through the amplification and retransmission, or increased virulence of pathogens or parasites.

Criterion 7 Summary

Evidence-Based Assessment

Pathogen and parasite parameters	Score	
C7 Disease Score (0-10)	8	
Critical?	YES	GREEN

Brief Summary

Mussels, like any animal, are susceptible to a range of pathogens and parasites, but there is little evidence of impactful disease outbreaks in either farmed or wild mussel populations. It is acknowledged that "no evidence of impacts" is not the same as "evidence of no impacts", and the mussel farming system remain open to the potential transfer of pathogens and parasites between wild and farmed populations. A potential example are parasitic pea crab (*Pinnotheres novaezelandiae*) populations in New Zealand, but this would be challenging to measure. Nevertheless, it is considered that any amplification of pathogen and parasite numbers resulting from farmed mussels is not currently having any detectible impact on wild populations, and the final numerical score for Criterion 7 – Disease is 8 out of 10.

Justification of Rating

There is little evidence of disease outbreaks in either farmed or wild mussel populations, but this is considered to be a characteristic of the mussels themselves rather than solely a limitation of the data or evidence available. However, it should be noted that a review of disease status in New Zealand by Castinel et al. (2019) highlighted that the industry had no significant disease outbreaks but also no specific trigger mechanism for reporting significant losses to the authorities or regulatory requirement to monitor stocks for disease. Additionally, parasitic pea crab (*Pinnotheres novaezelandiae*) populations in New Zealand may also be amplified by mussel farming, but this would be very challenging to assess (A. Jeffs 2020, personal communication). Even so, while the disease data quality and availability are limited, they are still considered to be representative (i.e. Criterion 1 score of 7.5 or 10 for the disease category). The Seafood Watch Evidence-based assessment was utilized.

Mussels, like any animal, are susceptible to a range of pathogens and parasites (Goulletquer 2004); however, unlike other farmed bivalves, such as oysters that suffer mass mortalities from pathogens such as oyster herpesvirus or *Marteilia* sp. (Ugalde et al. 2018; Osinki and Osinki 2019; OIE 2019), there is little evidence of significant disease events in either farmed or wild mussel populations that would indicate a risk to either population. According to the World Organisation for Animal Health (OIE) (2019), the only notifiable disease that can infect mussels is *Marteilia refringens*, a protozoan parasite that can infect *Mytilus* species and other bivalves. Mortalities from outbreaks of this disease are much higher with oysters (>98%) than mussels (>40%) (OIE 2019). *M. refringens* has been reported in several countries (Albania, Croatia, France, Greece, Italy, Morocco, Portugal, Spain, Sweden, Tunisia, and the U.K. (OIE 2019); however, there is no evidence that mussel farming (Spain is a significant producer) is amplifying any impact of this pathogen on wild species, which generally appears to be relatively minimal.

Conclusions and Final Score

Mussels, like any animal, are susceptible to a range of pathogens and parasites, but there is little evidence of impactful disease outbreaks in either farmed or wild mussel populations. It is acknowledged that "no evidence of impacts" is not the same as "evidence of no impacts", and the mussel farming system remain open to the potential transfer of pathogens and parasites between wild and farmed populations. A potential example are parasitic pea crab (*Pinnotheres novaezelandiae*) populations in New Zealand, but this would be challenging to measure. Nevertheless, it is considered that any amplification of pathogen and parasite numbers resulting from farmed mussels is not currently having any detectible impact on wild populations, and the final numerical score for Criterion 7 – Disease is 8 out of 10.

Criterion 8X: Source of Stock – independence from wild fisheries

Impact, unit of sustainability and principle

- Impact: the removal of fish from wild populations for on-growing to harvest size in farms
- Sustainability unit: wild fish populations
- Principle: using eggs, larvae, or juvenile fish produced from farm-raised broodstocks thereby avoiding the need for wild capture.

This is an “exceptional” criterion that may not apply in many circumstances. It generates a negative score that is deducted from the overall final score. A score of zero means there is no impact

Criterion 8X Summary

Source of stock parameters	Score	
C8X Independence from unsustainable wild fisheries (0 to 10)	0	
Critical?	NO	GREEN

Brief Summary

Worldwide mussel culture is primarily dependent on wild seed. The use of longline seed collectors increases overall larval settlement, but there is no evidence of significant reductions to wild populations as a result of seed collection. Hatchery production is possible but not generally price competitive with highly abundant wild seed; however, the benefits of consistent seed supplies and selective breeding may change this in the future, particularly as evidence from New Zealand is showing that production cycles for selected seed are significantly shorter than wild seed. Some industries, particularly in Europe, remain reliant on wild seed that is collected using dredging, but these represent a minor component of global mussel production. For this report, it is assumed that less than 10% of farmed stock is dependent on active (dredged) wild seed fisheries, as such the final numerical score for Criterion 8X – Source of Stock is a deduction of 0 out of -10.

Justification of Rating

Mussels are highly fecund, producing large quantities of free-swimming larvae, which actively seek suitable substrate on which to settle (Goulletquer 2004). According to Kamermans and Capelle (2018), there are three approaches to collecting seed; including fishing for recently settled individuals, the use of collectors suspended in the water column, or hatchery raised seed. Seed is usually available in sufficient quantities from the wild but hatchery production may be employed to supplement wild seed in times of shortage or to supply specialized seed, such as part of a selective breeding program, hybrid mussels, or polyploids (e.g., triploid) (Goulletquer 2004). In terms of cost, hatchery seed is the most expensive, followed by seed harvested from collectors, and finally fished (dredged or gathered) wild seed, but the latter is most susceptible to overexploitation and unreliable (Kamermans and Capelle 2019). The cost and effort associated with seed collection is usually reflected in the grow-out system, such that dredged seed is used for on-bottom culture but hatchery seed is used exclusively with longline systems (Kamermans and Capelle 2019).

On-bottom culture practiced in the Netherlands, Germany, the U.K. and Ireland for blue mussels (*M. edulis*) and are primarily supplied by fished seed (Kamermans and Capelle 2019). Seed mussels are transported from collection sites to leased shallow mudflats (Kamermans and Capelle 2019), areas with large food availability and limited competition from wild filter feeding species (Calderwood et al. 2016). The sustainability of these fishery resources is complex (e.g. see Maguire et al., 2007), but these production methods only account for a small proportion (less than 10%) of global mussel production.

In China, seed sources include both hatchery raised and wild collection, however, the percentage of each source is unclear. According to Mao et al. (2019) mussel seed collection from both sources were developed in the 1970's and currently "*bivalve breeding technology is the basis of large-scale farming in China*", however the authors also state "*the majority of mussel seed comes from natural sea area collection, and a small amount from artificial breeding*". Zhang (1984) described an artificial breeding system as collectors placed in tanks and wild collection as seed settlement on kelp longlines. Zhang (1984) also mentioned the use of longlines to hold adult mussels to increase regional seed production. Zhang et al. (2019) reported that demand for *M. coruscus* in China was increasing, and hatchery raised seed was now essential to meet the demand.

In New Zealand, around 70-80% of the seed used in mussel farming is collected from seaweed washed up on Ninety Mile Beach 70-80% (Jeffs et al. 2018). The SPATnz selective breeding program supplies an additional 5-10%, with the aim of increasing this to 30% (O'Connell 2019).

Fisheries and Oceans Canada (FOC) (2017) reported that the Canadian farmed mussel industry was reliant on wild seed collection on the east coast, which accounts for the majority of production, while hatchery production supplied the west coast industry. Seed collection is regulated using a licensing approach defined by the Gulf Region Molluscan Spat Collection Operational Policy (FOC, 2008). The policy outlines that spat collection is a fishery under the Canadian Fisheries Act, which requires a license to collect spat via a collector or from the seabed within defined regions. Licenses are issued considering user conflicts, as well as environmental impacts on migratory birds and fish habitat. Movement of collected spat between provinces is prohibited without health checks and authorization, with the Policy outlining how these controls maybe applied within a province, if required.

Carrasco et al. 2014 stated that "*mussel seed production in Chile depends exclusively on natural collection and currently faces a serious seed shortage crisis, with a decrease of 15% in natural collection during 2012*." The cause of the seed reduction was unknown; two possible causes were a reduction in available seston due to changing climate or ocean acidification affecting the recruitment of larval mussels (Carrasco et al. 2014). In the same study, the authors claimed that hatchery production would not be viable due to the low value of Chilean mussels on the national and international market.

According to Kamermans and Capelle (2019) various industries are testing triploid mussels (which grow year around as they do not spawn) for commercial viability.

Conclusions and Final Score

Worldwide mussel culture is primarily dependent on wild seed. The use of longline seed collectors increases overall larval settlement, but there is no evidence of significant reductions to wild populations as a result of seed collection. Hatchery production is possible but not generally price competitive with highly abundant wild seed; however, the benefits of consistent seed supplies and selective breeding may change this in the future, particularly as evidence from New Zealand is showing that production cycles for selected seed are significantly shorter than wild seed. Some industries, particularly in Europe, remain reliant on wild seed that is collected using dredging, but these represent a minor component of global mussel production. For this report, it is assumed that less than 10% of farmed stock is dependent on active (dredged) wild seed fisheries, as such the final numerical score for Criterion 8X – Source of Stock is a deduction of 0 out of -10.

Criterion 9X: Wildlife and predator mortalities

Impact, unit of sustainability and principle

- Impact: mortality of predators or other wildlife caused or contributed to by farming operations
- Sustainability unit: wildlife or predator populations
- Principle: preventing population-level impacts to predators or other species of wildlife attracted to farm sites.

This is an “exceptional” criterion that may not apply in many circumstances. It generates a negative score that is deducted from the overall final score. A score of zero means there is no impact.

Criterion 9X Summary

Wildlife and predator mortality parameters	Score	
C9X Wildlife and predator mortality Final Score (0-10)	**-5**	
Critical?	NO	**YELLOW**

Brief Summary

Mussel farming can result in several potential impacts on wildlife, include entanglement with farm structures and litter, changing prey abundance in and around the farm, and causing partial habitat exclusion by disturbance caused by the presence of the farm. Examples of beneficial impacts include increasing food availability for some species, such as seals, or providing roosting for some birds or haul-outs for seals in New Zealand. Several examples of negative impacts were also found, including very rare but significant examples of entanglements of endangered whales and sea turtles. Many of these species face cumulative threats, including fisheries bycatch, to which mussel farming may contribute additional risk. Mussel farming currently occurs mainly in shallow coastal waters, where fewer interactions with endangered whale species would be expected, however, these risks may increase as mussel farming moves further offshore. For these reasons, the precautionary final numerical score for Criterion 9X – Wildlife Mortalities is -5 out of -10.

Justification of Rating

Mussel farming can cover significant areas with many rows of longlines; for example, a three-hectare farm in New Zealand may have nine longlines over 100m long (EG 2018). Offshore farms maybe much larger, covering several thousand hectares (EG 2018). In the review of the environmental impacts of bivalve aquaculture on the environment, Gallardi (2014) identified the following potential effects on marine mammals and seabirds;

1. Entanglement with farm structures and litter.
2. Changes to prey abundance.
3. Partial habitat exclusion by disturbance.

Changes to prey abundance may be considered a positive interaction, while entanglements and habitat exclusions would be examples of negative interactions.

A literature review of mussel farming ecosystem services in New Zealand found that "*mussel farms provide an EcolS* [ecosystem service] *by providing feeding and roosting opportunities for some seabirds. Buoys on mussel farms provide EcolS* [ecosystem service] *haul-out for seals and at harvest foraging opportunities are afforded for seals. The common and bottlenose dolphins use farms to herd their prey*" (Stenton-Dozey and Broakhuizen 2019).

According to the FAO (2018) "*one of the greatest threats to species and population survival of marine mammals with their relatively slow growth and low fecundity comes from inadvertent interaction with, or capture in, fishing and aquaculture operations*." For fishing gear, there are two ways that marine mammals may interact with fishing gear, 1) they may actively seek out a food source associated with the gear (bait, farmed mussels, or food attracted to the gear) or 2) accidentally become entangled due to being unable to detect the gear or avoid it in sufficient time (FAO 2018).

Not all interactions are lethal or will cause population level impacts (FAO 2018) but the biggest impact would likely occur to endangered marine mammal species. Of 129 species of marine mammals, 33 are listed as critically endangered, endangered, or vulnerable on the IUCN Red List (2019).

Documented marine animal entanglements and mussel farming gear are relatively rare but include 10 interactions with both cetaceans and sea turtles. Price et al. (2017) and Young (2015) summarized these incidents;

- North Pacific right whale (*Eubalaena japonica*) in South Korea in February, 2015. The whale became entangled in a 50 ha longline mussel farm within 1 km of the coastline. The gear was cut and the whale was presumed to have escaped. A YouTube video of the event has been posted online. North Pacific Right Whales are listed as "endangered" on the IUCN's Red List (Cooke and Clapham 2018).
- A potential Southern right whale entanglement in Argentina in 2011 was reported, also associated with mussel spat collection lines (Price et al. 2017).
- Leatherback sea turtles (*Dermochelys coriacea*) in Newfoundland, Canada in 2010 and 2013. Both turtles became entangled in spat collecting ropes. The first was fatal, when the turtle drowned after becoming entangled at depth, the second was rescued at the surface by boaters, who posted a YouTube video of the event, and clearly shows loops of collecting rope wrapped around the head and flippers of the turtle. Another Leatherback sea turtle was entanglement with a mussel farm was cited in Price et al.

(2017). Leatherback sea turtle are listed as "vulnerable" on the IUCN's red list (Wallace et al. 2013).

- Humpback whale (*Megaptera novaeangliae*) in Iceland in August 2010 and two humpback whales (*M. novaeangliae*) in Australia between 1982-2010. The whale in Iceland was entangled in a 5m long spat collecting line, which had become wrapped around its tail. Reports from Australia indicate both were entangled in mussel farming lines. Humpback whales are considered to be "least concern" by the IUCN (Cooke, 2018).
- Two Bryde's whales (*Balaenoptera edeni*) in New Zealand in August, 1996: One whale was found dead and entangled in a spat collecting rope near to Great Barrier Island. According to Young's (2015) summary, "*the mussel line was found wrapped around the body and tightly lodged in the animal's mouth. An official necropsy was never performed on the carcass, which has led to some dispute over whether the whale was alive during the time of the entanglement (Clement, 2013)*." According to A. Jeffs (2020 personal communication) these whales came from a resident local inshore population, which has a "national critical" status in New Zealand.

Another entanglement occurred in China in 2017, in that case a humpback whale was entangled in a scallop farm, which used lantern nets hanging from a longline, similar to the approach used for mussels (Sohu 2017).

Regarding marine mammal interactions, Lloyd (2003) stated that "*the risk of entanglement is probably greater with thinner or untensioned ropes, such as spat collecting ropes and lost ropes*". A key difference in the risk of entanglements between baleen whales and dolphins are that former are much larger and unable to echolocate like dolphin species (Lloyd 2003). FAO (2018) reviewed a number of approaches to mitigate entanglements with aquaculture gear, including acoustic deterrents, weak lines or breakable gear that would allow an animal to escape an entanglement, high tension gear and others, but largely found that none of the current suite of approaches offered an ideal solution, additionally concerns over costs and other factors, such as the ability of gear to withstand extreme weather events, may also limit their suitability for off bottom mussel farming.

According to FAO (2018) "*An absence of bycatch does not necessarily mean that it is not occurring or that the events are fewer than reported. Most bycatch incidents likely go unreported, especially in countries where there is limited monitoring*." In New Zealand, under the Marine Mammal Protection Act, anyone who harms or kills a marine mammal must report it to the authorities (Lloyd, 2003). In China, where the vast majority of mussel farming occurs, there is no evidence of reporting of interactions between mussel farms and either marine mammals or sea turtles. However, in China, entanglements are likely rare as the main species around the farms are harbor seals and sea turtles are no longer present due to overfishing of the population in Southern Chinese waters (Wang pers. comm. 2019); entanglements of Western Pacific leatherback turtles would be extremely impactful as they are listed as "Critically Endangered" by the IUCN (Tiwari et al. 2013). The natural range of both leatherback sea turtles and humpback whales extends to key locations for mussel farming; including Canada, China, Chile, New Zealand and face cumulative threats including entanglements with fishing gear (Cooke, 2018, Wallace et al. 2013).

According to Price et al. (2017) the primary approach to managing risks of interaction is by "*siting in areas which minimize the likelihood of overlap with migration routes or critical habitats*", this is both in terms of spatial and seasonal considerations (noting that most mussel aquaculture takes between 1-3 years to reach market size, depending on species and location. However, the application of these approaches maybe challenging. For example, studies into the North Atlantic right whale migrations on the US East Coast have shown that their distribution has become increasingly unpredictable and that studies into potential impacts on marine mammals interacting with tensioned gear suggests that potential reduction in the risk of entanglements maybe offset with the risk of more severe harm to the animal (Thompson et al. 2019). This is particularly concerning as expansion of mussel farms into offshore environments may increase entanglement risks, for example in New Zealand expansion into these waters may overlap migration routes for both humpback and southern right whales (EW, 2008).

In addition to marine mammals, research summarized in Price et al. (2017) showed that "*seabird entanglement at mussel farms is a concern*" but unlikely to have population level impacts. Coastal mussel farms attract species such as gulls and cormorants by providing structures to perch on or access to food (e.g., mussels themselves or biofouling species). Sea ducks, especially eider ducks, are a major concern to mussel farmers as they are capable of removing significant amounts of mussels in a short period of time (Dobbins 2019). Some mussel farmers have taken to placing predator nets around the edges of their farms as a deterrent for eider ducks, as they will not dive between mussel lines (Dobbins 2019). According to Price et al. 2017, predator nets required a 4"-6" mesh size and, depending on the species of bird being deterred, netting deployed to 10 m depth from the surface to be effective. Entanglement risks with these predator nets were considered low (Price et al. 2017). Clement (2013) claimed there was no evidence of seabird entanglements on spat or mussel grow-out lines in New Zealand, however, Australian gannets (*Sula serrator*) used ropes ties from mussel farms in their nests and become entangled that way (Butler, 2003). These birds are not threatened (NZbirdsonline 2013).

Several examples of partial habitat disturbance to wildlife as a result of shellfish aquaculture have been documented, including three examples involving dolphins (Kemper et al. 2003);

- In Chile, dense coverage of mussel lines in Bahia Yaldad Bay (>60%), overlapped the habitat of 30-40 Chilean dolphins (*Cephalorhychus eutropia)*. The dolphins were observed feeding close to the farm edge but not between the mussel lines, reducing their available habitat to feed. According to the IUCN report (Heinrich & Reeves 2017), which lists this species as "near threatened" the "*exclusion of Chilean Dolphins from bays and fjords is mainly a result of large-scale shellfish farming operations but also of salmon farms (Kemper et al. 2003, Heinrich 2006, Ribeiro et al. 2007). It has been shown that boat traffic, mainly related to aquaculture, affects the behaviour of Chilean Dolphins (Ribeiro et al. 2005).*"

- In Australia, Indo-Pacific Bottlenose dolphins (*Tursiops aduncus*) were displaced from premium breeding grounds by the illegal installation of pearl oyster lines (Watson and Mann 2002 cited in Kemper et al. 2003). Indo-Pacific Bottlenose dolphins are listed as “Near Threatened” by the IUCN (2019).
- In Admiralty Bay in the Marlborough Sounds of New Zealand, dusky dolphins (*Lagenorhynchus obscurus*) were thought to be avoiding mussel farms sited in near-shore foraging habitat. Pearson et al. (2012) conducted a fine scale study of this issue, finding that dusky dolphins spent significantly less time inside mussel farms than other areas, and that mussel farms may hinder coordinated feeding strategies used by the dolphins, and that although foraging in the area varied annually, there was evidence to suggest that overall use of the habitat was declining. At the time, mussel farms only covering 1% of the total area of Admiralty Bay. Person et al. (2012) stated that “*expansion of mussel farms would represent further habitat loss and may limit the ability of dusky dolphins to forage effectively*.” Dusky dolphins are listed as “Least Concern” by the IUCN (2019).

In contrast to the examples above, López and Methion (2017) found that common bottlenose dolphins (*Turisops truncates*) were attracted to mussel farming rafts in Spain, largely because the gear acted as a fish aggregating device and increased the abundance of prey in the area. As López and Methion (2017) suggest, “*interactions between shellfish aquaculture and cetaceans seem to be affected by culture method and cetacean species involved*”, as such it is likely that potential impacts should be considered on a case specific basis.

Conclusions and Final Score

Mussel farming can result in several potential impacts on wildlife, include entanglement with farm structures and litter, changing prey abundance in and around the farm, and causing partial habitat exclusion by disturbance caused by the presence of the farm. Examples of beneficial impacts include increasing food availability for some species, such as seals, or providing roosting for some birds or haul-outs for seals in New Zealand. Several examples of negative impacts were also found, including very rare but significant examples of entanglements of endangered whales and sea turtles. Many of these species face cumulative threats, including fisheries bycatch, to which mussel farming may contribute additional risk. Mussel farming currently occurs mainly in shallow coastal waters, where fewer interactions with endangered whale species would be expected. For these reasons, the precautionary final numerical score for Criterion 9X – Wildlife Mortalities is -5 out of -10.

Criterion 10X: Escape of secondary species

Impact, unit of sustainability and principle

- Impact: movement of live animals resulting in introduction of unintended species
- Sustainability unit: wild native populations
- Principle: avoiding the potential for the accidental introduction of secondary species or pathogens resulting from the shipment of animals.

This is an “exceptional” criterion that may not apply in many circumstances. It generates a negative score that is deducted from the overall final score.

Criterion 10X Summary

Escape of secondary species parameters		Score	
F10Xa International or trans-waterbody live animal shipments (%)		8	
F10Xb Biosecurity of source/destination		1	
C10X Escape of secondary species Final Score		**-1.80**	**GREEN**

Brief Summary
Marine mussel introductions have mainly occurred by accident, primarily through ship ballast waters, and most of these introductions occurred decades ago. Nevertheless, ongoing mussel seed transportation between water bodies does occur. In some regions, this can account for the majority of seed supply, particularly for on-bottom culture in Europe, as well as the New Zealand industry. It also occurs to a limited degree in China and Spain. However, at the global level, it is estimated that between 10-20% of mussel production is associated with mussel seed transportation across waterbodies, and results in a score of 8 out of 10 for Factor 10Xa. The rest of global production is considered to be reliant on seed collected from the same water body as the farms. Controls to prevent the introduction of secondary species into new regions include prohibitions or monitoring of seed from one area or another, but both the seed source and farms are completely open systems, which resulted in a score of 1 out for 10 for Factor 10Xb. Despite few examples pathogen introductions associated with mussel farming, significant and ongoing concerns exist with the role that mussel farming can play in increasing both the spread and impact of invasive biofouling species, which can impact the health of both farmed and wild bivalve populations. With a limited reliance on live animal movements, the final score for Criterion 10X – Escape of Unintentionally Introduced Species is -1.8 out of -10.

Justification of Rating
Bivalve aquaculture has a significant history of seed movement across international water bodies (Gallardi 2014), and thus has the potential to also transport environmentally concerning hitchhiker species. McKindsey et al (2007) identified three main classes of these hitchhikers

associated with bivalve aquaculture, including "*(1) exotic macrospecies including algae and animals; (2) exotic phytoplankton (toxic and otherwise); and (3) exotic disease-causing organisms*".

Gallardi (2014) and McKindsey et al. (2007) summarized a large number of examples of introductions of these classes of hitchhikers, although most were associated with the movement of oysters rather than mussels for aquaculture. Specific mussel aquaculture examples highlighted in McKindsey et al. (2007) include the potential introduction and spread of invasive tunicates in PEI, and evidence that viable algal material from a toxic species has been found in mussel feces, suggesting they could be transported within the mussels themselves, should they be transported.

The movement of mussel seed from one region to another can be a significant pathway to introduce hitchhiker species. This type of activity is common in on-bottom culture in the Netherlands, Germany, UK, and Ireland for blue mussels (*M. edulis*) (Kamermans and Capelle 2019), where seed mussels are transported from collection sites to leased shallow mudflats (Kamermans and Capelle 2019). A relevant example of occurred in North Wales, where the transfer of mussel seed introduced invasive slipper limpets (*Crepidula fornicata*) to the Menai Strait (although they were successfully eradicated by dredging out the mussel seed and the limpets themselves) (Quinn, 2018). Gillardi (2014) found no evidence of significant pathogen introductions associated with mussel farming (Gillardi 2014), although they may be a vector and sink of pathogens that could affect other species, such as oysters (Castinel et al. 2019).

In addition to the initial introduction of hitchhikers, there is documented evidence that bivalve aquaculture infrastructure or practices can act as reservoirs of invasive species and facilitate their further spread (Fitridge et al. 2012). For example, the mechanical removal of biofouling species from mussel farms and the release of the removed material into the marine environment may facilitate the further spread of invasive biofouling species (Fitridge et al. 2012). A prime example is in PEI, where four species of invasive tunicates have invaded mussel farming gear, causing excessive fouling and impacts to mussel health. One of these, vase tunicates (*Ciona intestinalis*), has the ability to change the composition of natural sessile communities by reducing local species diversity (Fitridge et al. 2002). According to research summarized in McKindsey et al. (2007), these tunicates have become more invasive and impactful in areas of mussel aquaculture but not elsewhere where their introduction is more benign. The authors suggest that this may be a function of mussel aquaculture occurring near more eutrophic or stressed habitats that create the opportunity for the tunicates to be more competitive. Either way, it suggests that mussel farming can play a role in amplifying the spread and negative impacts of invasive biofouling species.

Factor 10Xa International or trans-waterbody live animal shipments

Most initial mussel introductions appear to have been accidental, resulting from transmission via ballast water or from growth on ship hulls (Branch and Stefani 2006), and long ago (before the 1970's), meaning that the introduction of hitchhikers would also have been accidental and initially introduced at the same time.

The vast majority of global mussel farming is reliant on seed obtained from the wild in collectors, which could be supplied from local spawning stock, as is the case in PEI (PEIMussels 2019). Canada has introduced seed movement controls between and within provinces to try to minimize the further spread of invasive biofouling species (FOC 2008). In Chile, mussels grow along the entire coast (Gonzalez-Poblete et al. 2018), meaning that seed collectors could likely be successfully deployed near farming locations. There is insufficient information to assess mussel seed transportation in China. Seed sources include both hatchery raised and wild collection, with an unknown percentage from each.

It is evident from Zhang et al. (2019) that *M. coruscus* broodstock are being collected from the wild to be spawned in a hatchery, so at least some of this seed would be expected to have been transported. It is assumed that the rest of Chinese production is using locally collected seed for grow out.

Bottom culture in Netherlands, Germany, UK, and Ireland is reliant on mussel seed transportation. In New Zealand, around 70-80% of the seed used in mussel farming is collected from seaweed washed up on Ninety Mile Beach 70-80% (Jeffs et al. 2018), with the SPATnz selective breeding program supplies an additional 5-10% (O'Connell 2019). Mussel seed is then transported all around the country (Castinel et al. 2019). Zhang et al. (2019) identified that *M. coruscus* broodstock were being collected from the wild and spawned in a hatchery, which may mean at least 8% of Chinese mussel production (over 900,000mt in 2017 (FIGIS 2019)) could require trans-waterbody live animal movement. According to Muelbauer at al. (2014), in Spain, mussel seed are obtained from collectors in the main production region of Galicia, but these spat are also "*transported to Menorca and Mallorca in the Mediterranea*n"; Spain produced approximately 250,000 mt of mussels in 2017 (FIGIS 2019), so it's possible that some of this total is reliant on trans-waterbody live animal movements. However, the combined production from Chinese *M. coruscus* farming, New Zealand, and European bottom, as well as a portion of Spanish production, that is reliant on trans-waterbody animal movements is unlikely to exceed 20% of global farmed mussel production (see figure 5). As such, it is assumed that between 10-20% of production is considered to be reliant on international/trans-waterbody animal movements, the score for Factor 10Xa is 8 out of 10.

Factor 10Xb Biosecurity of source/destination

Spat collection using dredges or collecting systems, as well as mussel grow-out systems, are entirely open to the marine environment. Biosecurity options to limit the introduction of secondary species would likely be limited to controls on where and how seed can be transported between areas. Examples of these controls exist, for example, PEI has rules that prohibit the movement of mussel spat collected from areas with invasive tunicates to areas without them, in an effort to slow their spread and with some success (FOC 2010). In the Netherlands, wild harvested mussel seed can be imported from other locations but this is regulated using seed source locations or through a monitoring system, with controls particularly focused on preventing introductions into the Wadden Sea (Muehlbauer et al. 2014).

However, in New Zealand, mussel seed can be transported without a quarantine period (Castinel et al. 2019).

As stated above, mussel seed transportation between water bodies is estimated to account for between 10-20% of global production, with the rest of production using locally harvested/collected seed. With limited evidence of control systems to prevent secondary species transfers from one area to another but the use of completely open seed collection and grow-out systems, the biosecurity score for the source of animal movements is scored at one out of ten, while the biosecurity of the destination (grow-out farms) is considered to be zero out of ten. Therefore, the score for Factor 10Xb is 1 out of 10 (the higher of the two scores).

Conclusions and Final Score

Marine mussel introductions have mainly occurred by accident, primarily through ship ballast waters, and most of these introductions occurred decades ago. Nevertheless, ongoing mussel seed transportation between water bodies does occur. In some regions, this can account for the majority of seed supply, particularly for on-bottom culture in Europe, as well as the New Zealand industry. It also occurs to a limited degree in China and Spain. However, at the global level, it is estimated that between 10-20% of mussel production is associated with mussel seed transportation across waterbodies, and resulted in a score of 8 out of 10 for Factor 10Xa. The rest of global production is considered to be reliant on seed collected from the same water body as the farms. Controls to prevent the introduction of secondary species into new regions include prohibitions or monitoring of seed from one area or another, but both the seed source and farms are completely open systems, which resulted in a score of 1 out for 10 for Factor 10Xb. Despite few examples pathogen introductions associated with mussel farming, significant and ongoing concerns exist with the role that mussel farming can play in increasing both the spread and impact of invasive biofouling species, which can impact the health of both farmed and wild bivalve populations. The final numerical score for Criterion 10X – Escape of Unintentionally Introduced Species is -1.8 out of -10.

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Scientific review does not constitute an endorsement of the Seafood Watch® program, or its seafood recommendations, on the part of the reviewing scientists. Seafood Watch® is solely responsible for the conclusions reached in this report.

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Appendix 1 - Data points and all scoring calculations

This is a condensed version of the standard and scoring sheet to provide access to all data points and calculations. See the Seafood Watch Aquaculture Standard document for a full explanation of the standards, calculations and scores. Yellow cells represent data entry points.

Criterion 1: Data quality and availability

Data Category	Data Quality (0-10)
Industry or production statistics	5
Management	5
Effluent	10
Habitats	7.5
Chemical use	7.5
Feed	10
Escapes	7.5
Disease	7.5
Source of stock	5
Predators and wildlife	5
Unintentional introduction	7.5
Other – (e.g. GHG emissions)	n/a
Total	**77.5**

C1 Data Final Score (0-10)	**7.05**	**GREEN**

Criterion 2: Effluents

Effluent Evidence-Based Assessment

C2 Effluent Final Score (0-10)	**10**	**GREEN**
Critical?	NO	

Criterion 3: Habitat

Factor 3.1. Habitat conversion and function

F3.1 Score (0-10)	8

Factor 3.2 – Management of farm-level and cumulative habitat impacts

3.2a Content of habitat management measure	3
3.2b Enforcement of habitat management measures	3
3.2 Habitat management effectiveness	**3.6**

C3 Habitat Final Score (0-10)	**6.53**	**YELLOW**
Critical?	NO	

Criterion 4: Evidence or Risk of Chemical Use

Chemical Use parameters	Score	
C4 Chemical Use Score (0-10)	8	
C4 Chemical Use Final Score (0-10)	**8**	**GREEN**
Critical?	NO	

Criterion 5: Feed

Feed Final Score

C5 Feed Final Score (0-10)	**10**	**GREEN**
Critical?	**No**	

Criterion 6: Escapes

6.1a System escape Risk (0-10)	0	
6.1a Adjustment for recaptures (0-10)	0	
6.1a Escape Risk Score (0-10)	**0**	
6.2. Invasiveness score (0-10)	**8**	
C6 Escapes Final Score (0-10)	**4**	**YELLOW**
Critical?	**NO**	

Criterion 7: Diseases

Disease Evidence-based assessment (0-10)		
Disease Risk-based assessment (0-10)	0	
C7 Disease Final Score (0-10)	**8**	**GREEN**
Critical?	NO	

Criterion 8X: Source of Stock

C8X Source of stock score (0-10)	0	
C8 Source of stock Final Score (0-10)	**0**	**GREEN**
Critical?	NO	

Criterion 9X: Wildlife and predator mortalities

C9X Wildlife and Predator Score (0-10)	**-5**	
C9X Wildlife and Predator Final Score (0-10)	**-5**	**YELLOW**

Critical?	NO

Criterion 10X: Escape of unintentionally introduced species

F10Xa live animal shipments score (0-10)	8.00	
F10Xb Biosecurity of source/destination score (0-10)	1.00	
C10X Escape of unintentionally introduced species Final Score (0-10	**-1.80**	**GREEN**
Critical?	n/a	