Environmental sustainability of farmed oysters using marine on-bottom and off-bottom culture systems

Draft Assessment for Reivew

November 2025

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Species:	Oysters (*Crassostrea* spp., *Ostrea* spp., *Saccostrea* spp.)
Location:	Worldwide
Method:	On-Bottom and Off-Bottom Culture
Type:	Aquaculture
Author:	Seafood Watch
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Assessed using [Seafood Watch Aquaculture Standard v4]

Table of Contents

Draft for Review

About Monterey Bay Aquarium Seafood Watch

The mission of the Monterey Bay Aquarium is to inspire conservation of the ocean and enable a future where the ocean flourishes and people thrive in a just and equitable world. To do this, the Aquarium is focused on creating extraordinary experiences that inspire awe and wonder, championing science-based solutions, and connecting people across the planet to protect and restore the ocean. We know that healthy ocean ecosystems are critical to enabling life on Earth to exist, and that our very survival depends on them. As such, our conservation objectives are to mobilize climate action, improve the sustainability of global fisheries and aquaculture, reduce sources of plastic pollution, and restore and protect ocean wildlife and ecosystems.

The aquarium is focused on improving the sustainability of fisheries and aquaculture given the role seafood plays in providing essential nutrition for 3 billion people globally, and in supporting hundreds of millions of livelihoods. Approximately 180 million metric tons of wild and farmed seafood is harvested each year (excluding seaweeds). Unfortunately, not all current harvest practices are sustainable and poorly managed fisheries and aquaculture pose the greatest immediate threat to the health of the ocean and the economic survival and food security of billions of people.

The Seafood Watch program was started 25 years ago as a small exhibit in the Monterey Bay Aquarium highlighting better fishing practices and grew into one of the leading sources of information on seafood sustainability, harnessing the power of consumer choice to mobilize change. The program's comprehensive open-source information and public outreach raises awareness about global sustainability issues, identifies areas for improvement, recognizes and rewards best practices and empowers individuals and businesses to make informed decisions when purchasing seafood.

We define sustainable seafood as seafood from sources, whether fished or farmed, that can maintain or increase production without jeopardizing the structure and function of affected ecosystems, minimize harmful environmental impacts, assure good and fair working conditions, and support livelihoods and economic benefits throughout the entire supply chain. As one aspect of this vision, Seafood Watch has developed trusted, rigorous standards for assessing the environmental impacts of fishing and aquaculture practices worldwide. Built on a solid foundation of science and collaboration, our standards reflect our guiding principles for defining environmental sustainability in seafood.

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Seafood Watch Ratings

The Seafood Watch Standard for Aquaculture is used to produce assessments for farmed seafood resulting in a Seafood Watch rating of green, yellow, or red. Seafood Watch uses the assessment criteria to determine a final numerical score as well as numerical subscores and colors for each criterion. These scores are translated to a final Seafood Watch color rating according to the methodology described in the table below. The table also describes how Seafood Watch defines each of these categories. The narrative descriptions of each Seafood Watch rating, and the guiding principles listed below, compose the framework on which the criteria are based.

Green	Final Score ≥6.665[1] and ≤10, and no red criteria, and no critical[2] scores	Wild-caught and farm-raised seafood rated green are environmentally sustainable, well managed and caught or farmed in ways that cause little or no harm to habitats or other wildlife. These operations align with all of our guiding principles.
Yellow	Final score ≥3.335 and ≤6.664, and no more than one red criterion, and no critical scores.	Wild-caught and farm-raised seafood rated yellow cannot be considered fully environmentally sustainable at this time. They align with most of our guiding principles, but there is either one conservation concern needing substantial improvement, or there is significant uncertainty associated with the impacts of the fishery or aquaculture operations.
Red	Final Score ≥0 and ≤3.334, or two or more red criteria, or one or more critical scores	Wild-caught and farm-raised seafood rated red are caught or farmed in ways that have a high risk of causing significant harm to the environment. They do not align with our guiding principles and are considered environmentally unsustainable due to either a critical conservation concern, or multiple areas where improvement is needed.

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Recommended Citation: Seafood Watch (2025) Environmental sustainability of Global Oysters using marine bottom and off-bottom culture systems. Monterey Bay Aquarium.

Guiding Principles

[1] Each criterion is scored from 1 to 10 based on sub-factor scores. Criteria scoring ≤3.334 are considered red criteria.

[2] Very severe conservation concerns receive critical scores, which result in a red rating.

Seafood Watch® defines "sustainable seafood" as seafood from sources, whether fished or farmed, that can maintain or increase production without jeopardizing the structure and function of affected ecosystems.

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:

- **Criterion 1 - Data: 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.

- **Criterion 2 - Effluent: 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.

- **Criterion 3 - Habitat: 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.

- **Criterion 4 - Chemicals: 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.

- **Criterion 5 - Feed: 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.

- **Criterion 6 - Escapes: 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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- **Criterion 7 - Disease: 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.

- **Criterion 8X - Source of Stock: 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.

- **Criterion 9X - Wildlife Mortalities: 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.

- **Criterion 10X - Introductions: 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.

Ratings scores range from zero to ten where zero indicates very poor performance and ten indicates the aquaculture operations have no significant impact.

Final Score = sum of C1-C7, adjusted by C8X-C10X, divided by 7

Green = Final Score ≥6.665, and no red criteria, and no critical scores

Yellow = Final score ≥3.335 and ≤6.664, and/or one red criterion, and no critical scores

Red = Final Score ≤3.334, or more than one red criterion, or one or more critical scores

Final Ratings

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Rating Details	**Species:** Oysters (*Crassostrea* spp., *Ostrea* spp., *Saccostrea* spp.) **Location:** Worldwide **Method:** Bottom and Off-Bottom Culture **Quantity:** 7,514,005 mt (2023)
Criterion 1 **Data**	7.7
Criterion 2 **Effluent**	8.0
Criterion 3 **Habitat**	8.1
Criterion 4 **Chemicals**	9.0
Criterion 5 **Feed**	10.0
Criterion 6 **Escapes**	4.0
Criterion 7 **Disease**	4.0
Criterion 8X **Source of stock**	0.0
Criterion 9X **Wildlife mortalities**	-2.0
Criterion 10X **Introductions**	-2.0
Rating	**GREEN** **6.69**

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Summary

The final numerical score for global farmed oysters is 6.69 out of 10, which is in the green range. There are no red or critical criteria. The overall rating for global farmed oysters is a green Best Choice recommendation.

This Seafood Watch assessment involves ten 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.

The species considered here are oysters, farmed worldwide using both on-bottom and off-bottom production systems. In 2023, global oyster aquaculture production reached 7.5 million mt across 39 countries. Production is highly concentrated in Asia, with China alone contributing 89% (6.7 million mt),

followed by South Korea (4%) and Japan (2%). The United States (2%) and France (1%) ranked fourth and fifth, respectively.

Because of China's dominance, the species it farms largely define the global production landscape. The most important is *Crassostrea angulata*, which represented about 41% of China's oyster output in 2018—equivalent to at least 35% of world production. Next is *C. hongkongensis* (35% of China; ~30% globally), followed by *C. gigas* (24% of China; ~17% globally). Outside of China, *C. gigas* is the dominant species in other major producing regions, including South Korea, Japan, and France. Other species such as *C. iredalei* and *C. virginica* are reported in smaller volumes outside of China, but the majority of FAO production remains aggregated under the broad categories *Crassostrea (spp.)* and Ostreidae.

Global oyster trade remains relatively small compared to production, totaling ~85,000 mt in 2023, with over 181 importing countries. The leading importers were India, the United States, and Vietnam.

Data
Information on production practices and ecological effects is generally available for dominant producing regions, though gaps remain for disease transmission and secondary species introductions. Criterion 1 score: 7.7 out of 10.

Effluent
Oysters do not require external feed, limiting nutrient-related concerns. Filtration can reduce water column nutrients, while biodeposits can elevate localized oxygen demand and affect sediments, particularly in poorly flushed sites. Effects are typically local, seasonal, and reversible after production ceases and do not appear to pose significant cumulative risks at the waterbody or regional scale. Criterion 2 score: 8 out of 10.

Habitat
Oyster farms operate mainly in tidal, intertidal, and nearshore subtidal coastal areas, which are considered to be high-value habitats. Gear configuration and harvest methods can alter fine-scale hydrodynamics or disturb benthos, but overall habitat impacts are generally low, and farms can provide habitat structure and shoreline benefits. Factor 3.1 score: 9 out of 10.

Siting and licensing frameworks are present in many regions, though enforcement strength varies by country and farm context. Factor 3.2 score: 6.4 out of 10. Combined Criterion 3 score: 8.1 out of 10

Chemical Use
Oyster farming does not typically employ the use of chemicals. Growout commonly relies on physical fouling control, instead of chemical methods. Hatcheries may use antibiotics, but growout treatments are not typical. Given the global scope of this report, there may be some circumstances in which chemicals are used for fouling, disease, or predation control, but the majority of evidence suggests chemicals used, if any, have no impact on non-target organisms. Criterion 4 score: 9 out of 10.

Feed
Oysters feed on naturally occurring seston. In nutrient-enriched systems, filtration can improve water quality; in low-nutrient settings, localized effects may occur but are context dependent and usually temporary. Net ecological outcomes are positive given no external feed inputs. Criterion 5 score: 10 out of 10.

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Escapes

Open growout and broadcast spawning create a high escape potential. Triploid spat reduces fecundity and is widely used in several countries, although adoption is uneven. Factor 6.1 (escape risk) score: 0 out of 10.

Oysters can be highly invasive due to their biological traits. However, considering historical establishment patterns, competition risks, limited genetic introgression evidence, and high post-escape mortality, Factor 6.2 score: 7 out of 10. Combined Criterion 6 score: 4 out of 10.

Disease, pathogen and parasite interactions

Disease challenges are common in farmed oysters at all stages of production and result in potential impacts on wild populations through pathogen amplification, retransmission, or increased virulence. Biosecurity measures and selective breeding are in place, but transmission dynamics between farms and impacts on wild species are not fully understood. Ultimately, farms experience disease challenges and are fully open to the introduction and discharge of pathogens. Criterion 7 score: 4 out of 10.

Source of Stock

Spat is sourced via passive collection or hatcheries. When wild broodstock are used, quantities are low relative to fecundity. Conservation risk is low. Criterion 8X deduction: 0 out of -10.

Wildlife and predator mortalities

Predator interactions are managed primarily with non-lethal methods. Serious wildlife impacts are uncommon, and population-level risks appear low. Criterion 9X deduction: -2 out of -10.

Escape of secondary species

Historic transfers sometimes moved hitchhiking organisms and pathogens. Since 2010, major new impacts have not been reported. Today most movements involve spat from hatcheries to farms, with varied biosecurity implementation across regions; however, trade and movement of oysters and spat appear to be generally regulated at state, national and international levels. Criterion 10X deduction: -2 out of -10.

Summary

The final numerical score for global farmed oysters is 6.69 out of 10, which is in the green range. There are no red or critical criteria. The overall rating for global farmed oysters is a green Best Choice recommendation.

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Introduction

Scope of the analysis and ensuing rating

Species

Crassostrea spp., *Ostrea* spp., *Saccostrea* spp.

Geographic Coverage

Worldwide

Production Method(s)

On-bottom and Off-bottom culture (suspended or floating systems, longlines, racks/bags)

Species Overview

Brief overview of the species

Oysters are bivalve mollusks, part of the shellfish family *Ostreidae*, in the phylum Mollusca. They possess large gills located within the mantle cavity, which are utilized for respiration and filter feeding. As water flows through the gills, they capture organic particles, particularly phytoplankton, which are then transported to the oyster's mouth for ingestion (NOAA, 2024; Laing & Bopp, 2019).

Oysters are often described as ecosystem engineers because they form reef structures which serve as habitat for other species in coastal estuarine environments (Litembu et al, 2023). Their life cycle begins with free-swimming larvae that drift for about two weeks, then develop a foot and an eyespot, become settlement-competent, attach to hard substrate, and metamorphose into the sessile spat stage (Figure 1). Once attached to a substrate, the juvenile oyster, or "spat," secretes a calcium-based adhesive to secure itself, maturing into an adult. Oysters are hermaphrodites, reproducing through broadcast spawning, and their sex can change based on environmental conditions and life stage. For example, when conditions worsen (higher temperatures, less food), female prevalence generally decreases (pers. comm., Jorge Chaves, CIBNOR, September 2025). Spawning is often triggered by temperature fluctuations (NOAA, 2024; Laing & Bopp, 2019).

Oysters exhibit a moderate growth rate and high reproductive rates, with the time required to reach market size varying significantly based on environmental factors such as temperature and food availability. For example, Pacific oysters generally reach market size (70–100 g, shell-on) in 18–30 months, whereas other oyster species grown in tropical or subtropical waters can do so in 6–12 months (pers. comm., Jorge Chaves, CIBNOR, September 2025; NOAA, 2024; Mercer et al., 2024). Nutrient-dense and rich in protein, oysters are a low-fat seafood option with beneficial omega-3 fatty acids. Commercially, oysters are valued for their ability to survive extended periods out of water at low temperatures, facilitating transport, storage, and sale (Laing & Bopp, 2019). Generally, oyster aquaculture is perceived as environmentally sustainable due to its low-trophic nature and minimal feed requirements, especially when compared to cultured finfish species (Litembu et al., 2023).

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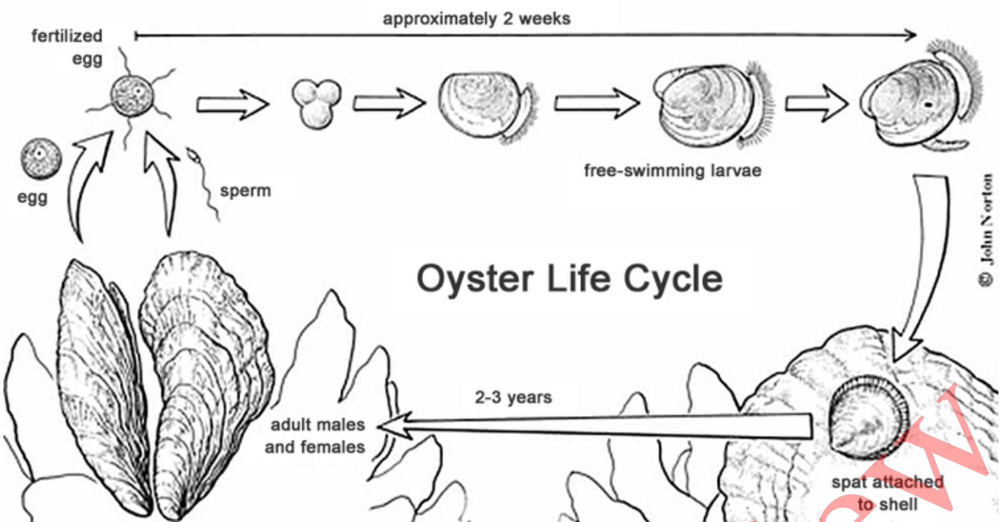

Figure 1. Oyster lifecycle: adult oysters spawn, releasing eggs or sperm into the water column; fertilized eggs become free-swimming larvae; larvae develop a foot and attach to the substrate where they remain as they grow and mature. Image from: https://www.pangeashellfish.com/blog/oyster-life-cycle-on-farm

Production system

Globally, oyster farming utilizes two primary production systems: on-bottom and off-bottom. The choice between these systems depends on various environmental and site-specific factors, including water depth, tidal action, natural food availability, broodstock or spat supply, water quality, predator presence, and sediment stability. Market and regulatory dynamics play a crucial role in determining the most suitable production system (Litembu et al., 2023; Webster et al., 2019). Additionally, oyster farms range in scale from small, family-run operations, which are often organized as cooperatives, to large commercial enterprises employing a diverse array of production system infrastructures (See introduction for more details on types of production systems; Yu et al., 2023; Webster et al., 2019; Doiron, 2008 Mercer et al., 2024; Strand et al., 2022). A brief description of oyster production systems is provided below, with further details on their regional prevalence outlined in the following Production Statistics section. This Seafood Watch assessment considers both on-bottom and off-bottom systems.

Recruitment

Spat collection occurs through two methods: passive collection via natural larva settlement or through hatchery and nursery production (Mercer et al., 2024; Laing & Bopp, 2019). Passive collection techniques employ various settlement materials, including rope, drainpipes, broken tiles, bamboo, plastic tubes, and oyster or scallop shells (collectively referred to as culch) placed in bags or suspended on wires (Laing & Bopp, 2019; Queensland Government, 2018; Doiron, 2008).

In areas where wild spat supply is inconsistent or insufficient, land-based hatcheries serve as an alternative, enabling the production of larger quantities of spat and ensuring availability year-round (Mercer et al., 2024; Doiron, 2008). Additionally, hatcheries offer a controlled environment that often enhances spat health, facilitates the cultivation of non-native species, and supports production in regions previously affected by disease outbreaks (Mercer et al., 2024; Element Seafood, 2013). Ultimately, given the global scope of this assessment, and the perceived regional variations in practices, estimating the proportion of global oyster production that comes from wild-collected versus hatchery-raised stocks is challenging. No published figures or estimates are readily available. However, according to recent consultations with industry experts, and the available peer-reviewed literature, hatchery production is

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now considered the predominant method globally (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025; pers. comm. Wenbo Zhang, Shanghai Ocean University, March 2025; pers. comm., B. Rheault, 2019; Yu et al., 2023; Ying et al., 2021). This is evident with Pacific oyster, which has been introduced in many countries, and where wild populations are absent, making passive spat collection impossible, and leaving hatchery-produced spat as the only source. (pers. comm., Jorge Chaves, CIBNOR, September 2025).

Growout

Oysters have been cultured for thousands of years in open marine and estuarine environments using a variety of techniques, which include plastic or wire-mesh containers, cages, trays, and bags, deployed on-bottom or from floating or fixed structures (Webster et al., 2019; Doiron, 2008). Figure 2 outlines different cage configurations used for oyster grow-out in both on-bottom and off-bottom culture systems (Cerino, 2016). All of these production methods are covered in this Seafood Watch assessment.

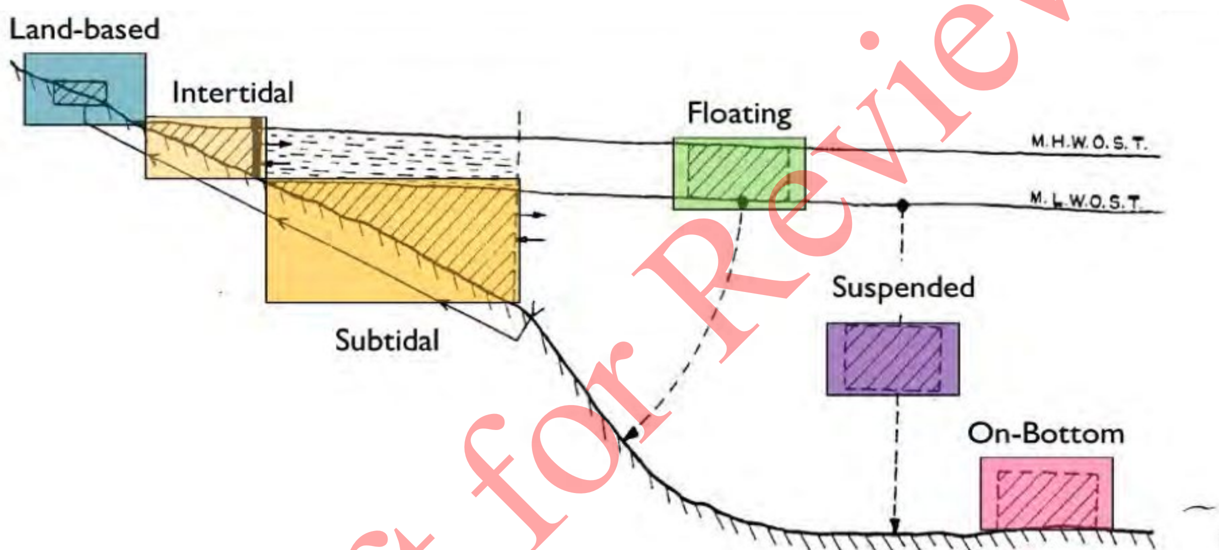

Figure 2. Examples of different zones in which oyster aquaculture growout methods can be located: Land-based, Intertidal, Subtidal, Off-Bottom (Floating, Suspended) and On-Bottom methods are all depicted (Taken from Cerino, 2016).

Oysters can be cultivated directly on the intertidal and subtidal substrates using on-bottom culture systems, which are the most extensive and inexpensive form of oyster farming, often referred to as sea-ranching (Mercer et al., 2024; Strand et al., 2022). This on-bottom culture method (Figure 3a) involves stocking young oysters over a flat, expansive seabed, where they either grow to commercial size (1–2 years) or are later dredged and relocated from high-density settlement areas to intertidal or subtidal culture plots. This relocation allows for lower stocking densities, promoting better growth and fattening, while also helping to control predation.

Before stocking spat, sites are typically dredged to remove stones, predators, and competitors, with the aim of creating a more uniform substrate. To prevent losses from strong currents and predators, growers often enclose spat settlement areas with protective structures such as bags or fences (see Figure 3b) (Strand et al., 2022; Pangea Shellfish Company, 2015; Doiron, 2008; Garrido-Handog, 1990; Héral & Deslous-Paoli, 1991).

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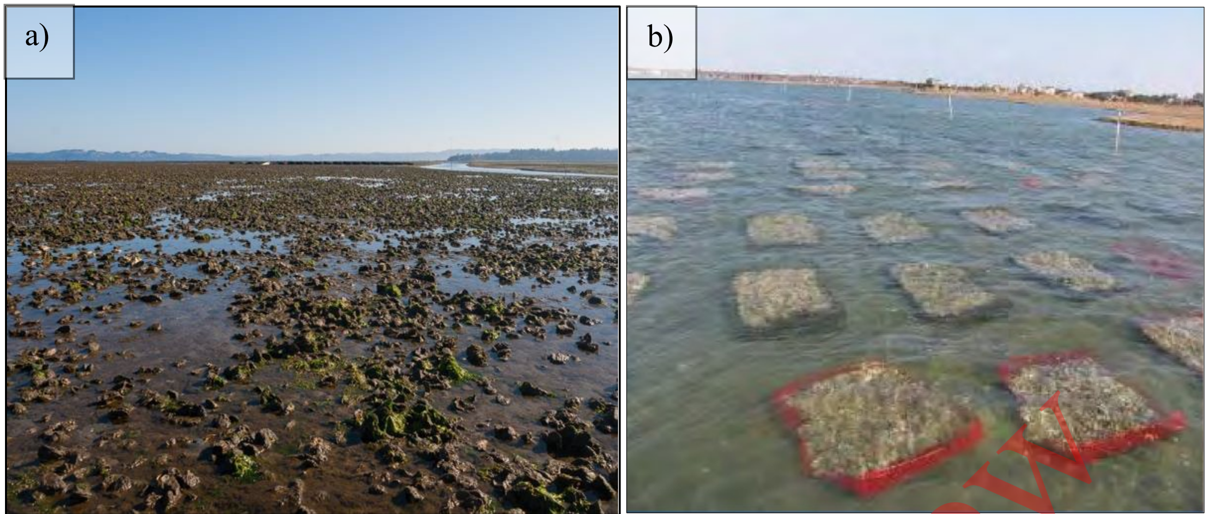

Figure 3. Examples of on-bottom oyster cages. Oyster cages or bags are placed directly on the seabed to prevent predation and sinking into the substrate (Taken from Strand, 2022; Cerino, 2016).

In areas lacking suitable substrate and wave action, or where nearshore space is limited, suspended (off-bottom) oyster culture methods, such as rafts, racks, and stakes, are employed to expand bay production capacities (Figures 4 and 5) (Litembu et al., 2023; Lu, 2015). In intertidal or subtidal longline culture, oysters are contained in mesh cages, suspended from a longline that can be hauled up (or accessed from the shore intertidally) for maintenance or harvest when they reach market size (Figure 4). In bag culture, oysters are housed in bags made of various materials, which are attached to buoys that allow movement with the tide and help reduce fouling, or placed on racks (with the bags routinely turned to reduce fouling). Cages and bags in intertidal areas are typically deployed so that oysters are only exposed to air for short periods during low tide. Stake culture, often used in shallow lagoons unsuitable for raft and rack methods, holds oysters in a vertical position, with the stakes sometimes serving as spat collectors themselves (Litembu et al., 2023; Strand et al., 2022; Lu, 2015; Doiron, 2008; Garrido-Handog, 1990). Additionally, suspended systems in subtidal areas are expected to remain the preferred production method, as their continuous feeding ability can yield higher-quality oysters with better meat-to-shell ratios (Mercer et al., 2024; Botta et al., 2020).

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Figure 4. An adjustable suspended longline culture system. Baskets hanging from lines are adjusted vertically in and out of the water column to control the amount of water they are exposed to, which is a tactic used to reduce biofouling. This is one method of off-bottom culture (BST Oyster Supplies[3], accessed February 2025).

Figure 5. An off-bottom oyster culture method using floating mesh bags (left) and oyster baskets suspended from an above water mounted structure (right) in Sweden farm. Bags can be flipped up onto floats occasionally to control for biofouling through periodic drying. Floating systems are considered off-bottom culture methods ((pers. comm., Asa Strand, Marin naturvårdsförvaltare, 2025; Lu, 2015).

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Production Statistics

[3] https://bstoysters.com/gallery/

In 2023, global oyster production from aquaculture reached 7,514,005 mt, and was produced in 39 countries (FishStat, 2024). The top three producers, all in Asia, accounted for over 94% of total production: China led with 6,671,199 mt (89%), followed by the Republic of Korea with 310,753 mt (4%), and Japan with 146,312 mt (2%). The United States ranked fourth, producing 155,516 mt (~2%), while France was the fifth-largest producer, contributing 90,430 mt (~1%). While the top ten oyster-producing countries accounted for 99.07% of global production in 2023, oysters are cultivated in a total of 39 countries worldwide (FishStat, 2024). Over the past five years, global farmed oyster production has grown at an average annual rate of 4.5%, according to FAO statistics.

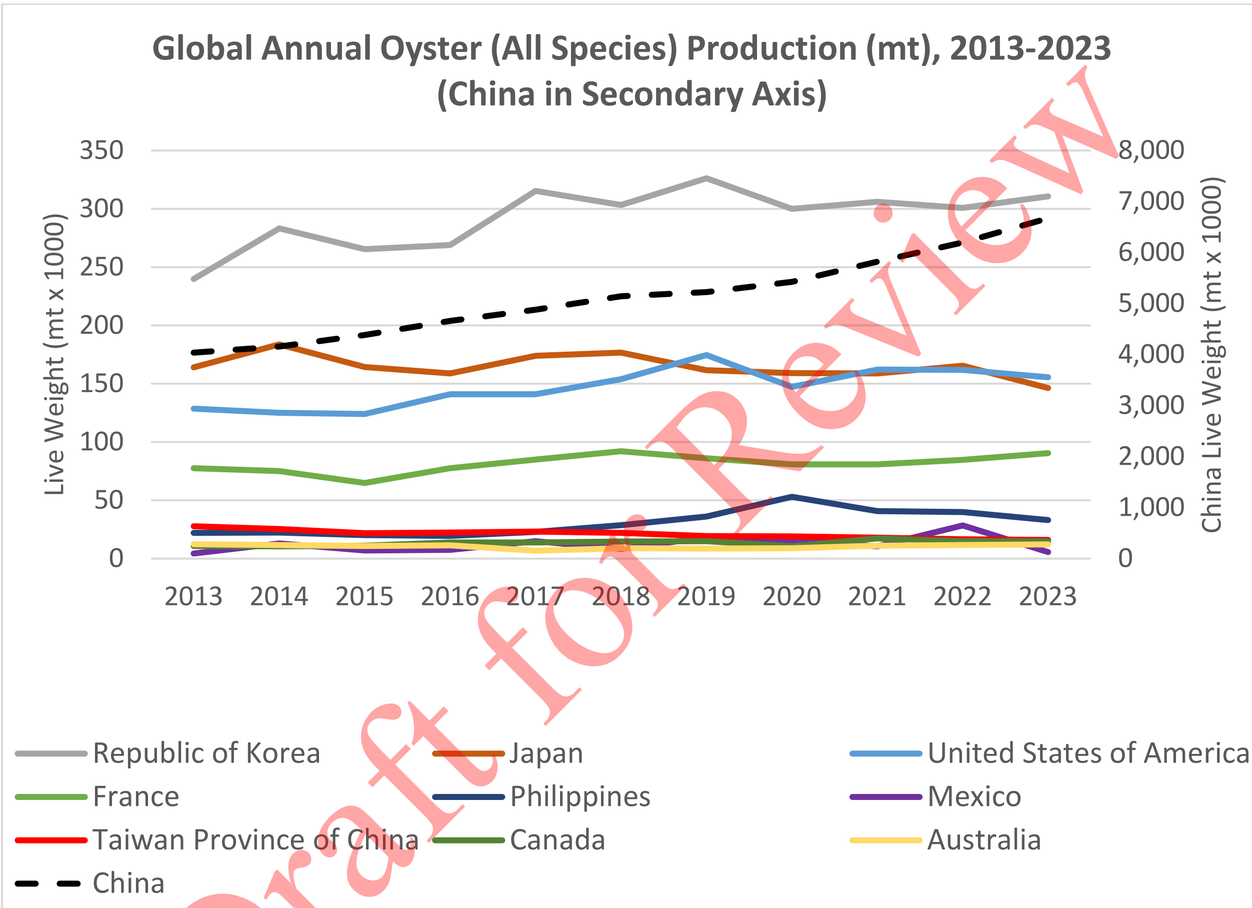

Figure 6. Top 10 countries' global production by weight. China's output (i.e., black line) is included in the secondary axis.

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While numerous oyster species are farmed worldwide for human consumption, global production is heavily concentrated among a few key species. FAO's production statistics, report 18 oyster species under the Aquatic Sciences and Fisheries Information System, but over 99% of the total farmed harvest comes from just five categories (see Table 1). The FAO reports species-specific production data for three farmed species including, *Crassostrea gigas* (Pacific oyster), *Crassostrea iredalei* (slipper cupped oyster), and *Crassostrea virginica* (Eastern oyster). However, the majority of the FAO's reported farmed oyster production (i.e., approximately 88.3%) is attributed to the broader categories of *Crassostrea* (spp.) and *Ostreidae* (family), which encompass a variety of species under these classifications. The aggregation of oyster categories likely stems from the use of multiple common names for a single species. For example, *C. gigas* is referred to as Pacific, Japanese, cupped, or giant oyster, leading to inconsistencies in FAO production reports, where multiple cupped oyster species may be grouped together (Martinez-Garcia et al., 2021).

Given China's dominant role in global oyster farming (~89%), the species it cultivates are likely to have a significant role on worldwide oyster production. For instance, while *Crassostrea angulata* and *C. gigas* share a close relationship and are considered sister species due to their ability to hybridize successfully, *C. angulata* is the predominant species farmed in China, accounting for 41.2% (2,126,662 mt) of the country's total oyster production in 2018, equivalent to at least 35.3% of global oyster production (FishStat, 2024; Peng et al., 2021). *Crassostrea hongkongensis* (Hong Kong oyster) contributed 34.7% of China's total oyster production in 2018, representing at least 29.7% of global production. The third most produced species in China is *C. gigas*, which made up 24.2% of the country's output in 2018 (equivalent to 1,249,156 mt). However, estimating its global production contribution is challenging, as it may be double counted when considering both China's reported output and FAO's global statistics for this species (FishStat, 2024; Peng et al., 2021; Ying et al., 2021; Botta et al., 2020).

Table 1. Global farmed oyster production by species in 2023 (FishStat, 2025).

Species	Quantity (mt)	% of Total Production
***Crassostrea* spp.**	6,705,610	89.2
C. gigas	530,648	7.1
C. virginica	128,764	1.7
C. iredalei	90,395	1.2
***Ostreidae* (family, not elsewhere included)**	38,092	0.1
Total	7,514,005	99.73

<u>China:</u>
Since the mid-20th century, oyster aquaculture outside China has experienced minimal growth, while China's industry has expanded significantly, representing 89% of global production in 2023 and maintaining an average annual growth rate of 5.4% from 2018 to 2023 (FishStat, 2024; Yu et al., 2023). While it appears that Chinese production of oysters consists mainly of *Crassostrea hongkongensis* predominantly cultivated in the southern regions (Fujian, Guangdong, Hainan, and Guangxi), *C. angulata* in central areas (Zhejiang, Fujian, and Taiwan), and *C. gigas* in the northern provinces (Liaoning, Hebei, Shandong, and Jiangsu); several other species are produced on a smaller scale, including *C. ariakensis*, *C. plicatula, Ostrea denselamellosa, C. rivularis, C. sikamea,* and *Pinctada martensii* (FishStat, 2024; Peng et al., 2021; Yu et al., 2023; Botta et al., 2020; Mao et al., 2019).

Oyster farming methods in China also vary regionally, encompassing raft and rack systems, intertidal longlines, floating baskets, stake planting, and on-bottom culture. In central Zhanjiang, the most widely used production system is suspended raft and rack culture, adopted by 41.9% of farmers (848 individuals). On-bottom culture is practiced by 36.76% (744 farmers), followed by 16.25% of intertidal longlines (329 farmers), and 5.09% of producers use floating baskets (103 farmers) (Yu et al., 2023). In the autonomous region - Guangxi, mostly off-bottom methods are used, including raft and rack hanging, and intertidal stake planting. Raft hanging is most prevalent in Qinzhou and Fangchenggang, where calm waters and lower salinity create favorable conditions. In Beihai, intertidal stake planting is the dominant method due to stronger currents. The oyster industry in Guangxi remains predominantly traditional and small-scale farming (Ying et al., 2021).

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South Korea:

In 2023, South Korea produced 310,753 mt of oysters, accounting for 4.14% of global production (FishStat, 2024). According to FAO data, the country's oyster production has remained relatively stable over the past decade, with an average annual rate of -0.11% from 2018 to 2023. Although 14 native oyster species exist in South Korea, and several are considered potential candidates for aquaculture, *C. gigas* (Pacific oyster) appears to be the only species cultivated on a commercial scale (FAO, 2023; Botta et al., 2020; Choi, 2008). While wild native oysters are harvested to some extent along the western coast, most cultured oyster production occurs in small bays along the south coast, where *C. gigas* is farmed using the suspended longline system (Choi, 2008). Since South Korea's oyster production plateaued in the 1990s, the industry is expected to remain stagnant, as further expansion may be constrained by environmental limitations (Botta et al., 2020).

Japan:

In 2023, Japan produced 146,312 mt of oysters, representing 1.95% of global production (FishStat, 2024). Japan has a long history of oyster farming, dating back to the mid-16th century (FAO, 2025b). Approximately 60% of the country's total production is concentrated in Hiroshima Bay, likely due to its nutrient-rich, phytoplankton-abundant waters, enclosed geography that retains nutrients, and calm waves with moderate tides, all of which create optimal conditions for oyster growth (ISE Hiroshima Sodachi Co., Ltd. [4], 2024; Wahyudin, 2020). In addition to Hiroshima, smaller-scale oyster production occurs in Iwate, Miyagi, Niigata, Mie, and Okayama prefectures (Japan Atlas[5], 2024).

The primary cultivated species is the native *Crassostrea gigas*, with *C. nippona* (Iwagaki oyster) produced in smaller quantities during the summer (Botta et al., 2020; Little Creek Oyster Farm, 2016; FAO, 2018a). Oyster farming in Japan primarily follows a two-stage process: larvae are first placed on tidal flats with shelves that emerge at low tide, allowing attachment. Once settled, the attached shells are transferred to suspended rafts, the dominant production system, where oysters grow for at least a year.

The 2011 earthquake and tsunami caused widespread destruction of oyster farms, prompting a rebuilding effort supported by French oyster producers and aquaculture technology (Botta et al., 2020; The Japan Times, 2019; Japan Atlas, 2019; TheFishSite.com, 2016). Production declined from 200,298 mt in 2010 to 158,925 mt in 2016 and has since remained stable (i.e., average annual growth rate of 0.49%, 2010-2022), though it has not yet recovered to pre-2010 levels (FishStat, 2024). Additionally, declining domestic production, coupled with rising consumer demand, led to a 49% increase in Japanese oyster imports in 2016 (FAO, 2016).

United States:

By the mid-19th century, oyster farming emerged as a solution to depleting natural stocks and growing market demand in the United States (Lavoie, 2005). In 2023, the U.S. produced 155,516 mt of oysters, accounting for 2.07% of global production, with an average annual growth rate of 2.17% from 2018 to 2023 (FishStat, 2024). The American cupped oyster (*C. virginica*) constituted approximately 83% of total production, while the Pacific cupped oyster (*C. gigas*) accounted for 15% (ibid.). The U.S. utilizes both on-bottom and off-bottom oyster farming methods, with on-bottom techniques accounting for most of its production, and can include directly stocking spat on seafloor, mesh bags, or rack bag systems (pers. comm., Asa Strand, Marin naturvårdsförvaltare, 2025; Botta et al., 2020). However, floating and hanging

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[4] http://matcha-jp.com/en/23337

[5] https://web-japan.org/atlas/nature/nat30.html

culture methods have seen increasing adoption (Botta et al., 2020). Most oyster operations are small, privately owned, family businesses (Pers. comm., B. Rheault, 2019).

According to the 2023 USDA Census of Aquaculture, the U.S. has 900 reported oyster farms, with 63% (565 farms) concentrated in the top five producing states: Massachusetts (21%), Washington (13%), Florida (10%), Virginia (10%), and Maine (9%). The remaining 38% are distributed across 15 other states (USDA, 2024). Additionally, Massachusetts accounts for the majority (i.e., approximately 68%) of total production by weight (Sackton, 2018). However, experts indicate that USDA-reported farm counts are underestimated, given that their organization's on-going market research suggests that there are over 1,000 oyster farms on the U.S. East Coast alone (pers. comm., Robert Rheault, ECSGA, October 2025). Although *C. virginica* represents the majority of production in terms of weight and number of farms (707 out of 900 farms), its total reported sales in 2023 were only $2,137 higher than those of *C. gigas* ($151,939 vs. $149,802). This narrow difference in revenue despite higher production suggests that *C. gigas* receives a premium price in the market (USDA, 2024).

<u>France:</u>
Oyster farming in France dates back to the 17th century, when *Crassostrea angulata* was cultivated in intertidal zones using a ranching approach. This was later followed by the 19th-century introduction of *Ostrea edulis* along the French Atlantic coast. However, the introduction of *C. gigas* between 1966 and 1970 led to its dominance in French shellfish aquaculture. By 2022 *C. gigas* accounted for over 98% of France's total 84,786 mt of oyster production, which represents 1.20% of global production (Buestel et al., 2009; FishStat, 2024). Oyster farming is concentrated in seven main regions, including Normandy, North Brittany, South Brittany, Vendée, Charente-Maritime, Arcachon, and the Mediterranean, which encompasses Thau, Leucate, and Corsica (Driver, 2018). Nearly all oysters produced in France are sold live and consumed raw (Buestel et al., 2009).

In France, approximately 65% of oyster production utilizes off-bottom culture methods, and the remaining 35% uses on-bottom culture (Botta et al., 2020; Beustel, 2009). On-bottom culture occurs in intertidal and deep-water areas, while off-bottom techniques include plastic mesh bags in the intertidal zone, a type of longline system that allows oyster bags to float, as well as suspended raft culture (pers. comm., Asa Strand, Marin Naturvårdsförvaltare, 2025; FAO, 2025; Botta et al., 2020). Oyster spat for aquaculture is sourced from both natural reefs (80-85%) and hatcheries (15-20%). Hatchery-produced spat in France are exclusively triploids. Disease outbreaks have significantly impacted natural spat collection, posing challenges to production (Botta et al., 2020).

<u>Proportion of the Industry by Production System</u>
While on-bottom systems require less initial investment, off-bottom culture methods (i.e., rafts, racks, and stakes) offer greater versatility, allowing oyster farming in areas with unsuitable substrates, limited nearshore space, or low wave action, making them ideal for expanding bay production capacities (Mercer et al., 2024; Litembu et al., 2023; Strand et al., 2022; Lu, 2015). Although the exact proportion of on-bottom versus off-bottom production in global oyster farming remains unclear, there is a growing trend toward the adoption of off-bottom systems. This shift has led to suspended, off-bottom culture becoming the dominant production method in the top five oyster-producing countries: China, South Korea, Japan, the United States, and France.

Import and Export Sources and Statistics

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In 2023, the global oyster trade reached approximately 85,000 mt, with oysters imported by over 181 countries worldwide (Volza[6], accessed in 2025; FAO, 2024). The top three importers by weight between March 2023 and February 2024 were India, the United States, and Vietnam (Volza, accessed in 2025). Although the United States remains the largest oyster market, economic uncertainty and high inflation have led to reduced consumer spending on premium seafood, negatively affecting both shrimp and oyster trade (FAO, 2024). France is the world's leading oyster exporter, shipping approximately 16,700 mt, despite ranking only fifth in total production (ibid.). France is also a major importer, with 8,000 metric tons imported in 2017 (FAO, 2018). In contrast, while China is the world's largest oyster producer, less than 1% of its farmed oysters were exported in 2016 (Botta et al., 2020). Most oysters are sold live, fresh, frozen, or dried, with canned or preserved products accounting for a small fraction of the industry (WHO, 2010).

In 2024, the United States imported 15,525 mt of oysters, of which 9,470 mt were classified as farmed, 648.3 mt were designated as wild or spat, and 5,407 mt were not differentiated (e.g., canned) (NOAA Foreign Trade, 2025; see Table 2). The top supplier to the U.S. market in 2024 was Canada, accounting for 32% of total imports by weight, followed by South Korea (26%), China (21%), Mexico (19%), and Japan (1%), with smaller quantities imported from New Zealand, Vietnam, and Italy (ibid.; see Figure 7). It is worth noting that U.S. imports from China consist of canned or frozen oysters, since live imports are not permitted (pers. comm., Robert Rheault, ECSGA, October 2025; NOAA Foreign Trade, 2025).

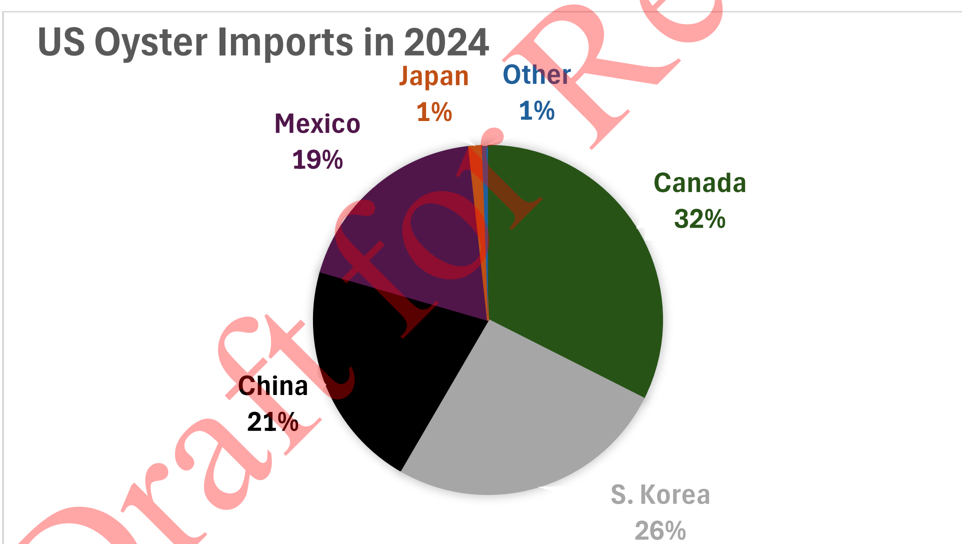

Figure 7. US oyster imports in 2024; total = 15,525 mt (NOAA Foreign Trade, 2025).

As previously noted, U.S. domestic oyster production continues to expand; however, the country maintains a significant trade deficit (FishStat, 2024). In 2024, the U.S. exported only 2,592 mt while importing over 15,000 mt (NOAA Foreign Trade, 2025; see Table 2). Canada was the largest importer of U.S. oysters, accounting for 56% of total U.S. exports (note: this is expected to change substantially in 2025[7]), followed by China-Hong Kong (14%), Singapore (6%), Taiwan (5%), and Italy (4%) (ibid.; see Figure 8). The majority (88%) of exported oysters were classified as live or fresh farmed, with smaller shares

[6] https://www.volza.com/p/oyster/import/import-in-united-states/

[7] Trade tariffs introduced in the first quarter of 2025 are projected to reduce U.S. oyster exports to Canada to near zero, per industry stakeholders (pers. comm., Robert Rheault, ECSGA, October 2025; NOAA Foreign Trade, 2025).

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exported as frozen (7%) and dried (3%). Additionally, 15 mt of oyster spat were exported (ibid.; see Table 2).

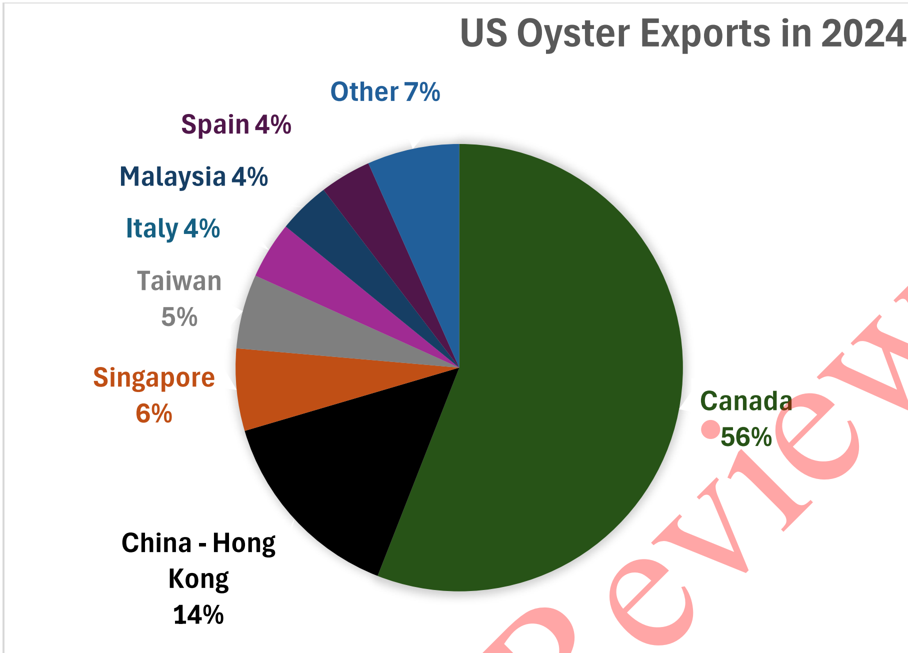

Figure 8. US oyster exports in 2024 (NOAA Foreign Trade, 2025).

Table 2. U.S. Oyster product trade by value (USD) and weight (kg) in 2024 (NOAA Foreign Trade, 2025).

Oyster product	Import		Export	
	Value (USD)	Weight (kg)	Value (USD)	Weight (kg)
Live/fresh farmed	63,484,319	7,462,900	17,238,087	2,302,302
Canned smoked	23,375,470	3,518,471	-	-
Frozen farmed	14,972,991	1,863,021	836,147	179,522
Canned/preserved	11,865,798	1,784,151	153,139	13,784
Live/fresh wild	2,429,083	233,826	-	-
Dried/salted/brine farmed	1,883,263	144,067	450,597	80,786
Dried/salted/brine wild	1,657,713	51,566	-	-
Frozen wild	1,070,213	148,173	-	-
Spat	985,071	214,718	126,747	15,626
Products prepared dinners	463,446	104,461	-	-
Total	122,187,367	15,525,354	18,804,717	2,592,020

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Common and Market Names

Farmed oysters are available on the U.S. market as "oysters." Species include:

Common Name	Scientific Name
European flat oyster	*Ostrea edulis*
Pacific oyster (also known as the Japanese oyster and Giant oyster)	*Crassostrea gigas*
Eastern oyster (also known as the Atlantic or Virginia oyster)	*Crassostrea virginica*

Sydney rock oyster	*Saccostrea glomerata (formerly S. commercialis)*
Kumamoto oyster	*Crassostrea sikamea*
Olympia Oyster (also known as the West Coast Native oyster)	*Ostrea lurida*
Angasi/ Australian flat oyster	*Ostrea angasi*

Product forms

North American and European markets prioritize whole live or raw half-shell oysters, which command higher prices, while shucked meat for canning, frozen meals, and oyster sauce are also common in Asian markets (Seafish[8] accessed August 2025; Botta et al., 2020).

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[8] https://www.seafish.org/responsible-sourcing/aquaculture-farming-seafood/species-farmed-in-aquaculture/aquaculture-profiles/oysters/sources-quantities-and-cultivation-methods

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.*

Data Category	Data Quality
Industry or production statistics	10
Management	7.5
Effluent	7.5
Habitat	7.5
Chemical use	7.5
Feed	10
Escapes	7.5
Disease	5
Source of stock	7.5
Wildlife mortalities	10
Escape of secondary species	5
Final Score (0-10)	**Green (7.7)**

Criterion 1 Summary

Data and information describing the production and ecological impacts of oyster aquaculture globally are generally available, but often generalized at the global level, and in other cases very specific to individual situations or locations. While limitations in data availability are inevitable in some regions of this global assessment, by focusing on the dominant oyster producing regions, there is good data availability for the bulk of global oyster production. The most significant information gaps concern the transmission of pathogens and unintended introductions of secondary species from cultured oysters to wild populations. The final numerical score for Criterion 1 – Data is 7.7 out of 10.

Justification of Rating

Industry or production statistics

While comprehensive data describing oyster species, production volumes, and international trade are readily available and relatively up to date, FAO-FishStatJ aggregates several species under "*Crassostrea* (spp.)". However, national production data from major producing regions often provided enough context to infer which species are farmed globally. Information describing the production systems used and locations of farms are generally found in grey literature and journal articles. These data and information may vary, but at the highest level, they generally provide country- or region-level insights. Overall

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available data are considered to give a reliable representation of the production of global oyster farming, and are considered good, scoring 10 out of 10.

Management

Information on aquaculture management is generally accessible through government resources and official websites. National, regional, and local laws, as well as industry management measures, are clearly established in the main oyster-producing regions, such as China, Europe, South Korea, Japan, and the United States. Comparative analyses of these frameworks, both within and across countries, are also available in secondary sources and published research. However, while the legal and regulatory structures are transparent, reliable information on the effectiveness of enforcement remains limited for most regions. The data are considered moderate-high and score 7.5 out of 10.

Effluent

The fundamental biology of oysters, including their filter-feeding behavior and the production of feces and pseudofeces that contribute to nutrient extraction and subsequent biodeposition, is well established. A broad body of literature also documents the effluent-related impacts of oyster farming on surrounding waterbodies, highlighting the role of oyster presence in shaping water quality and ecological processes, especially in China which is by far the largest oyster producing region globally (i.e., 88% of global production). Numerous studies have specifically examined the effects of oysters on nitrogen cycling, though conclusions remain inconsistent: while some demonstrate benefits such as enhanced denitrification and nutrient removal, others point to increased organic loading and benthic impacts, resulting in contradictory findings that are typically context-dependent to regions. Despite the extensive research base, there are no readily available national or regional monitoring records of effluent discharges from oyster farming. The data are considered moderate-high and score 7.5 out of 10 for effluent.

Habitat

There are numerous studies describing the main habitats where oyster aquaculture occurs, along with data that allow for rough estimates of the industry's global coverage. Research on ecosystem impacts from oyster farming is also widely available, although these studies are often site-specific in scope. More recent work has examined broader-scale drivers of environmental change, particularly hydrodynamic alterations, benthic impacts, and harvesting practices. Information on relevant laws and regulations is accessible for the world's principal oyster-producing regions, such as China, Europe, South Korea, Japan, and the United States. However, detailed evidence on the effectiveness of enforcement remains more limited. This results in moderate data quality and confidence, and a data score of 7.5 out of 10.

Chemical Use

Historically, the minimal use of chemical treatments (e.g., pesticides, parasiticides, disinfectants, antibiotics, antifoulants, anaesthetics and herbicides) in mollusk aquaculture is established in academic and grey literature. Communication with oyster industry stakeholders further indicates that non-chemical antifouling methods remain the most widely applied, while the few substances still in use (i.e., calcium hydroxide), are associated with minimal adverse effects on surrounding habitats and non-target species. The available research and data on chemical use are relatively accessible, comprehensive, and consistent, although the global scope of this assessment introduces some uncertainty regarding a full understanding of practices across all regions. The data score is 7.5 out of 10 for chemical use.

Feed

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Although oyster culture is extractive and does not require external feed inputs, in low-nutrient environments, excessive nutrient removal by farmed oyster feeding can suppress primary productivity. These dynamics are documented in the scientific literature, with several studies highlighting the context-dependent nature of such impacts. The data score for the Feed criterion is 10 out of 10.

Escapes
Information on oyster escape risk is readily available. A general understanding of oyster biology (e.g. broadcast spawning), and the openness of production systems, combined with research on oyster gene flow and invasiveness, is readily available in published literature. While it is well established in the literature that historic intentional introductions of non-native oysters for aquaculture have displaced native species, the extent to which such introductions still occur remains unclear. Additionally, precise numbers of escapes and scale of impact is impossible to accurately measure given the nature of the oyster life cycle, though the impacts of non-native farmed oyster escapes have also been well-documented and there is a large body of research continuing to investigate these interactions. This results in good data quality and confidence, and a score of 7.5 out of 10 for escapes.

Disease
While many general examples of disease outbreaks and their impacts on oyster farms are well documented, robust data on the specific prevalence of disease across the global oyster industry remain limited. Information on disease prevention, identification, best management practices, and biosecurity measures is available and well-documented in reports and literature. Peer-reviewed studies provide some insights into transmission pathways for certain key pathogens, such as OsHV-1, between wild and farmed oysters, but comparable information is lacking for most other relevant diseases and their associated impacts. The knowledge gaps that exist create uncertainties about key information, particularly regarding any impacts of the potential amplification and retransmission of pathogens from oyster farms to wild species. This results in moderate data quality and confidence, and a score of 5 out of 10 for disease.

Source of Stock
The range of spat sources used in oyster aquaculture is well described in peer-reviewed literature. While available studies and stakeholder communications provide a broad understanding of these sourcing practices, precise quantitative data on the relative contribution of each source remain limited. The global scope of this assessment further complicates efforts to comprehensively quantify stock origins across all producing regions. Nonetheless, the practices used to obtain spat for oyster production are well established in the literature, and none are currently considered to pose significant conservation concerns. Therefore, the data quality and availability can be considered good overall, resulting in a score of 7.5 out of 10 for source of stock.

Predator and Wildlife Mortalities
Information on the main groups of animals that may prey upon or interact with oyster farms is widely available, though the specific species involved vary regionally and are therefore more difficult to define comprehensively. Current understanding of predator and wildlife mortalities primarily comes from the application of passive exclusionary measures, which are widely used across the industry, and from global reviews in published literature. Additionally, expert communications and peer-reviewed studies provide confidence in the level of implementation of these measures, and the limited negative interactions with predators. Due to the global scale of this assessment, true mortality rates remain uncertain, but such gaps are considered minimal.
Therefore, the data score for predator and wildlife mortalities is 10 out of 10.

Draft for Review

Escape of Secondary Species
There are many historical, well-documented cases of secondary species being unintentionally introduced into new locations through oyster movements, both via aquaculture introductions and routine transfers (e.g., from hatcheries to grow-out farms). However, reliable data quantifying the extent of current international or trans-waterbody movements of live oysters are not available. Instead, current knowledge comes from indirect indicators such as production practices (e.g., reliance on wild spat collection versus hatchery-produced spat), species used, domestication status, and reported biosecurity measures. While information describing biosecurity protocols at both the source and destination of oyster movements is available, the global scope of this assessment makes it difficult to determine how consistently these best management practices are applied in practice. This results in moderate data quality and confidence, and a score of 5 out of 10 for escape of secondary species.

Conclusions and Final Score

Data and information describing the production and ecological impacts of oyster aquaculture globally are generally available, but often generalized at the global level, and in other cases very specific to individual situations or locations. While limitations in data availability are inevitable in some regions of this global assessment, by focusing on the dominant oyster producing regions, there is good data availability for the bulk of global oyster production. The most significant information gaps concern the transmission of pathogens and unintended introductions of secondary species from cultured oysters to wild populations. The final numerical score for Criterion 1 – Data is 7.7 out of 10.

Draft for Review

Criterion 2: Effluent

Impact, unit of sustainability and principle

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

Evidence-Based Assessment	
Final Score (0-10)	**Green (8.0)**
Critical?	NO

Criterion 2 Summary

In contrast to fed aquaculture systems, oyster farming does not rely on external feed or nutrient inputs, which limits many of the nutrient-related concerns typically associated with other forms of aquaculture. By filtering seston, oysters can remove nitrogen and phosphorus from the water column, often improving water quality in nutrient-enriched environments. These benefits, however, are highly context dependent and are assessed under Criterion 5 – Feed. At the same time, oyster feeding generates nutrient-rich feces and pseudofeces that settle rapidly to the seabed, introducing labile organic matter at higher rates than would occur naturally. The impacts of these particulate effluents are assessed here. This biodeposition elevates microbial activity and oxygen demand, which can create localized hypoxic or anoxic conditions, particularly in poorly flushed systems. Such oxygen depletion can shift sediments from acting as nutrient sinks to nutrient sources, releasing inorganic nitrogen and phosphorus into the water column, potentially exacerbating eutrophication and altering microbial communities. However, it is important to consider that the extent of these impacts depends on site conditions, hydrodynamics, farming intensity, and baseline nutrient loads. For instance, even in high-intensity production areas such as China, research indicates that benthic impacts from oyster biodeposition are often moderate, seasonal, or outweighed by external nutrient sources, underscoring the complexity and context-dependence of observed outcomes. Notably, these effects are usually restricted to the immediate footprint of farms, recover relatively quickly once production ceases, and do not appear to pose significant cumulative risks at the waterbody or regional scale. As such, the final score for Criterion 2 – Effluent is 8 out of 10.

Justification of Rating

As effluent data quality and availability are good (i.e. Criterion 1 score of 7.5 out of 10 for the effluent category), the Evidence-Based Assessment was utilized. Note that the production system's structural benthic impacts directly beneath the farms are considered in Criterion 3 – Habitat, but benthic impacts resulting from the feeding activity (e.g., feces) are considered in this criterion.

In contrast to fed aquaculture systems, oyster farming does not rely on external feed or nutrient inputs (Ward 2016; Nuffield Australia 2012; Helm et al. 2004), which limits many of the nutrient-related

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concerns typically associated with other forms of aquaculture. The filter feeding activity of oysters results in the extraction of key nutrients from the environment in the form of seston (phytoplankton, zooplankton, and particulate organic matter – also see Criterion 5 - Feed) and as a result of this demonstrable extraction of nutrients, there is no discharge of soluble nutrients as "effluent". However, the feeding activity of oysters also results in the production of nutrient rich feces and pseudofeces[9] which settle to the seabed, and are assessed here in this Effluent Criterion.

The following sections will present evidence of the reported beneficial effects observed in both the water column and benthic habitats at oyster farms, followed by contrasting evidence of the negative impacts and potential risks. A discussion of contradictory case studies from key oyster-producing regions around the world is also provided, and these sections conclude with an overview of effluent-related measures and regulations applicable to these regions. In these discussions, it is important to note that human activities in coastal ecosystems around the world typically play a major role in shaping the distribution and deposition of organic matter (OM). This is primarily due to the accumulation of key nutrients such as carbon (C), nitrogen (N), and phosphorus (P), which can reach excessive concentrations in marine environments. When inputs of C and N enter the marine environment from various sources, they can build up to levels that trigger eutrophication, which is a process linked to numerous ecological issues, including harmful algal blooms, hypoxic zones, and the degradation or loss of benthic habitats (Mangi et al., 2021).

<u>Effluent Benefits Associated with Oyster Aquaculture</u>

When oysters feed, they filter particulate OM from the water column, which reduces turbidity and removes nutrients. In particular, they absorb inorganic nitrogen and phosphorus primarily from phytoplankton, and incorporate them into their tissues and shells. These nutrients are permanently removed from the ecosystem when oysters are harvested (Mangi et al., 2021; Duball et al., 2019; Rose et al., 2015; Kellog et al., 2013; Pollack et al., 2013). However, the impact of oyster production on nutrient budgets and primary production varies with factors such as oyster abundance, location, system flushing rates, and residence time. Similarly, nutrient delivery to sediments can lead to different outcomes depending on local conditions (Mangi et al., 2021; Ray et al., 2020; Gallardi, 2014). More about these nuances will be discussed ahead under the contradicting results section.

In situations where nutrients from anthropogenic sources are in excess, this nutrient uptake can help mitigate eutrophication (e.g., harmful algal blooms) by reducing phytoplankton abundance and detritus in the water column, improving water clarity and facilitating the growth of adjacent vegetated habitats (e.g., seagrass), which serve as important carbon sinks and nurseries (Litembu et al., 2023; Mangi et al., 2021; Gentry et al., 2019; Bricker et al., 2018; Silva et al., 2017; Smith et al., 2016; Rose et al., 2014). Additionally, oyster aquaculture enhances silicon (Si) cycling, supporting diatom populations and contributing to the regulation of the biological pump, which has implications for global climate processes (Ray et al., 2021).

Oyster aquaculture has also been reported to positively influence benthic environments by altering the composition of sedimentary organic matter (SOM) through potential mechanisms of oyster biodeposition of feces and pseudofaeces, which can stimulate microbial activity and enhance nutrient cycling, such as carbon degradation ability and increased denitrification (Humphries et al., 2016). For example, this has

[9] As oysters filter seston from the water column, they selectively ingest and digest some of it, from which they subsequently produce feces. The seston that they don't ingest is bound in mucus and ejected as pseudofeces. The combined feces and pesudofeces sink to the seabed and are referred to as "biodeposits".

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been reported to improve sediment levels of total organic carbon, total nitrogen, and their stable isotopes (Xie et al., 2024; Mangi et al., 2021). Additionally, in systems where oysters are farmed on or near the seafloor (i.e., on-bottom systems), their shells and biodeposits create complex three-dimensional structures that have been reported to promote biodiversity by providing habitat for various fauna and seaweed, especially in soft-sediment areas (also see Criterion 3 – Habitat), which Yang et al., (2023) considered could potentially result in improved water quality and ecosystem health. In some cases, these organic inputs have been reported to shift net metabolic rates in sediments, such as promoting a transition from nitrogen fixation to beneficial denitrification processes (Ayvazian et al. 2021; Fulweiler et al., 2007; Newell et al., 2002). Similarly, oyster shell formation sequesters carbon as calcium carbonate ($CaCO_3$), potentially contributing to long-term carbon storage within ocean–atmosphere carbon cycles (Xie et al., 2024; Feng et al., 2023; Yixin et al., 2022; Gentry et al., 2019). While the net impact on SOM dynamics is limited, this process may hold greater relevance for atmospheric CO_2 regulation (ibid.).

<u>Effluent Concerns Associated with Oyster Aquaculture</u>

While oyster aquaculture is often promoted for its environmental benefits (as discussed above), a growing body of literature has documented a range of negative environmental impacts associated with this activity, particularly when practiced at high intensities or in environmentally sensitive areas. Although also reported as a potential benefit, one of the most critical concerns lies in the alteration of biogeochemical cycles, specifically those of nitrogen, phosphorus, and oxygen, which are tightly regulated by benthic processes in coastal ecosystems (Ray et al., 2020).

The accumulation of oyster biodeposits, including feces and pseudofeces, can significantly increase the input of labile organic matter into sediments, as these particles settle at much higher rates than they would in the absence of cultured oysters (Tan et al., 2024). These biodeposits can be more bioavailable than other organic inputs, such as those from terrestrial or marine autogenic sources, and thus decompose rapidly (Xie et al., 2024; Hatakeyama et al., 2021; Mangi et al., 2021). This microbial degradation process significantly increases oxygen demand, often leading to localized hypoxic or anoxic conditions, especially in poorly flushed systems (Xie et al., 2024; Hatakeyama et al., 2021). These oxygen-depleted conditions can further shift sediment function from a nutrient sink to a source, releasing inorganic forms of nitrogen and phosphorus into the overlying water and potentially exacerbating eutrophication and shifting microbial community composition (Xie et al., 2024; Hatakeyama et al., 2021; Mangi et al., 2021; Martínez-García et al., 2021; Ray et al., 2020). This is particularly relevant in soft-sediment environments where microbial diversity is sensitive to oxygen fluctuations and organic inputs. In some cases, even low densities of oysters have been shown to affect decomposition dynamics and microbial function, potentially reducing the resilience and functionality of the benthic ecosystem (Martínez-García et al., 2021). Over time, these pressures may lead to non-linear or oscillatory changes in ecosystem structure and function, as feedback mechanisms between different trophic guilds develop and interact. This could result in greater temporal variability and abrupt shifts in community characteristics, which complicates management and prediction of ecosystem responses (Ray et al., 2020; Hatakeyama et al., 2021). Additionally, oyster aquaculture may drive community shifts in benthic and epibiont organisms. While such shifts, toward species like polychaetes and isopods represent an environmental impact, their influence on overall ecosystem productivity remains uncertain (Smith et al., 2018; Kwan et al., 2018; Huang et al., 2018).

Interestingly, some studies have also shown that sediments beneath oyster farms can function as net nitrogen sources, while adjacent bare sediments act as nutrient consumers, further questioning the

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generalized perception of bivalve aquaculture as a nutrient sink (Ray et al., 2020). This highlights the need for site-specific assessments when planning or expanding oyster operations.

Contradicting results

As described in the previous sections, oyster aquaculture has been recognized for its potential to mitigate nutrient pollution through the filtration of particulate organic matter and the assimilation of nitrogen and phosphorus into tissues and shells. However, its effects on sediment-water nutrient exchange and biogeochemical cycling remain complex and sometimes contradictory due to the interplay of microbial processes, site conditions, and culture intensity. In nutrient-rich systems suffering from anthropogenic nitrogen loading, oyster aquaculture has shown promise in enhancing denitrification, a microbial process that converts reactive nitrogen to inert N_2 gas, thereby removing bioavailable nitrogen from coastal ecosystems (Ayvazian et al. 2021; Ray et al., 2020; Newell et al., 2005). This effect has been shown to persist over multiple years, supporting the potential of oyster farming as a nutrient management strategy. On the other hand, in nutrient-poor systems, this same nitrogen removal may reduce productivity by limiting nutrient availability to phytoplankton and other primary producers (see Criterion 5 – Feed for details on these concerns). The impact, therefore, may vary from beneficial to detrimental depending on baseline nutrient conditions in different scenarios (Ray et al., 2020).

Moreover, enhanced nitrogen recycling in the benthos beneath oyster farms can support productivity within the estuary by making nitrogen available for multiple cycles of primary production before eventual export or removal. Yet, studies show significant variability in nitrogen fluxes, even within the same site, suggesting that denitrification rates and nitrogen retention are influenced by both seasonal dynamics and aquaculture age (Ray et al., 2020). Extensive studies across multiple Atlantic regions have described the nutrient biomitigation potential of oyster aquaculture, particularly through the assimilation and removal of nitrogen and phosphorus in oyster biomass. Nitrogen removal associated with oyster harvest ranges from 4.68 to 9.37 kg N per mt of fresh weight (FW) biomass, while phosphorus removal varies between 0.75 and 1.4 kg P per mt FW, depending on species, growing conditions, and geographic location (Marinho et al., 2022). For instance, Pacific oysters (*C. gigas*) and American cupped oysters (*C. virginica*) cultivated in the North Atlantic region (including North America and Europe) showed similar N removal rates, ranging from 5.67 to 7.2 kg N per mt FW. Comparable values were observed in *C. gigas* farmed in South Africa and Namibia (5.84 kg N per mt FW), whereas Brazilian oysters exhibited higher removal rates: 9.37 kg N per mt FW in *C. gigas* and 8.52 kg N per mt FW in the native species *C. gasar*. This enhanced nutrient removal in Brazilian systems is likely linked to higher flesh yields reported for oysters in the region (Marinho et al., 2022).

Phosphorus removal followed a similar geographical trend. The highest P removal values were recorded in Brazil, with 1.32 to 1.4 kg P per mt FW for *C. gigas* and *C. gasar*. In contrast, *C. virginica* in North America exhibited values between 1.05 and 1.06 kg P per mt FW, while European *C. gigas* showed slightly lower removal (0.82 to 0.94 kg P per mt FW). The lowest values were observed in oysters from South Africa and Namibia (0.80 kg P per mt FW). Meanwhile, the native European oyster (*O. edulis*) demonstrated the lowest overall nutrient removal, with 4.68 to 4.87 kg N and 0.75 to 0.76 kg P per mt FW, likely due to reduced burial rates of feces and pseudofaeces in the sediment. When scaled to the average oyster production in the Atlantic (233,276 mt FW between 2015–2019), oyster aquaculture is estimated to remove approximately 1,525 mt of nitrogen and 231 mt of phosphorus annually from coastal waters (Marinho et al., 2022; Duball et al., 2019; Ward, 2016).

At the sediment-water interface, the release or uptake of nitrogen compounds (e.g., ammonium, nitrate, dinitrogen gas) is largely governed by the prevailing microbial metabolic pathways, which can shift over

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time in response to organic loading, oxygen availability, and microbial competition (Ray et al., 2020). The addition of organic material via biodeposits does not consistently alter sedimentary C:N ratios or concentrations of nitrogen and carbon, even after sustained aquaculture activity (ibid.). Field studies have shown that porewater ammonium (NH_4^+) concentrations beneath oyster aquaculture sites can be 30 to 100 times higher than those in overlying waters and tend to increase over time as biodeposits accumulate and decompose. Yet, no direct relationship has been observed between porewater NH_4^+ concentrations and NH_4^+ flux to the water column, suggesting that ammonium may be either retained in sediments or processed internally through coupled nitrification–denitrification rather than being released into the water (ibid.). Furthermore, the accumulation of oyster biodeposits enhances microbial decomposition, which increases oxygen demand and can promote phosphorus release from sediments, particularly under low-oxygen conditions where the sediment's ability to retain P is reduced (Foster & Fulweiler, 2019; Ingall & Jahnke, 1994). Despite this, no significant differences in O_2 consumption or phosphate (PO_4^{3-}) flux have been consistently observed between oyster aquaculture sediments and bare sediments, suggesting high spatial and temporal variability in these effects (Ray et al., 2020).

Given the global significance of China's oyster production, and the unique intensity and scale of its industry, several case studies examining effluent discharge and nutrient-related changes in coastal ecosystems are presented ahead.

Xie et al. (2024) conducted a study in the Maowei Sea comparing sediment nutrient dynamics between an intensive mariculture area (IMA, north) and a non-intensive area (NIMA, south). As samples were collected across the bay rather than directly beneath oyster structures, the observed nutrient changes are considered reflective of broader effluent-related impacts, while infrastructure-related sediment modifications should be evaluated under the habitat criterion.
Stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) were used to trace nutrient sources and assess aquaculture influence. Significantly higher $\delta^{13}C$ values were recorded in the IMA during August 2016 and July 2022, pointing to enhanced sedimentary organic matter accumulation driven by oyster activity in summer months (Yang et al., 2023). This pattern aligns with findings from Han et al. (2024), which link high oyster density to elevated particulate organic matter deposition and subsequent microbial degradation, resulting in heavier $\delta^{13}C$ values (Cifuentes et al., 1988; Lao et al., 2023). Similarly, Yang et al. (2022) and Xu et al. (2020) found higher concentrations of shellfish-biodeposited total organic carbon (TOC) in IMA sediments across all sampling events. However, seasonal analysis revealed that differences in TOC between IMA and NIMA were minimal during winter months (December 2016, 2021, and 2022), likely due to reduced oyster biomass following autumn harvests, indicating that SOM impacts from oyster biodeposition may be temporary and seasonal (Xia et al., 2019; Pomeroy et al., 2007). Furthermore, a significant negative correlation between $\delta^{15}N$ and $\delta^{13}C$ values ($R^2 = 0.40$, $p < 0.05$, $n = 12$) observed in July 2010 suggests that elevated $\delta^{15}N$ levels (~8‰) in estuarine sites may be attributed to municipal wastewater inputs rather than oyster farming, as these stations coincide with areas of high oyster farm density (Gao et al., 2021). This suggests that nutrient enrichment in this region of the bay might be driven by non-aquaculture sources (Xie et al., 2024).

Furthermore, during the sampling periods, the most important contributor to SOM was from terrestrial sources discharging into the bay, followed by marine primary production deposition, and lastly by oysters biodeposition (See Figure 9) (Xie et al., 2024). However, an increasing trend was observed in the contributions of oysters biodeposition during the entire sampling period. As previously reported, the introduction of oyster rafts near the outlet channel regions since 2019 has resulted in substantial growth of bottom oyster cultures underwater, which may be a potential factor for the increased contribution of oysters biodeposition to SOM in the surface sediments around these areas (Jiang et al., 2020). While the

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average proportion of SOM per source suggests oyster production has the lowest contribution of the three sources assessed in the study, there are some field observations indicating as great as 50.3% contribution from oyster production in some sampling sites (Xie et al., 2024). The contribution of oysters biodeposition to SOM increased from 12.0 ±5.7 % in July 2010 to 19.3 ±11.5 % in July 2022; the proportions of shellfish-deposited organic matter in SOM increased by 60.8 %, which closely paralleled the annual production growth rate (68.4 %) of oysters in the study area (Xie et al., 2024).

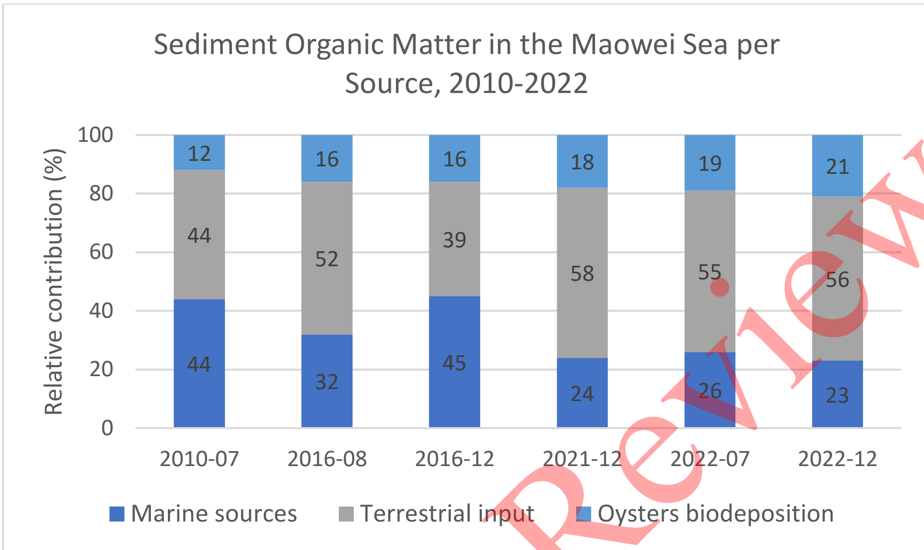

Figure 9. Relative contributions of marine sources, terrestrial input, and oysters biodeposition to sediment organic matter in the Maowei Sea in years, 2010, 2016, 2021, and 2022 (Reproduced from Xie et al., 2024).

In Shenzhen Bay, China, enhanced isotopic turnover with enriched $\delta^{13}C$ and $\delta^{15}N$ values was observed at oyster culture sites compared to reference areas, indicating more dynamic nitrogen and carbon cycling under aquaculture influence (Mangi et al., 2021). This suggests that oyster farming alters sedimentary processes, likely by stimulating microbial activity that facilitates the transformation and reintegration of nutrients into the ecosystem. Multiple studies support this pattern, reporting that oyster biodeposition can alleviate sedimentary TOC and total nitrogen loads, potentially aiding eutrophication management (Mangi et al., 2021; Ayvazian et al. 2021; Ledford et al., 2020; Gentry et al., 2019; Reis et al., 2017; Yang et al., 2017; Hoellein et al., 2015; Hoellein and Zarnoch, 2014). Moreover, increased oxygen demand from settling particulate organic matter in oyster farms was found to be manageable when farms were located in deeper waters, reducing hypoxia risk near the benthos (Hatakeyama et al., 2021). These findings are consistent with earlier research indicating minimal benthic impacts from bivalve aquaculture under suitable environmental conditions (Crawford et al., 2003; Burkholder and Shumway, 2011). Broader analyses of molluscan mariculture across nine coastal Chinese provinces found that the industry contributes minimally to water pollution, solid waste, and sulfur dioxide emissions (Peng et al., 2023). Applying the Environmental Kuznets Curve framework, Peng et al. concluded that in most regions (78%), environmental pressures from mollusk farming follow an inverted U- or N-shaped pattern, which indicates that while impacts may initially rise with industry growth, they tend to decline as development matures, supporting the intrinsic sustainability of molluscan mariculture.

Therefore, oyster aquaculture can provide significant nutrient mitigation benefits by removing nitrogen and phosphorus from the water column and enhancing sediment nutrient cycling; however, its environmental effects vary widely depending on factors such as site conditions, farming intensity, hydrodynamics, and baseline nutrient loads (Xie et al., 2024; Mangi et al., 2021; Ayvazian et al. 2021; Ray et al., 2020). Even in high-intensity, large-scale industries like those in China, research has shown that

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oyster biodeposition impacts may be moderate, seasonal, or outweighed by external nutrient sources, underscoring the complexity and context-dependence of observed outcomes (Xie et al., 2024; Gao et al., 2021; Peng et al., 2023).

Management

While the Evidence-Based Assessment option in this criterion does not require the governance aspects to be considered, a brief overview of the relevant laws and regulations governing oyster aquaculture in key producing regions (i.e., China, the U.S., France, South Korea, and Japan) is provided in Appendix 2. Additionally, a more detailed discussion (i.e., particularly regarding habitat-related provisions) can be found in Criterion 3 – Habitat (Factor 3.2).

Overall, the available evidence suggests that management measures addressing effluent risks are in place across major oyster-producing regions. While some gaps in implementation and enforcement may persist, these measures, combined with the natural filter-feeding capacity of oysters, support the conclusion that when the industry is well managed and ecologically planned, it can operate as a low-impact and environmentally beneficial form of aquaculture (see Appendix 2).

Conclusions and final score

In contrast to fed aquaculture systems, oyster farming does not rely on external feed or nutrient inputs, which limits many of the nutrient-related concerns typically associated with other forms of aquaculture. By filtering seston, oysters can remove nitrogen and phosphorus from the water column, often improving water quality in nutrient-enriched environments. These benefits, however, are highly context dependent and are assessed under Criterion 5 – Feed. At the same time, oyster feeding generates nutrient-rich feces and pseudofeces that settle rapidly to the seabed, introducing labile organic matter at higher rates than would occur naturally. The impacts of these particulate effluents are assessed here. This biodeposition elevates microbial activity and oxygen demand, which can create localized hypoxic or anoxic conditions, particularly in poorly flushed systems. Such oxygen depletion can shift sediments from acting as nutrient sinks to nutrient sources, releasing inorganic nitrogen and phosphorus into the water column, potentially exacerbating eutrophication and altering microbial communities. However, it is important to consider that the extent of these impacts depends on site conditions, hydrodynamics, farming intensity, and baseline nutrient loads. For instance, even in high-intensity production areas such as China, research indicates that benthic impacts from oyster biodeposition are often moderate, seasonal, or outweighed by external nutrient sources, underscoring the complexity and context-dependence of observed outcomes. Notably, these effects are usually restricted to the immediate footprint of farms, recover relatively quickly once production ceases, and do not appear to pose significant cumulative risks at the waterbody or regional scale. As such, the final score for Criterion 2 – Effluent is 8 out of 10.

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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.*

Habitat parameters	Value	Score
F3.1 Habitat conversion and function		9
F3.2a Content of habitat regulations	4	
F3.2b Enforcement of habitat regulations	4	
F3.2 Regulatory or management effectiveness score		6.4
C3 Habitat Final Score (0-10)		**8.1**
Critical?	No	**Green**

Criterion 3 Summary

Oyster aquaculture is predominantly carried out in tidal, intertidal, and nearshore subtidal coastal areas, which are generally considered to be of high habitat value. The total global area occupied by oyster farming is estimated to be 1,882 km². Based on this estimate global oyster farms occupy about 1.3–1.5% of the total tidal flat area worldwide.

One of the main concerns associated with the introduction of culture infrastructure into coastal ecosystems and their interaction in these locations is its potential to alter local hydrodynamics. These alterations are primarily driven by the configuration, density, and spatial extent of farming gear, which

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can change current velocity and flow regimes. In addition, harvesting methods such as mechanical or suction dredging are known to cause disruption to benthic habitats. Despite these concerns, the overall impact of oyster farming on habitat functionality is generally considered low. In fact, oyster culture is often associated with a range of positive ecosystem services, including, habitat provision for other marine species, and shoreline stabilization. The score for Factor 3.1 is 9 out of 10.

Globally, evaluating the management of oyster farm siting remains complex. However, licensing and site selection frameworks are, in many regions, reasonably robust and supported by regulatory oversight. The degree of enforcement varies across major producing countries and is influenced by national governance structures, farm-specific characteristics, and the associated environmental risks. While detailed enforcement data (e.g., sanctions or inspection frequency) are not consistently available, general indicators of regulatory activity and oversight were identified for most major oyster-producing regions. The score for Factor 3.2 is 6.4 out of 10. The combination of Factors 3.1 and 3.2 result in a final Criterion 3 – Habitat score of 8.1 out of 10.

Justification of Rating

Factor 3.1. Habitat conversion and function

Oyster aquaculture operations, whether employing on-bottom or off-bottom production methods, are predominantly located in coastal environments, occupying intertidal or subtidal zones within bays, coastal lagoons, ponds, and sheltered to moderately exposed nearshore areas (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025; Mercer et al., 2024; Yu et al., 2023; Strand et al., 2022; Liu et al., 2021; Gao et al., 2020; Wang et al., 2018; Gentry et al., 2017). While offshore oyster farming is technically feasible, it remains less common than nearshore siting (See Figure 10I'; Mercer et al., 2024). Consequently, the habitat most representative of oyster production areas is coastal subtidal and intertidal waters, a category classified as high-value habitat under the Seafood Watch standard.

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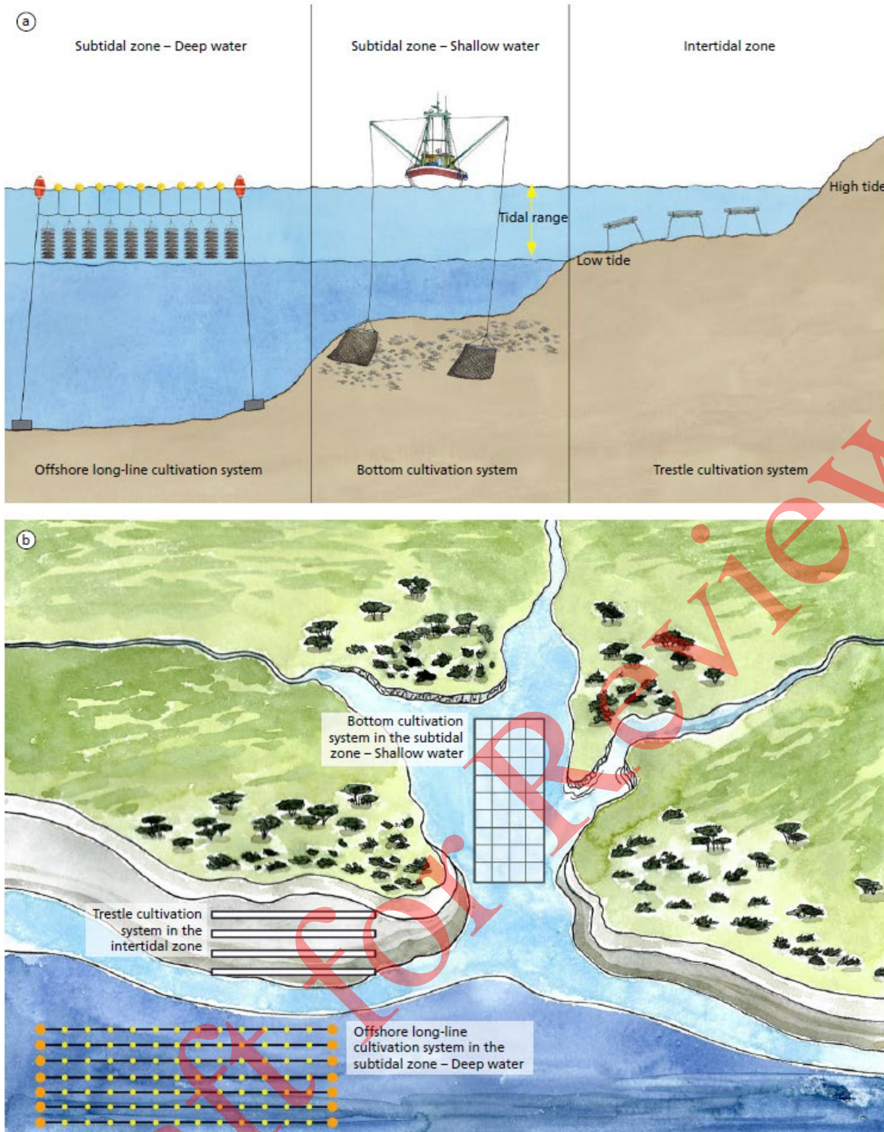

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Figure 10. Overview of suitable site typologies. (a) Cross-section view of different oyster farming zones and the most suitable cultivation technique based upon their position in relation to the water depth and tidal range. (b) Aerial view of different cultivation zones (Taken from Mercer et al., 2024).

Coastal ecosystems where oyster farming typically occurs provide critical ecosystem services that sustain both ecological processes and human well-being; for example, these environments are central to supporting coastal communities by offering food resources, livelihoods, recreation opportunities, clean environments, and natural protection against storms (Gentry et al., 2019). Beyond local benefits, coastal systems play key roles in global processes, including carbon sequestration and biodiversity enhancement (ibid.).

Oyster aquaculture typically takes place in dynamic coastal environments such as estuaries, lagoons, and continental shelf zones. These areas are recognized for their ecological complexity and productivity, playing a central role in global biogeochemical cycling. More than 90 percent of oceanic organic carbon sequestration occurs in these coastal systems, where organic matter is either buried in sediments or exchanged with open ocean waters, influencing large-scale nutrient dynamics (Xie et al., 2024; Middelburg and Levin, 2009). In addition to their carbon storage function, these coastal ecosystems deliver a wide range of ecosystem services. Supporting services include the production and recycling of biomass across multiple trophic levels, including microbes, benthic invertebrates, fish, birds, and aquatic mammals. They also provide critical habitat functions and facilitate processes such as decomposition and sediment formation that support nutrient cycling (Rodrigues-Filho et al., 2023). Regulating services include contributions to water quality maintenance, disease control, climate regulation, and water purification. Provisioning services are also significant, as these habitats supply food, biochemical and genetic materials, pharmaceutical and ornamental compounds, and raw materials such as fertilizers and natural fibers (Rodrigues-Filho et al., 2023).

Importantly, although coastal regions represent only a small fraction of the ocean's surface, they are critical to human society by producing the majority of sea-based food and resources (Martínez et al., 2007). The increasing human population and rising seafood demand have consequently driven the rapid expansion of coastal mariculture in recent decades (Clawson et al., 2022), intensifying the relevance of these ecosystems for both food security and environmental health.

<u>Industry coverage:</u>
As by-far the largest global oyster producer, China's reported total oyster aquaculture area in 2020 was 1,649.34 km^2 (Yu and Mu, 2023). With a total production of 6,199,500 mt the average Chinese industry yield is calculated to be 3,758.78 mt/km^2. In order to extrapolate these Chinese figures to a global oyster area, it is noted that specific oyster yield values vary widely across different farmer categories and between the primary species produced. For example, Yu et al. (2023) report the lowest average unit production in Zhanjiang for *C. gigas* at 187.49 mt/km^2, while the highest at the same location for *C. hongkongensis* at 4,462.85 mt/km^2 (using 2021 production data). This wide range in yields, combined with species-specific and location production differences, makes it challenging to make a global estimate of oyster farming area based solely on production figures. An estimate of the total area coverage for global oyster production was not readily available in the literature. Nonetheless, using China's reported average yield of 3,758.78 mt/km^2, and the global oyster harvest of 7,073,955 mt (see the Production Statistics section in the Introduction), it is possible to approximate the global oyster farming area coverage to 1,882 km^2. It is important to note that this estimate, along with the reported 1,649.34 km^2 for China's shellfish farming, exceeds the total global mariculture area (inclusive of finfish, crustacean, and bivalve aquaculture) estimated by Ma et al. (2025) at 1,087 km^2 for 2020. This discrepancy highlights the uncertainty in available area-use estimates across 36 oyster producing countries.

In a broader context, it is relevant to estimate what proportion of the available global intertidal or subtidal coastal area is occupied by oyster farming. Zhang et al. (2023) mapped global tidal flats, which are defined as sand, rock, or mud flats that undergo regular tidal inundation, such as areas where oyster aquaculture often occurs. The study was performed at a spatial resolution of 30 m (each pixel representing a 30 × 30 m area on the ground) using Google Earth Engine. Their methodology achieved an overall accuracy of 90.34% and estimated a total global tidal flat area of approximately 140,922.5 km^2 in 2020. This estimate is slightly higher than the earlier figure reported by Murray et al. (2019), who calculated at least 127,921 km^2 (124,286–131,821 km^2, 95% confidence interval). When compared with the estimated 1,881.97 km^2 of global oyster aquaculture area, oyster farms occupy about 1.3–1.5% of the total tidal flat area available worldwide (Yu & Mu, 2023; Yu et al., 2023; Zhang et al., 2023; Murray et al., 2019). Looking ahead, Ma et al. (2025) project that global mariculture area will need to expand by 40.5% by 2050 to meet future bivalve and finfish production demands. While this projection includes bivalve aquaculture such as oysters, it is important to note that the growth rate in oyster production appears to have slowed (Litembu et al., 2023; Lindblom et al., 2022; Wang et al., 2018). Although production continues to rise, it has stagnated in most countries, with current increases largely driven by the Asian

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market (ibid.). Therefore, the 40.5% expansion figure should be considered on the higher end of what the oyster industry may realistically experience over the coming decades. Applying this projection to oyster aquaculture suggests that total oyster farming area could reach approximately 2,644.17 km² by 2050 and still represent only between 1.8 and 2.1% of current global tidal flats area.

Potential habitat impacts and benefits

Assessing the ecosystem-level impacts of oyster aquaculture infrastructure remains challenging, particularly given the scale of global production coverage, roughly estimated at 1,882 km² for 2021 (Yu et al., 2023; Yu and Mu, 2023). The variability in production methods and environmental contexts makes it difficult to generalize the potential impacts on benthic habitats directly beneath farming installations and ecosystems functionality. This complexity is echoed in the literature, which presents a nuanced picture: while oyster farming can deliver valuable ecosystem services such as water filtration and habitat provision, concerns remain regarding its potential to alter habitat structure and function. The following sections explores the primary habitat-related concerns associated with the addition of artificial structures in coastal environments used for oyster production globally.

Physical infrastructure and habitat hydrodynamics

One of the main concerns regarding the introduction of infrastructure for oyster culture into coastal ecosystems is its potential to alter local hydrodynamics, particularly through changes in current velocity and flow regimes due to the spatial arrangement, size, and density of culture structures. The degree of hydrodynamic alteration depends on several factors: gear porosity, spatial configuration, and vertical positioning in the water column. Research shows that current velocities are generally lower within oyster farms compared to surrounding waters, with observed reductions of up to 15% in some cases (e.g., Windmill Point in Chesapeake Bay; Turner et al., 2019), although these changes are less pronounced than those reported for other aquaculture systems like kelp or mussel farming, where reductions of 30–70% have been noted (ibid.).

These hydrodynamic alterations can, in turn, affect sedimentation processes (e.g., sediment accumulation) and overall habitat quality, potentially fostering hypoxic conditions (Turner et al., 2019; Kraft, 2017; Gallardi et al. 2014; MPI, 2013). These conditions could worsen if the site's carrying capacity is exceeded and nitrifying bacteria in the sediments are unable to process the nutrient loads from oyster biodeposits (Rice, 2008). Such alterations have also been documented across various shellfish farming systems similar to those used for oyster farming, including scallop-kelp farms in China, mussel farms in New Zealand and South Africa, and floating scallop farms in Canada (Turner et al., 2019). However, while infrastructure can alter the hydrodynamics of the habitat, it may also contribute to nutrient-related effects, such as compromising the stability of marine food webs due to shifts in the biomass and species composition of phytoplankton and zooplankton (Wang et al., 2018). However, these impacts are evaluated under Criterion 2 - Effluent, and are not considered here.

Farm siting and design can play a critical role in mitigating these impacts. For example, placing culture structures parallel to prevailing currents and choosing sites with high tidal exchange can help minimize siltation and enhance water flow (MPI, 2013; Rice, 2008). Yet, the extent to which such best practices are applied globally remains unknown.

In terms of farming systems, on-bottom structures (e.g., mesh bags) are in direct contact with the seafloor but are generally considered less invasive than off-bottom systems (e.g., bag-and-rack structures or suspended longlines-or-rafts), which still involve physical contact with the substrate plus floating or other off-bottom components. Nonetheless, both types require some form of anchoring, and the

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resulting differences in hydrodynamic impacts between these systems are considered minimal (Strand et al., 2022). Therefore, regardless of the production system, oyster aquaculture infrastructure has been associated with degraded benthic habitat quality, especially in coastal areas with poor water circulation (Choi et al., 2008; Botta et al., 2020).

When looking at the cumulative hydrodynamic alterations attributed to oyster aquaculture, it appears that oyster farming still plays a minor role in altering hydrodynamics and contributing to ecological pressure in this semi-enclosed system (Wang et al., 2018). For instance, oyster aquaculture in Sanggou Bay and in Heini Bay (i.e., important aquaculture producing bays in China), contributes to hydrodynamic drag and reductions in current velocity, both within the bay and at its interface with the Yellow Sea, but evidence presented by Wang et al. (2018) indicates that kelp cultivation is the primary driver of these changes. Kelp, farmed at large scale using long-line systems, exerts a substantially greater influence on water flow compared to oyster rafts or cages (ibid.). However, while earlier assessments (e.g., Zhang et al., 2009, 2019, 2020) concluded that the bay had not yet exceeded its ecological carrying capacity, more recent findings from Gao et al. (2020) suggest otherwise. They estimate that oyster farming currently exceeds the ecological carrying capacity by nearly threefold in the 30 km² area where it is concentrated. Despite stable sediment conditions, indicators such as declining phytoplankton diversity and increased aquaculture-related drag point to growing environmental stress in the bay (ibid.). Therefore, although oyster farming is potentially contributing to the cumulative impacts in these bays, their contribution level is not clear due to these contradicting findings.

Physical infrastructure and increased habitat complexity

While oyster aquaculture infrastructure can alter the hydrodynamics of coastal habitats, several studies have found minimal negative impacts and even evidence of ecological benefits, including enhancements to ecosystem functionality. For instance, extractive aquaculture systems such as oyster farming have been recognized as potential ecosystem services providers, as there have numerous studies where they act as artificial habitats, offering similar ecological functions to natural structures (e.g., reefs) in coastal habitats, such as increased species abundance and diversity, increasing spawning biomass, and serving as habitat or foraging areas for a range of marine organisms, including fish, invertebrates, birds, and marine mammals (Barrett et al., 2022; Nature Conservancy, 2021; Gentry et al., 2019 and references therein; Alleway et al., 2019). The addition of oyster-farming structures has been estimated to support 300–1,100 kg more fish per hectare per year (TNC[10], 2023). As such, the physical structure of oysters may be associated with restorative or regenerative aquaculture (e.g., Colsoul et al., 2021).

Although shellfish farms may not fully replicate natural estuarine environments, and natural features may still be preferred by some species, in some cases shellfish farm structures have been considered to mimic or exceed the habitat complexity of natural reefs. For instance, biological fouling on aquaculture gear has been shown to enhance habitat complexity, attracting species like mummichogs and feather blennies, which use the fouled surfaces for shelter and nesting (Ambrose and Munroe, 2025; Martínez-García et al., 2021; Duball et al., 2019; Ward, 2016; Rice, 2008; Muething, 2015). For example, floating bags with heavy fouling supported a greater abundance of these species than oyster cages, suggesting that gear type and fouling condition play a role in determining the type or degree of change in the coastal habitat. Floating bags have also shown to particularly favor species like blue crabs, grass shrimp, and mummichogs (Ambrose and Munroe, 2025). Moreover, observations during farm tending activities have

[10] https://www.nature.org/en-us/what-we-do/our-insights/perspectives/restorative-aquaculture-for-nature-and-communities/

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also indicated that farm tending activities did not deter wildlife, with some species, such as Atlantic silversides, even observed more frequently during these events (Mercaldo-Allen et al., 2023; Ambrose and Munroe, 2025).

Physical oyster farm structures can also result in negative impacts, this time relating to shorebirds, which can be observed in oyster aquaculture in Delaware’s Inland Bays (United States). Oyster farming in this bay has seen gradual growth since 2018 when the first harvest occurred. As of 2023, there were 21 acres of leased area dedicated to shellfish aquaculture, with ten commercial and one scientific lease in operation (F&WS, 2023). The primary method of cultivation is off-bottom, intertidal rack-and-bag systems. The bays hold significant ecological importance as a designated Ramsar Wetland of International Importance, an Audubon Important Bird Area, and a site in the Western Hemisphere Shorebird Reserve Network. Its intertidal beaches and mudflats serve as critical stopover habitats for several at-risk migratory shorebirds, notably the rufa red knot (*Calidris canutus rufa*), ruddy turnstone (*Arenaria interpres*), semipalmated sandpiper (*Calidris pusilla*), and sanderling (*Calidris alba*) (Maslo et al., 2020). Concerns have been raised regarding potential negative interactions between oyster aquaculture and these migratory species, particularly regarding the displacement of shorebirds from prime foraging habitats. Potential mechanisms of disturbance include the physical exclusion created by aquaculture racks, behavioral disruption caused by maintenance activities, and possible changes in benthic prey availability (ibid.).

A field study by Maslo et al. (2020) directly evaluated these interactions in Delaware Bay. The findings indicate that when oyster racks are located following conservation guidelines (i.e., outside core shorebird foraging zones), intertidal aquaculture has limited influence on shorebird distribution. Although oyster tending slightly reduced the likelihood of bird presence (by approximately 1.6–7%), this impact was minimal compared to natural factors like the presence of gulls and other shorebirds. Importantly, the study found no significant change in foraging rates among the focal species, suggesting that at existing densities and with buffer zones, current aquaculture practices can coexist with migratory shorebird use of intertidal habitats without substantial ecological conflict.

Moreover, nearshore shellfish aquaculture in southwest Ireland, had neutral or even positive effects on seabird abundance and diversity, with species like gulls and cormorants benefiting from increased food availability and perching structures (Bath et al., 2023). However, such benefits are unlikely at submerged offshore sites, where perching structures are absent.

Although hypothesizing that sea otters (*Enhydra lutris*, a protected marine mammal species) preferentially used oyster farms in Alaska for foraging and resting activities compared to undisturbed habitat areas, Reynolds et al., (2025) showed no discernible differences in overall sea otter activity or foraging behavior in the modified habitats of oyster farms (noting that there were no observations of otters consuming oysters).

Additionally, oyster aquaculture infrastructure may also modify hydrodynamic conditions, influencing the dynamics of particulate matter. For instance, elevated oyster farming on steel trestles with meshed

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plastic bags is common in intertidal areas of northwestern European shelf seas, especially in western Brittany and Normandy, to reduce predation, minimize losses, and increase productivity (Guillou, 2023). However, these structures act as artificial barriers to tidal flow, reducing current velocity, limiting particle dispersal, and substantially increasing sedimentation near the farms. Hydrodynamic modeling in the Aber Wrac'h estuary (northwestern Brittany) revealed that current velocities decreased over and around the oyster tables, with localized flow acceleration at the sides due to reduced cross-sections, particularly noticeable during peak flood and ebb tides. These changes can affect biodeposition, fouling, and suspended particulate matter dynamics, influencing sediment transport, seabed morphology, and the extent of depositional footprints (ibid.). Although limited, some evidence also suggests physical oyster infrastructure could contribute to coastal protection, such as wave attenuation, which may reduce erosion risks (Plew et al., 2005; Gentry et al., 2019).

Harvesting practices

Off-bottom oyster aquaculture is typically harvested by hand using rakes or tongs, although mechanical equipment may also by employed (Muething 2015, Stokesbury et. al. 2011). Even when harvested by hand, the strings or trays can be heavy enough to require mechanical assistance. Harvesting and other farm-tending activities involve vessel movements and physical disturbances from boats, vehicles (e.g., tractors), and foot traffic, which can reduce sediment shear strength, making it more susceptible to erosion and resuspension, and thereby altering benthic community composition beneath oyster farms (Ogunola & Onada, 2016, and references therein; Luczak[11], 2016). In many cases, small vessels equipped with mechanical washing and grading equipment are used to improve product consistency, growth rates, and survivorship (Muething 2015, Stokesbury et. al. 2011).

For on-bottom culture, hand-harvesting is generally considered to have lower environmental impact, but mechanical or suction-based dredging remains in use. For instance, in certain European countries such as France, Denmark, and Spain, it remains an integral part of deep-water and on-bottom culture (Kamermans et al., 2020; Litembu et al., 2023). In contrast, countries like Sweden and Norway rely more on hand-picking methods in intertidal locations (Kamermans et al., 2020).

Dredging, whether mechanical or suction-based, is widely recognized as a disruptive harvesting method for benthic habitats. Mechanical dredges, operated from boats, penetrate soft sediment to extract oysters and shell material, while suction dredges pump water from the seafloor and can also be utilized to relocate oysters, shell, or cultch, and can also be used for predator removal (Mercado-Allen & Goldberg, 2011).

The ecological impacts of dredging include immediate declines in benthic species biomass and abundance, affecting both target and non-target organisms (Stokesbury et al., 2011; Mercado-Allen & Goldberg, 2011). However, studies have shown that these impacts are typically localized, reversible, and of limited duration in high-energy environments where resident communities are naturally adapted to frequent disturbances, such as storms (pers. comms., Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025; pers. comms., B. Rheault, 2019, Stokesbury et al. 2011, Rice 2008). Recovery of infaunal communities often occurs within a year (Rice, 2008), and scavengers and opportunistic predators may

[11] https://www.alamy.com/oyster-farm-kilcolgan-county-galway-july-2016-tractor-carrying-oysters-image150979506.html

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temporarily benefit from prey exposure following dredging (Mercado-Allen & Goldberg, 2011). Additionally, habitat restoration measures, such as replanting shell or spat, can support biodiversity recovery (Dumbauld, 2009; Mercado-Allen & Goldberg, 2011).

Despite these recovery mechanisms, seagrass beds, particularly those composed of Zostera marina, are more sensitive to harvest disturbance. Mechanically dredged areas have been shown to result in significantly lower eelgrass cover, density, and biomass compared to uncultivated areas. For example, eelgrass plant density was 70% lower in dredged beds and 30% lower in hand-harvested beds (Tallis et al., 2009), suggesting that both methods contribute to habitat degradation, though mechanical dredging is more detrimental (Gardner et al., 2017; Dumbauld & McCoy, 2015). The competition for space between oysters using on-bottom methods and seagrass is a central driver of these effects (Gardner et al., 2017).
Interestingly, sediment disruption from dredging may also offer some temporary benefits. In certain cases, sediment resuspension and re-oxygenation associated with dredge harvesting can improve habitat conditions over medium time scales, particularly in areas with high organic matter accumulation (Goldberg et al., 2012, 2014; Meseck et al., 2014). Still, such benefits are site-dependent and less likely to offset impacts in ecologically sensitive areas.

While both manual and mechanical harvesting methods affect benthic habitats, the severity of impact is strongly tied to the method used and the ecological context. Hand-harvesting is generally associated with less disturbance, and the increasing shift toward off-bottom culture systems reflects a broader trend toward minimizing environmental impact in oyster aquaculture (Gardner et al., 2017; Muething, 2015).

Benthic effects

Effects on Submerged Aquatic Vegetation

Similarly, oyster aquaculture can produce both beneficial and adverse effects on nearby seagrass beds, depending on factors like gear type, stocking density, farm management, and proximity to the vegetation. On the positive side, oyster filtration reduces phytoplankton and suspended sediments in the water column, leading to improved water clarity and greater light penetration, which can enhance eelgrass productivity and extend the euphotic zone (Sandoval-Gil et al., 2015; Oyster BMP Expert Panel, 2016; Dumbauld et al., 2009; Ward, 2016; Rose et al., 2015; Gallardi et al., 2014; Rice, 2008). While these filtration-related benefits are considered under Criterion 5 – Feed, physical interactions between oyster aquaculture and seagrass habitats can also lead to localized negative effects. In particular, some localized impacts have been documented beneath and directly adjacent to aquaculture gear. These include reduced eelgrass shoot density and cover due to physical shading or space competition (Coe, 2019; Gardner et al., 2017; Ahmed & Solomon, 2016; Bulmer et al., 2012; Barillé et al., 2010; Martin et al., 2010). Longline and rack systems, for example, can reduce light availability beneath gear, thereby inhibiting seagrass photosynthesis (Ahmed & Solomon, 2016). Additionally, a review on ecological consequences of oyster farming suggests that oyster farming can significantly alter benthic environments by increasing organic matter, silt, and pigments in sediments beneath cultivation structures, largely due to reduced current velocities (Ogunola and Onada, 2016 and references therein). These changes, combined with shading from oysters and farm infrastructure, have been linked to declines in macrofaunal abundance and temporary reductions in seagrass cover in multiple locations, including Tasmania and New Zealand (ibid.).

While these effects are usually confined to the immediate footprint of the farm and do not extend into surrounding habitats, they may contribute to measurable declines in eelgrass density and reproductive output, with one study reporting a 44% decline in density and 61% decline in reproduction associated

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with longline gear (Ferriss et al., 2019). Although some declines in seagrass cover can be substantial like the ones just described, in other cases when declines were observed near off-bottom systems like hanging baskets, they have been generally minor and spatially limited (Bulmer et al., 2012; Gardner et al., 2017).

Additionally, seagrass ecosystems are highly sensitive to physical disturbances such as foot traffic and vessel activity (Ahmed & Solomon, 2016). A meta-analysis of 125 studies examining the relationship between bivalve aquaculture and eelgrass found that such aquaculture activities negatively affect eelgrass density, often leading to the transformation of eelgrass beds into hard-bottom habitats (Ferris, Conway-Cranos and Sanderson, 2019). While seagrass degradation has been associated with broader declines in coastal habitat biodiversity (Bishop et al., 2023), the extent of these impacts appears to depend on site-specific environmental conditions and the nature of the aquaculture operation. For example, some studies have found no significant differences in invertebrate abundance or community composition between eelgrass beds located near oyster farms and those in non-farmed areas, suggesting that impacts are not universal and may be limited under certain conditions (Coe, 2019).

Effects on Benthic Conditions and Biodeposition
The influence of oyster aquaculture on benthic ecosystems is complex and context-dependent. Materials such as live oysters, shell fragments, discarded farming gear, and fouling organisms often accumulate on the seabed beneath oyster racks (Ogunola and Onada, 2016 and references therein). These deposits can create new habitat structures that attract various fouling species and mobile marine life. Because such materials can remain for years after farming stops, they have the potential to cause lasting changes in the composition and structure of benthic communities (ibid.). However, in field studies across the Chesapeake Bay, no significant differences were found in benthic macrofauna diversity, sediment quality, or water chemistry between oyster farm areas and reference sites. In some locations, benthic organism abundance was even higher within farm footprints (Kellogg & Massey, 2018). Research in Xiangshan Bay, China, also revealed that macrobenthic community structure differed beneath oyster farms compared to reference sites, though biodiversity and abundance significantly increased three years after farm removal, indicating the system's capacity for recovery (Liao et al., 2022). Finally, bioindicator taxa such as polychaetes have been used to assess the ecological status of benthic habitats under aquaculture influence. While these organisms are sensitive to environmental stressors, no significant declines in polychaete abundance or richness have been linked to oyster gear presence. Site-level factors such as broader anthropogenic stressors (e.g., algal blooms) often better explain variations in their communities (Fuoco et al., 2021).

Overall, the effects to habitat function from oyster culture are expected to be minimal, reversible and to some level, mitigated by the ecosystem services that oysters provide. The score for Factor 3.1 is 9 out of 10.

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Factor 3.2. Farm siting regulation and management
Given the global scope of this report, Factors 3.2a (Content of management measures) and Factor 3.2b (Enforcement of management measures) will be considered under each country's governance overview.

Aquaculture management varies country-to-country, and while in some cases the associated environmental impact risks of oyster aquaculture production are well accounted for in the content of regulation and existing management strategies, the nuances of individual circumstances at a global scale of this report's scope makes it challenging to gauge the appropriateness of their content (Ross et al. 2013). Innovations in the industry, such as farm site selection tools and data-sharing have been instrumental in the continued integration of an ecosystem-based approach to site selection (Ross et al. 2013, Silva et al. 2011). Historical decisions of site selection were based on available space and productivity limits; however, there is a push towards an ecosystem-based approach to global aquaculture management (EAA), which focuses on ecosystem services, social impacts, governance, carrying capacity and long-term aquaculture effects to ecosystems (Ross et al. 2013, Silva et al. 2011). One 10-year study of the incorporation of EAA in aquaculture management found that EAA may be raising awareness of, and steering aquaculture towards greater sustainability (Brugère et al. 2018). However, uptake of EAA by different user groups varies (Brugère et al. 2018).

This has been evident in how similar what is stipulated in the main laws, acts, and requirements governing the primary productive sector more broadly, and the aquaculture industry in specific across countries, when it comes to ecosystems conservation and natural resource management. Each oyster-producing country regulates aquaculture and enforces aquaculture policies differently, but often with the same goal of maximizing production while maintaining impacts within acceptable limits. The following is an overview of habitat and farm management measures in the top oyster aquaculture producing countries or regions (i.e., accounting for over 97% of global production).

<u>China</u>
While there are no specific laws for aquaculture site selection, there is a comprehensive regulatory framework that encompasses national laws, administrative regulations, and local policies, which oversee the siting, permitting, and environmental management of the aquaculture industry. The Fisheries Law of the People's Republic of China (1986) includes – Chapter II Aquaculture – through which the state encourages the development of aquaculture on suitable tidal and water areas (Article 9), and local governments (county level and above) are authorized to allocate these areas to qualified entities and grant aquaculture licenses to confirm legal usage rights (Article 10). These rights can be further contracted to collectives or individuals, and are protected by law from unauthorized encroachment. This legal framework ensures orderly access to marine space for oyster farming, protects user rights, and balances aquaculture development with state land use priorities. FAO[12] (2025) states that under this Fisheries Law - "units or individuals, who wish to use those designated areas, must apply for an aquaculture permit through the competent fisheries administration at or above the county level, and the aquaculture permit will be granted by the people's government at the same level to allow using the area for aquaculture activities". The Sea Area Use Management Law (2002) plays a key role in regulating oyster farming in China by addressing increasing conflicts over marine space.

Administered by the State Oceanic Administration (SOA) under the Ministry of Land and Natural Resources, the law requires all users of sea areas (i.e., including oyster farmers) to apply for use permits and pay associated fees to legally operate in marine zones (FAO, 2025). This administration also establishes Marine Functional Zonation Schemes, which prioritize and define allowable uses for specific sea areas. As a result, aquaculture activities such as oyster farming must align with these zonation plans and be coordinated with broader coastal development strategies, including port operations, urban expansion, and land use planning (ibid.). This ensures that oyster farming is conducted within designated zones, promoting both sustainable marine resource use and conflict reduction among competing sea area users.

China's Environmental Protection Law (1989) requires environmental impact assessments (EIAs) for projects that may cause pollution, including large-scale aquaculture operations like oyster farms (ASC, 2023). Although aquaculture is not explicitly mentioned, EIAs must evaluate potential environmental

[12] https://www.fao.org/fishery/en/legalframework/nalo_china

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impacts and outline mitigation measures. China's EIA Law (2002), states that regional and sectoral development plans (i.e., inclusive of those for agriculture and aquaculture) must incorporate EIA during the planning stage, especially for the use of marine and coastal space, which are usually considered sensitive marine ecosystems (Articles 7, 8, and 9). The exact type of EIA that a given farm will need depends on the scale and type of project, resulting in one of the following EIA types (Article 16).

- EIA Report for large-scale or environmentally sensitive sites.
- EIA Form for moderate impacts.
- Registration Form for minimal-impact projects.

If a given aquaculture project is required to submit an EIA report, this one should include the project's overview and surrounding environmental conditions, predicted impacts (e.g., nutrient loading, benthic disturbance), proposed mitigation measures and economic cost-benefit analysis, and monitoring plans (Article 17). Without an approved EIA or authorization by the applicable regulatory agencies, any given aquaculture project cannot legally begin construction. Additionally, if a farm's scope, location, or technology changes significantly, or if its operation results in unexpected or worsened impacts during operation a new or revised EIA is required depending on the situation (Articles 22, 24, and 27). The environmental authority must monitor environmental effects after project operation begins. If serious pollution, ecosystem damage, or cumulative impacts (e.g., nutrient enrichment in bays) occur, adaptive measures should be proposed, and both the construction unit and the EIA consultants may be held legally accountable (Article 14, 15, and 28).

The Ministry of Ecology and Environment[13] and its local counterparts (city/county level) are responsible for EIA classification, approval, and enforcement; as well as conducting assessments, monitoring and post-construction follow-ups within their jurisdictions (FAO, 2025).

China has significantly strengthened its regulatory framework for oyster aquaculture by introducing stricter permitting systems, spatial planning tools, and environmental protections that aim to manage cumulative impacts and promote sustainable development. A wave of oyster farm closures across key coastal provinces including Shenzhen, Zhuhai (i.e., cleared of oyster farming was about 72.19 km^2 and a coastline of 134 km), Fuan (i.e., 420 mt of illegally farmed oyster was decommissioned), and Fangchenggang; highlights the growing enforcement of regulations targeting unlicensed operations, environmental concerns, and conflicts with urban and maritime infrastructure. These clean-up efforts have not only removed illegal or disorganized farming activities but have also triggered an industry-wide restructuring (Yu et al., 2023; Godfrey, 2021).

Historically, the oyster farming sector was marked by weak regulation, fragmented management, and widespread non-compliance, with fewer than 10% of producers holding marine use permits (Li et al., 2017). However, the launch of the Marine Ecological Red Line (MERL) policy in 2016 marked a turning point. MERLs now protect 85,000 km^2 of China's offshore[14] waters, including coastal areas, (i.e., roughly 30% of the total) by designating zones with strict limits or full prohibitions on development, including aquaculture. The 11 types of MERLS include "mangroves, seagrass beds, coral reefs, coastal salt marshes, important estuaries, important mudflats and shallow waters, distribution areas of rare and endangered species, spawning grounds of fishery resources, especially in protected islands, the high coastal protection function

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[13] https://english.mee.gov.cn/About_MEE/History/

[14] The term "offshore" is used by Zeng et al. (2024) to refer broadly to marine waters. While the term "offshore" is also commonly used to refer to aquaculture located at considerable distances from the coast, it is used here for consistency with Zeng et al's reference to the MERL areas which are further articulated in the main text.

areas, and the high coastal erosion and sand loss vulnerability areas (Zeng et al., 2024). The original MERLs included 7,400 km^2 of authorized human activities, which hindered enforcement of development restrictions. After adjustments, this area was reduced to 2,400 km^2, cutting activity intensity by 68%. This has curbed habitat degradation and significantly reduced human activity within ecologically sensitive areas, demonstrating the state's commitment to spatially managing ecological impacts (Zeng et al., 2024; Yu et al., 2023).

In leading oyster-producing provinces like Fujian, Shandong, and Guangdong, MERL zones cover 20–32% of offshore waters, directly influencing site allocation and requiring farms to comply with ecological zoning mandates (MARA, 2024; Zeng et al., 2024).

Despite the introduction of various spatial planning and siting policies intended to guide the sustainable development of aquaculture in China, the actual implementation of these initiatives remains unclear. The governance of mariculture spans multiple sectors, such as marine spatial planning, resource utilization, and environmental protection; and each of these falls under the authority of different agencies, including the Ministry of Natural Resources, the Ministry of agriculture and Rural Affairs, and the Ministry of Ecology and Environment. This fragmented, multi-agency oversight has led to overlapping mandates and policy incoherence, creating significant barriers to effective implementation (Yu et al., 2023).

Moreover, rapid coastal industrialization and urban expansion have intensified spatial competition, further compressing the area available for mariculture. Cities like Shanghai have already seen a reduction in aquaculture zones due to the prioritization of other marine industries. Yet, given mariculture's strong ties to local traditions, diets, and employment, ensuring its sustainable development remains a critical challenge, and one that requires better policy coordination and local government support (Yu and Yin, 2019).

<u>Europe</u>

The EU, including main oyster producers France, Italy, and Spain employs a Common Fisheries Policy (CFP) that was amended in 2014 and includes regulations for oyster aquaculture (European Commission, 2019). The CFP (Regulation (EU) No 1380/2013) mandates that aquaculture activities be environmentally sustainable and follow an ecosystem-based approach (EBA) (Art. 2(1), 2(3)). Additionally, the European Commission published the Strategic Guidelines for Sustainable Aquaculture (2021–2030), which points out that the EU promotes coordinated spatial planning through the Maritime Spatial Planning Directive (Directive 2014/89/EU), requiring Member States to designate areas suitable for aquaculture based on environmental suitability, stakeholder consultation, and compatibility with other uses. For instance, in Sweden a benthic habitat survey is required prior to the establishment of an aquaculture farm to confirm that the proposed site does not overlap with ecologically sensitive or valuable habitats, such as eelgrass beds (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025). Planning applies to marine, transitional, freshwater, and land-based systems (e.g., RAS) and should also anticipate offshore aquaculture growth. Important aspects include:

- Mapping potential and existing aquaculture zones, including abandoned or underutilized areas.
- Evaluating site carrying capacity, water quality (especially for molluscs), pollution sources, and ecosystem services.
- Promoting co-location with other marine uses (e.g., wind energy).

European aquaculture siting management is often state-specific, generally robust and utilizes an ecosystem-based approach (Ross et al., 2013; European Parliament, 2009). While the licensing remains fragmented across EU Member States, these guidelines recommend harmonizing licensing processes and

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consolidating relevant legislation; implementing "one-stop-shop" mechanisms for license applications; and adopting longer-term licensing tied to monitoring obligations and enforceable environmental conditions (European Commission, 2021). Additionally, Section 2.2.1 – Environmental Performance of the Strategic Guidelines for Sustainable Aquaculture, requires prioritizing the simultaneous application of the Water Framework Directive, Marine Strategy Framework Directive, and Environmental Assessment Directive. Particularly relevant for this criterion, The Marine Strategy Framework Directive (MSFD) Evaluation 2025 highlights key regulatory intersections between the MSFD and the CFP regarding the siting, land-use, and environmental planning of aquaculture in Europe. However, the Commission and stakeholders have noted persistent gaps and inconsistencies between the CFP and MSFD frameworks, often resulting in fragmented or delayed conservation efforts (European Court of Auditors, 2020).

As mentioned previously, France is the largest oyster producer in Europe and its licensing requirements listed ahead will be considered as a representative example for oyster aquaculture in Europe. France is primarily governed by the Law No. 97-1051 on Maritime Fisheries and Mariculture and the Decree of January 9, 1852 on Maritime Fisheries (Roman et al., 2023; FAO, 2025x). Oyster farms operating in intertidal areas must obtain a concession to access the Public Maritime Domain, which is owned by the State and administered by the Directorate of Maritime Affairs (Barillé et al., 2020; Roman et al., 2023). Concessions are typically granted for up to 30–35 years and may be renewed, amended, suspended, or revoked (FAO, 2025x). The Commission des cultures marines (Commission for Marine Aquaculture) evaluates the proposal, along with advice from IFREMER[15], local health authorities, municipal councils, and other relevant bodies (FAO, 2025a). The applicant must provide the following documentation (FAO, 2025a):

- Identification of the applicant.
- Name and type of watercourse or waterbody, including a map of the area.
- Detailed map of the aquaculture farm.
- Type of aquaculture.
- Fish farming method, farmed species, production or experimentation goals, and harvesting techniques
- Recommended measures to ensure fish movement, water quality, and avoid endangering the surrounding fish population.
- Drainage program.

Marine aquaculture activities in France are generally exempt from mandatory EIAs unless they exceed specific thresholds or are expected to cause substantial environmental impact (Roman et al., 2023; FAO, 2025a). However, for both inland and marine aquaculture projects, an EIA may be required under Book I of the French Environmental Code, depending on the size of the project and the extent of its potential environmental effects (FAO, 2025a).

Even in small and developing aquaculture sectors such as Sweden's, a complex institutional landscape, fragmented licensing procedures, and limited coordination between regulatory authorities have created significant barriers to oyster industry expansion (Franzen et al., 2024). Establishing a farm requires sequential approvals, including landowner consent, a Natura 2000 permit for protected areas, an exemption from shoreline protection, a culture and operational license, harvesting permits, a farming license under the Fishing Act, and a facility permit from the Swedish Maritime Administration. Furthermore, all farms must be located within aquaculture production areas designated by the Swedish

[15] IFREMER stands for "Institut Français de Recherche pour l'Exploitation de la Mer," which translates to English - Research Institute for Exploitation of the Sea.

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Food Agency to ensure food safety compliance (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025). While these emerging industries aim to align with broader EU aquaculture strategies, such as streamlining permitting and integrating ecosystem-based principles, implementation challenges remain substantial (Franzen et al., 2024).

The European framework for oyster aquaculture appears to be designed to be robust and grounded in an ecosystem-based approach to licensing and permitting. However, based on recent evaluations on-the-ground effectiveness appears limited. For instance, the European Commission's 2025 evaluation of the MSFD acknowledges that despite the presence of comprehensive planning mechanisms, "good environmental status" has not been reached in Europe's marine ecosystems. This is corroborated by the 2023 Quality Status Reports from regional bodies such as OSPAR, HELCOM, and the Barcelona Convention (UNEP/MAP), which collectively show that biodiversity loss and ecosystem degradation persist across European seas (European Commission, 2025). Similarly, the European Environment Agency's SOER[16] 2020 report and the IPBES regional assessment for Europe and Central Asia (2018) present additional evidence that the ecological health of marine environments continues to decline, pointing to systemic implementation gaps rather than deficiencies in the formal legislative structure.

The level of enforcement across Europe varies significantly depending on the country and the specific characteristics of the aquaculture operation. In regions with ongoing aquaculture development, such as Sweden, active dialogue between industry and regulatory authorities often results in periodic inspections, typically a few times per year (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025). Routine inspections by sanitary authorities, which usually take place once or twice annually, are common practice to verify farm documentation and animal health. In Sweden, inspections are typically conducted annually by the licensing authority; and operating without a license may result in the confiscation of equipment, criminal charges, or forced removal of infrastructure with associated fines if noncompliance persists. While regulatory agencies are generally accessible across Europe, effective exchange of information between stakeholders is often hindered by differing institutional mandates, expertise, and political priorities (ibid.).

Further, as noted under the Effluent Criterion, a survey of commercial aquaculture producers in 16 Atlantic-bordering countries found that statutory monitoring systems do include sanctions for noncompliance (Hughes, Diakos, & Irwin-Moore, 2023). The most frequently cited penalties included suspension of trading rights, revocation of health certifications required for commercializing or exporting products, loss of operating licenses, fines, and in isolated cases, the potential for criminal charges. However, the study did not report quantitative data on the frequency or scale of these penalties (ibid.).

United States

In the US, oyster aquaculture occurs along each of the coasts, and is regulated at the federal and state level (Farquhar et al. 2017), though local regulations can also impact oyster aquaculture permits. In its Strategic Plan to Enhance Regulatory Efficiency in Aquaculture, the National Science and Technology Council Subcommittee on Aquaculture noted that the regulatory framework for aquaculture in the United States is complex, involving multiple jurisdictions, laws, regulations, and agencies, such that the multiple Federal and State approvals required to farm seafood create time-consuming and costly processes and an uncertain operating environment for aquaculture businesses (NSTC, 2022).

[16] https://www.eea.europa.eu/soer/2020

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The Federal National Environmental Policy Act (NEPA) and State Environmental Policy Acts (SEPA) are the primary regulatory measures relating to potential land use change and habitat impacts. Several states have enacted their own Environmental Policy Acts, mirroring NEPA's requirements. These laws require state and local agencies to assess the environmental impacts of proposed projects, including oyster aquaculture, and to consider alternatives and mitigation measures. Both NEPA and SEPAs require consideration of cumulative impacts, which include describing how a proposed project, in combination with past, present, and reasonably foreseeable future actions, may affect the environment. Agencies assess whether the incremental impact of the project is significant in the context of other activities (40 C.F.R. § 1508.7; Cal. Code Regs. tit. 14, § 15355).

The U.S. Army Corps of Engineers (ACoE) issues aquaculture permits before a farm can be established, and these permits require consultation with the ACoE, the National Marine Fisheries Service and the US Fish and Wildlife Service, as well as approval by states to ensure the farm is consistent with the coastal zone management programs. For shellfish aquaculture, ACoE often utilizes Nationwide Permit 48 (NWP 48), which streamlines authorization for commercial shellfish activities, provided they result in no more than minimal adverse environmental effects individually or cumulatively. Additionally, state and local agencies are involved in permitting, however legislation varies from state to state. Each state must develop a Coastal Zone Management Plan (CZMP) that is consistent with (or more stringent than) the requirements of the federal Coastal Zone Management Act (1972). CZMPs are implemented through local level Shoreline Master Programs (SMP) which are specific to individual coastal counties. Counties are not required to coordinate SMPs to account for cumulative impacts. These programs regulate land and water use in the coastal zone, balancing economic development with environmental conservation. The following summarizes the information a shellfish producer must generally submit in relation to siting when applying for a lease considering some variation between states (Maryland Department of Natural Resources[17], n.d; Florida Department of Agriculture and Consumer Services[18], 2020):

- Use the Aquaculture Siting Tool to identify low-conflict lease areas.
- Submit corner coordinates of the proposed site in DMS or DDM format.
- Provide maps and aerial diagrams indicating the proposed lease area, including the staging/equipment storage site and offloading site.
- Visit the site under different seasonal and weather conditions to assess traffic, bottom type, and co-use potential.
- Record tidal depths, bottom characteristics, nearby land use, and human activity.
- Include cross-section diagrams showing water depth, bottom substrate, and height of added shell or equipment (e.g., cages, floats).
- demonstration that the proposed site complies with legal siting and spacing requirements, including: Avoiding navigation conflicts and maintaining required buffer zones.
- Sample equipment layout with the location and spacing of cages, lines, anchors, and markers.
- Plan for potential site restoration obligations upon lease termination.

If aquaculture activities will impact protected or endangered species, NOAA, or a designated agent for NOAA, may issue permits pertaining to the Endangered Species Act (ESA) and the Marine Mammal Protection Act (Fisheries.noaa.gov 2018). Consultations for new farms also seek to ensure compliance with the ESA and Essential Fish Habitat before aquaculture activities commence (NMFS, 2016). Permits are re-authorized every 5 years, dependent on re-assessment (NMFS, 2016). The NEPA regulates the process of conducting an EIA. Parameters assessed include protection of critical habitat (e.g. compliance

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[17] https://dnr.maryland.gov/fisheries/pages/aquaculture/getting-started.aspx
[18] https://www.fdacs.gov/About-Us/Publications/Aquaculture-Publications

with water use planning) and essential fish habitat, impact on historic resources and navigation, and impact on migratory fish and submerged aquatic vegetation (ECSGA, 2018).

South Korea

South Korean aquaculture activities are regulated by both the central government through The Ministry of Maritime Affairs and Fisheries, as well as provincial governments (FAO 2005a). The Fisheries Act (1990) and The Fishery Resources Protection Act (1953, as amended) make up the regulatory framework of Korean aquaculture, and cover aquaculture licensing and planning, natural resource management, and conservation (FAO 2005a). Along with these acts, the Aquaculture Industry Development Act (2019) clearly stipulates the licensing requirements that an oyster farmer would need to comply with to legally operate, many of which consider directly or indirectly an area based or cumulative management system in place for aquaculture in consideration of other industries for maintaining ecosystem functionality. This framework positions local governments as the primary permitting authorities, supported by the Ministry of Oceans and Fisheries for policy coherence and technical oversight, while environmental safeguards are embedded in site-specific licensing conditions and ongoing evaluations.

- Article 9 requires that the head of the local government (Si/Gun/Gu) or Mayor/Do Governor formulate development plans for licensed fish farms, considering environmental restrictions. All licenses must conform to a pre-existing development plan.
- Article 25 requires that the Ministry of Oceans and Fisheries to oversee notional policies, examination and evaluation of licenses.
- Article 10 requires oyster farmers (as part of shellfish aquaculture) to obtain a business license from local authorities according to the following criteria. Licenses are evaluated based on factors including site boundaries and distance between fish farms, aquaculture methods, facility standards, use of harmful organism repellents, and environmental safeguards
- Articles 20 and 49 state that the approval for use of public waters, should be granted simultaneously with the aquaculture license, and it is governed by the Public Waters Management and Reclamation Act.
- Article 25 states that license renewal requires evaluation of sediment pollution and farm management practices.
- Article 26 allows authorities to restrict or suspend licenses for reasons including military use, public projects, and ecological concerns.
- Article 56 requires that upon license expiration or revocation, aquaculture facilities must be removed unless exempted.
- Article 60 states that Aquaculture Industry Complexes should be promoted and financially supported, suggesting that spatial planning exists but is not necessarily mandatory.

When an aquaculture project is located on coastal land or included in a plan to develop water resources, it must undergo a comprehensive EIA process. It appears that the level of detail to develop in the required EIA, varies on a case-by-case basis, but the general basic requirements include the following items (filtered but not limited to those included ahead; relevant for Criterion 3 – Habitat) (Articles 9, 11, 22–24):

1. The area subject to strategic environmental impact assessment
2. A land use plan
3. Alternative plans
4. Locational conditions, status of existing land-use, and environmental features of the relevant area and its environments.
5. Changes in seasonal characteristics (an area with substantial environmental and ecological value).

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6. Other matters related to the maintenance of environmental standards.

Approval requires coordination through an Environmental Impact Assessment Council, which includes experts, relevant government agencies, and potentially representatives of affected residents (Article 8). Public consultation and consensus-gathering from residents and stakeholders are mandatory (Article 25). While the Act does not explicitly reference "aquaculture zones," it mandates land-use planning and zoning considerations as part of the strategic EIA (Article 11). Boundaries of allowable development areas are determined during this process using overlapping national environmental standards and laws (Articles 5–7). If environmental degradation is anticipated or detected, the Ministry of Environment can require mitigation or restoration measures as part of the "agreed terms and conditions" or during follow-up monitoring (Articles 31-32, 36, 40). These obligations are enforceable and can include suspension of operations for noncompliance.

According to FAO, (2025c) the Aquaculture Ground Management Act (2000) delineates strategies to improve sustainable and sanitary production. However, the full piece of legislation was not available at the time of writing. Additionally, the Framework Act on Marine Development (1987, as amended) deals with the economic development of the aquaculture industry, as well as the preservation and management of marine ecosystems (FAO 2005a). The Framework Act on Marine Development calls for science-based policy and management of aquaculture through research subsidies and support of research facilities.

Japan

In Japan, aquaculture legislation is regulated by the Ministry of Agriculture, Forestry and Fisheries (MAFF), but in practice many tasks have been delegated to the prefecture governments (FAO, 2025b). Japan is politically separated into different territories, or prefectures, with distinct Sea Areas. Each Sea Area has a designated Sea Area Fisheries Adjustment Commission as set forth in The Fisheries Law (1949, revised 1962), which also regulates licenses and fishing rights (FAO, 2025b).

The Central Fisheries Adjustment Council, as well as Sea Area Fisheries Adjustment Commissions (under the joint jurisdiction of the prefecture governments and the MAFF) regulate policy, and implement and enforce laws within the national framework (FAO 2004-2019). Aquaculture is regulated under the Sustainable Aquaculture Production Assurance Act (1999) which is specifically designed to promote environmentally responsible aquaculture practices. This legislation outlines comprehensive measures for siting, land-use, habitat impact mitigation, and cumulative environmental management. The Act applies to all aquaculture activities, encompassing both marine and inland operations (Refer to the following articles within the legislation for more details: Articles 1 - 5).

- It mandates that aquaculture areas, such as those used for oyster farming, must be maintained or restored to conditions that support the healthy growth of aquatic organisms.
- The Aquaculture Area Improvement Plan under Japan's Sustainable Aquaculture Production Assurance Act is a key, mandatory planning tool that regulates aquaculture siting and development, particularly for operators with demarcated fishery rights (e.g., Fisheries Cooperative Associations). Plans must detail the location, species, the suitability of the site for aquaculture activities, environmental improvement goals, implementation timelines, necessary facilities, and organizational structures. These plans must outline targeted measures (e.g., reducing organic loading, removing bottom sediment, and installing treatment infrastructure) to improve local water quality.

The Environmental Impact Assessment Act of Japan (1997) provides a procedural framework for identifying, assessing, and mitigating environmental risks, including those posed by oyster aquaculture

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effluent. Farm siting must undergo review for environmental considerations at the early planning stage. Proponents are required to assess the project's impact on specific environmental components, especially when changes in landform or new structures are involved (Art. 2, Art. 3-2). Aquaculture developments in Japan, such as oyster farms, may be subject to an EIA but its need depends on the scale, location, and anticipated environmental impacts of the project. For smaller-scale or less impactful projects, other laws and local zoning rules (e.g., Fishery Act, Sustainable Aquaculture Production Assurance Act) may apply instead. The following provisions of the EIA Act are central to determining the siting and planning requirements for aquaculture development in Japan.

- Aquaculture farms may require permits for land use or reclamation under associated legislation (e.g., Public Water Body Reclamation Act), and such permits can trigger the need for an EIA (Art. 2.2(ii)(a), Art. 4). Notification and screening by competent ministry determine if a Class-2 project must undergo EIA.
- The EIA Act mandates land-use planning and site-specific environmental review. Boundaries and zoning implications may emerge through scoping documents (Art. 5–7), public consultations, and coordination with local governments and the Ministry of the Environment. Additionally, through the EIA scoping process, cumulative and overlapping impacts can be assessed, potentially leading to indirect restrictions based on environmental thresholds.
- Project implementation areas ("target project implementation areas") must be defined and justified during scoping (Art. 5.1.iii), taking into account surrounding environmental conditions. The affected area is confirmed with prefectural and municipal authorities (Art. 6), ensuring alignment with national and local land-use policies.
- the law requires that environmental impacts be forecasted, mitigation measures proposed, and potential restoration actions evaluated within the EIA documents (Art. 11–13, and 21). Follow-up actions may be required if adverse impacts are detected.

The Basic Environment Law provides the broader regulatory framework for pollution control and environmental governance across all industries, including aquaculture.

- Requires farms to report on farm population density, feeds and other materials used on the farm, and measures taken to improve environmental conditions. The program is enforced through prefecture government oversight (Takeda 2010).
- Implementation of Environmental Pollution Control Programs in areas where pollution is or may become a concern.

The Ministry of Agriculture, Forestry and Fisheries, along with the Fisheries Cooperative Associations are responsible for the implementation of the Sustainable Aquaculture Production Assurance Act, while the Ministry of the Environment Prefectural Governments share responsibility in implementing the Basic Environment Law and the Environmental Impact Assessment Act. The Fisheries Agency, under the MAFF, manages Japan's marine resources and fisheries, as well as marine research institutes that contribute to the management of these resources (FAO 2004-2019). The MAFF enacted the Law to Ensure Sustainable Aquaculture Production (1999) to mitigate environmental degradation due to fish farming. In addition to this law, the MAFF put forth “Basic Guidelines to Ensure Sustainable Aquaculture Production” (1999) and "Aquaculture Ground Improvement Programmes" were designed and implemented by the Fisheries Cooperative Associations (FAO 2004-2019). Specific information on the level of enforcement, sanctions and policies was not readily available.

Overall, evaluating the management of oyster farm siting globally remains complex. However, licensing and site selection frameworks are, in many regions, reasonably robust and supported by regulatory

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oversight. As such, the score for Factor 3.2a – Content of Management Measures is 4 out of 10. The degree of enforcement varies across major producing countries and is influenced by national governance structures, farm-specific characteristics, and the associated environmental risks. While detailed enforcement data (e.g., sanctions or inspection frequency) are not consistently available, general indicators of regulatory activity and oversight were identified for most major oyster-producing regions. The score for Factor 3.2b – Enforcement of Management Measures is also 4 out of 10. The score for Factor 3.2 – Management Effectiveness is 6.4 out of 10.

Conclusions and final score

Oyster aquaculture is predominantly carried out in tidal, intertidal, and nearshore subtidal coastal areas, which are generally considered to be of high habitat value. The total global area occupied by oyster farming is estimated to be 1,882 km². Based on this estimate global oyster farms occupy about 1.3–1.5% of the total tidal flat area worldwide.

One of the main concerns associated with the introduction of culture infrastructure into coastal ecosystems and their interaction in these locations is its potential to alter local hydrodynamics. These alterations are primarily driven by the configuration, density, and spatial extent of farming gear, which can change current velocity and flow regimes. In addition, harvesting methods such as mechanical or suction dredging are known to cause disruption to benthic habitats. Despite these concerns, the overall impact of oyster farming on habitat functionality is generally considered low. In fact, oyster culture is often associated with a range of positive ecosystem services, including, habitat provision for other marine species, and shoreline stabilization. The score for Factor 3.1 is 9 out of 10.

Globally, evaluating the management of oyster farm siting remains complex. However, licensing and site selection frameworks are, in many regions, reasonably robust and supported by regulatory oversight. The degree of enforcement varies across major producing countries and is influenced by national governance structures, farm-specific characteristics, and the associated environmental risks. While detailed enforcement data (e.g., sanctions or inspection frequency) are not consistently available, general indicators of regulatory activity and oversight were identified for most major oyster-producing regions. The score for Factor 3.2 is 6.4 out of 10. The combination of Factors 3.1 and 3.2 result in a final Criterion 3 – Habitat score of 8.1 out of 10.

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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.*

Chemical Use parameters	Score	
C4 Chemical Use Score (0-10)	**9**	
Critical?	NO	**Green**

Criterion 4 Summary

Evidence suggests that oyster farming does not typically employ the use of chemicals. Best management practices for oyster farming worldwide designate physical methods (e.g., pressure-washing, hand removal, freshwater baths and/or air drying) to prevent and remove predators and fouling organisms from gear and from oysters themselves. Calcium hydroxide (hydrated lime) may also be used as a dip or spray to control biofouling, but this is not associated with any significant environmental concern. While antibiotics may be used in the hatchery phase, they are not used to treat disease during growout, as their application is not practical given the production systems used. Overall, the use of physical and non-chemical methods of biofouling control are effective and appear to be widely utilized in oyster culture. Given the global scope of this report, there may be some circumstances in which chemicals are used for fouling, disease, or predation control, but the majority of evidence suggests chemicals used, if any, have no impact on non-target organisms. The final numerical score for Criterion 4 – Chemical Use is 9 out of 10.

Justification of score

One of the widely recognized advantages of shellfish aquaculture is its relatively minimal use of chemical inputs, both in terms of type and quantity (Hughes et al., 2023). As a result, low trophic aquaculture, such as oyster farming, is generally not associated with the release of novel chemical compounds into the environment (ibid.). Although antibiotics may occasionally be applied at the hatchery stage to manage bacterial diseases, their use during the grow-out phase is not practical due to the open nature of production systems and the rapid dilution of any substances introduced into the surrounding waters

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(Pernet et al., 2016). Although pesticides like copper sulfate, calcium oxide, trichloroethylene-coated sand, and insecticides were used in oyster farms starting in the 1930s to control biofouling (Gan et al., 2025; Loosanoff et al., 1960; Jory et al., 1984; Shumway et al., 1988), concerns over their environmental and human health risks led farms to abandon chemical controls in favor of manual measures (ECSGA, 2010; Creswell & McNevin, 2008).

Instead, disease management in oyster culture relies more heavily on preventative and non-chemical strategies, including appropriate stocking densities, selective breeding, culling of diseased animals, and, at the hatchery level, controlling salinity and temperature alongside other biosecurity protocols (Mercer et al., 2024; King et al., 2018; Sweet and Bateman, 2016; Pernet et al., 2016).

Consistent with these observations, a global review by Lulijwa et al. (2020) highlights that while therapeutic antibiotic use remains common in finfish and crustacean aquaculture, particularly in major producing regions such as China, Europe, and the Americas, mollusk farming is notably different. In addition, import rejection records for oysters compiled by the U.S. Food and Drug Administration in 2024 reported no detections of either chemical residues or relevant disease agents, further corroborating the minimal chemical use in oyster production (FDA, 2024).

Biofouling represents a persistent operational challenge in oyster aquaculture, affecting both farm infrastructure and the oysters themselves (Freitas et al., 2023). Given the toxicity, persistence, and potential for bioaccumulation of many conventional antifouling agents in the oysters (examples listed above), current biofouling management strategies in shellfish aquaculture favor non-chemical methods (ibid). However, calcium hydroxide (hydrated lime) remains one of the few broadly accepted substances in oyster farming, used primarily for biofouling control, pH stabilization, and nutrient supplementation. Its continued use is attributed to its low environmental impact, with studies indicating minimal adverse effects on surrounding habitats and non-target species (Boyd, 2017; PEIDFARD, 2014; Fitridge, 2012).

Commonly adopted non-chemical approaches to control biofouling include air drying, freshwater or brine dips, power washing, and mechanical scrubbing, all of which are widely recognized as effective and environmentally benign (although labor intensive) (Sühnel and Strand, 2020; PEIFARD, 2014; Fitridge et al., 2012; Doiron, 2008; pers. comm., H. Pearson, Island Creek Oysters, 2018). In addition, material selection plays a key role in fouling resistance: high-density polyethylene (HDPE) is now the preferred material for aquaculture gear, such as longlines, baskets, trays, and mesh bags, due to its smoother surface, which delays fouling onset and facilitates easier maintenance (Freitas et al., 2023).

These findings are further supported by direct communication with aquaculture experts, who confirmed that no chemical treatments are used in the grow-out phase of low trophic species, inclusive of oysters, across key producing regions such as Europe, Brazil, China, and the United States (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025; pers. comm. Wenbo Zhang, Shanghai Ocean University, March 2025). No further evidence was identified to suggest that chemical use in oyster aquaculture presents a significant area of concern.

Conclusions and final score

Evidence suggests that oyster farming does not typically employ the use of chemicals. Best management practices for oyster farming worldwide designate physical methods (e.g., pressure-washing, hand removal, freshwater baths and/or air drying) to prevent and remove predators and fouling organisms from gear and from oysters themselves. Calcium hydroxide (hydrated lime) may also be used as a dip or

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spray to control biofouling, but this is not associated with any significant environmental concern. While antibiotics may be used in the hatchery phase, they are not used to treat disease during growout, as their application is not practical given the production systems used. Overall, the use of physical and non-chemical methods of biofouling control are effective and appear to be widely utilized in oyster culture. Given the global scope of this report, there may be some circumstances in which chemicals are used for fouling, disease, or predation control, but the majority of evidence suggests chemicals used, if any, have no impact on non-target organisms. The final numerical score for Criterion 4 – Chemical Use is 9 out of 10.

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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.*

C5 Feed Final Score (0-10)		10.0
Critical?	NO	GREEN

Criterion 5 Summary

Oysters feed naturally on phytoplankton and other suspended particles (seston), eliminating the need for external feed inputs during production cycle (i.e., excluding the hatchery phase). Their filtration can benefit coastal ecosystems affected by excess nutrients by reducing phytoplankton and suspended sediments, and improving water quality. In low-nutrient environments, excessive nutrient removal due to the increased biomass introduced to the ecosystem through farming may limit primary productivity and trigger food-web changes. However, it appears that these effects are context-dependent and typically localized and temporary. Overall, given global concerns about nutrient pollution, the reliance on naturally occurring seston, and the absence of external feed inputs are considered to result in net ecological benefits for oyster aquaculture. Therefore, the final score for Criterion 5 – Feed is 10 out of 10.

Justification of score

Because oysters are filter-feeders, they consume naturally occurring phytoplankton and other particulate matter (i.e., seston) for food (Sun et al., 2025; Pangea Shellfish Company 2015, Doiron 2008). The culture of bivalve shellfish in open systems therefore does not require the provision of an external feed for the vast majority of the production cycle (except in the hatchery setting[19] which is outside of the scope of this report) (MPI 2013; Doiron 2008). No external marine or terrestrial ingredients (e.g., fish meal, fish oil, soy etc.) are involved in feeding bivalve shellfish.

As discussed in Criterion 2 – Effluent, the removal of nutrients in the form of seston by filter-feeding oysters is typically seen as beneficial where nutrients such as nitrogen and phosphorous are in excess (i.e., from anthropogenic sources). For instance, oyster filtration can reduce phytoplankton and suspended sediments in the water column, leading to improved water clarity and greater light penetration, which can enhance eelgrass productivity and extend the euphotic zone (Sandoval-Gil et al., 2015; Oyster BMP Expert Panel, 2016; Dumbauld et al., 2009; Ward, 2016; Rose et al., 2015; Gallardi et al., 2014; Rice, 2008).

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[19] Feed in the form of cultured microalgae is provided in oyster hatcheries.

However, in some contexts, the removal of nutrients by oysters may in fact be detrimental. For example, in low-nutrient ecosystems, denitrification and nutrient uptake by oyster tissues may suppress primary productivity by limiting the availability of nitrogen to phytoplankton and other base-level producers (Ray et al., 2020). This can trigger trophic cascades in which key food resources are depleted (Ward 2016, Wiedenhoft 2017, Mote.org 2018). Oyster filtration has been shown to reduce the biomass of zooplankton groups that compete for similar food resources, including macro- and mesozooplankton, leading to subsequent declines in higher trophic levels such as zooplanktivorous fish, carnivorous fish, and cephalopods (Gao et al., 2020; Gallardi et al. 2014; Tan et al., 2024). Some farms with extractive species have exceeded the local carrying capacity causing food depletion for native species around the farms (Lindblom et al., 2022). For example, In Sanggou Bay, where oyster farming is currently concentrated in approximately 30 km^2 of the inner bay, farming densities have reached up to 2943 $t\ km^{-2}$ (i.e., roughly three times the ecological carrying capacity of 976 $t\ km^{-2}$). Such intensification has driven declines in oyster competitors (e.g., zooplankton, benthic crustaceans, and polychaetes), which cascades into significant reductions in higher trophic levels, including zooplanktivorous and carnivorous fish and cephalopods. For instance, long-term ecosystem modeling suggests that increases in oyster biomass beyond 1.5–2.0 times the present level can cause zooplanktivorous fish populations to collapse to below 10% of their original standing stock in Sanggou Bay (Gao et al., 2020; Umehara et al., 2018; Liu et al., 2015). Moreover, a 14-month field study conducted in Daya Bay, southern China, found that chlorophyll-a concentrations in oyster farming areas were approximately 60% lower compared to those at the reference site (Jiang et al., 2016). Similarly, reductions in chlorophyll-a concentrations ranging from 27% to 48% have been observed in other oyster-growing regions, including Denmark, Norway, Canada, and France’s Thau Lagoon in the Mediterranean, and have been associated with the depletion of phytoplankton abundance (Tan et al., 2024).

Building on the evidence of potential impacts from oyster aquaculture, some studies suggest that such effects on oyster-feeding dynamics are often temporary and spatially limited. For example, a long-term study in Tapong Bay, Taiwan, found that chlorophyll-a concentrations inside the farm increased fourfold after harvest, indicating temporary nutrient depletion (Tan et al., 2024). Likewise, research on four commercial farms in lower Chesapeake Bay found statistically significant but small and inconsistent water-quality differences between farm and non-farm sites, implying that farms resulted in localized impacts (Turner et al., 2019). These findings suggest that nutrient removal by oyster farming is typically localized, with the magnitude and direction of effects depending heavily on site-specific conditions and management practices (Tan et al., 2024; Turner et al., 2019).

Given the global concerns regarding nutrient pollution in coastal ecosystems (Ray & Fulweiler, 2021), instances of nutrient or plankton depletion associated with oyster farming in low-nutrient environments are considered exceptional cases. Consequently, the marine feed resources (i.e., seston) utilized by oyster farms are generally regarded as sustainable, and the absence of a need for externally supplied feed is recognized as a net ecological benefit of oyster culture in coastal environments. Therefore, the final numerical score for Criterion 5—Feed is 10 out of 10.

Conclusions and final score

Oysters feed naturally on phytoplankton and other suspended particles (seston), eliminating the need for external feed inputs during production cycle (i.e., excluding the hatchery phase). Their filtration can benefit coastal ecosystems affected by excess nutrients by reducing phytoplankton and suspended sediments, and improving water quality. In low-nutrient environments, excessive nutrient removal due to the increased biomass introduced to the ecosystem through farming may limit primary productivity and

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trigger food-web changes. However, it appears that these effects are context-dependent and typically localized and temporary. Overall, given global concerns about nutrient pollution, the reliance on naturally occurring seston, and the absence of external feed inputs are considered to result in net ecological benefits for oyster aquaculture. Therefore, the final score for Criterion 5 – Feed is 10 out of 10.

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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.*

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		7
C6 Escape Final Score (0-10)		**4**
Critical?	NO	**Yellow**

Criterion 6 Summary

The risk of larval escape in oyster farming is inherently high due to the open nature of grow-out systems and the highly fecund broadcast spawning behavior typical of most cultured oyster species. To mitigate this risk, the use of triploid spat (i.e., functionally sterile oysters) has emerged as a key best management practice. This approach has been widely adopted in major oyster-producing countries such as China, the United States, and France. However, uptake remains uneven across regions and species, and it cannot be considered to be fully adopted across the global industry. It is also noted that while the use of triploid spat reduces fecundity to approximately 2% of standard diploid spat (and thereby substantially reduces the numbers of oysters escaping during spawning events), as a single female diploid oyster can release approximately 60 million eggs, even the 98% reduction in triploids still represents a high escape risk from the combined spawning output of the farmed stock The overall risk of escape is high, and the score for Factor 6.1 is 0 out of 10.

Oysters can be highly invasive due to their biological traits, with species like *C. gigas* now established in many regions outside their native range, largely through aquaculture or unintentional introductions. While non-native oysters often compete with native species and alter ecosystem structure, in regions where farming occurs within their native range, ecological risks are generally lower, and genetic introgression from cultured to wild populations has been minimal. Early introductions (pre-1970) often led to establishment, but appears to have become rare in recent decades (although, there is no readily available evidence on whether new introductions are still occurring or to what extent), partly due to management measures such as the widespread adoption of triploid spat. While oysters are highly fecund, triploids produce negligible viable offspring beyond larval stages, making introgression risks from them minimal compared to diploids. Overall, considering high post-escape mortality, widespread historical establishment, limited evidence of genetic impacts, and the remaining risks of competition, an intermediate score is assigned. The score for Factor 6.2 is 7 out of 10.

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Factors 6.1 and 6.2 combine to result in a final numerical score of 4 out of 10 for Criterion 6 – Escapes.

Justification of score

Factor 6.1. Escape risk

One of the main threats associated with shellfish aquaculture is the non-native farmed species spreading beyond production areas (Lindblom et al., 2022). In oyster culture, this "escape" risk is inherent, as all grow-out systems are open to the environment. While adult oysters, being sessile, cannot escape physically, they are highly fecund broadcast spawners, and are mostly harvested after reaching sexual maturity. For instance, *C. gigas* females measuring 8–15 cm can release up to 60 million eggs per spawning event (Martinez-Garcia et al., 2021). As a result of the uncontrolled spawning, and regardless of species, production region, and farming system, oyster aquaculture is considered to be vulnerable to large dispersal (i.e., escape) events, with no possibility of recapturing[20] escaped individuals (pers. comm. F. Chen, 2018; Doiron, 2008; Anglès d'Auriac et al., 2017; MPI, 2013). This issue is particularly evident with the Pacific oyster, which has been translocated worldwide over the past century (both accidentally but primarily through deliberate introductions for aquaculture) and is now considered one of the most invasive marine species globally (Sutherland et al., 2020; Méndez et al., 2015).

A key strategy to reduce the risk of spawning-related escapes is the use of triploid oysters, which are functionally (but not completely) sterile (Bishop et al., 2023). For example, while Pacific oysters are naturally diploid, triploid spat minimizes the likelihood of genetic interaction with wild native populations, and reduces the risk of the species becoming established (or extending their range) where they are non-native (Chen et al., 2024; Jiang et al., 2023; Element Seafood, 2016; Pers. comm., B. Rheault, 2019; L. Cruver, 2019). Triploid technology was originally developed and patented in the U.S. (Moore, 2012; Hollier, 2014; Pacific Shellfish Institute, 2015). Female triploids exhibit drastically reduced fecundity (i.e., around 2% that of diploids), and offspring from triploid parents suffer high mortality, and is further discussed under Factor 6.2. Competitive and genetic interactions (Chen et al., 2024; Jiang et al., 2023; Oregon State University, 2019; Go Deep Shellfish Aqua, 2019; Miller, 2014). Beyond reproductive control, triploid oysters also offer advantages such as improved growth after sexual maturity and better meat quality in warmer months compared to diploids (Chen et al., 2024; Vignier et al., 2024; Jiang et al., 2023). However, triploid larvae show higher mortality and lower D-stage yields (i.e., first fully shelled larval stage) than diploids (Vignier, 2017; Vignier et al., 2025).

The global prevalence of polyploid spat use in oyster aquaculture remains uncertain; however, triploid spat has become standard practice in several major producing regions (Chen et al., 2024; Vignier et al., 2024; Jiang et al., 2023). Triploids comprise around 30% of global Pacific oyster production, and 50% of American cupped oyster (*C. virginica*) production (Vignier et al., 2024). In the United States, triploids comprise 50% of Pacific oyster hatchery output in the Pacific Northwest and nearly all commercial spat for American cupped oyster in the Atlantic Northeast (pers. comm., Emily Johns, Hog Island Oysters Co., October 2025; Vignier et al., 2024). As of 2019, approximately 30% of France's Pacific oyster production and about 50% of New Zealand's harvests used triploid spat (Vignier et al., 2024). China has widely adopted triploid spat production technology. Early estimates suggested over 68% of its Pacific oyster production used triploids (Gong et al., 2004), and more recent data from 2023 indicate that in northern China, triploid spat accounts for roughly 80% (equivalent to 1 million metric tons) of what is specifically

[20] It is noted here that as there is no practical way to "recapture" these "escaping" oysters, a recapture adjustment is not allocated in this assessment.

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reported as Pacific oyster (i.e., potentially representing an even higher amount when considering broader *Crassostrea spp.* classifications) (Sun, Zhao, & Yang, 2025; Vignier et al., 2024; Fishstat, 2024). In contrast, uptake remains limited in some regions: in Australia, triploids represent just 15% of the country's 8,000-tonne oyster production, and in Sweden, biosecurity restrictions banning spat imports prevent any triploid production (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025; Vignier et al., 2024). With China representing approximately 88% of global oyster production (see Production Statistics section), and potentially using up to 80% triploid stocks, it can be assumed that the global use of triploids is substantial. And more broadly, the use of triploid spat is expected to gradually become a standard industry practice, continuing a trend observed over the past few decades (Yu et al., 2023).

The risk of larval escape in oyster farming is inherently high due to the open nature of grow-out systems and the species' broadcast spawning behavior. The use of triploid spat, which reduces fecundity to approximately 2% of standard diploid spat substantially reduces the numbers of oysters escaping during spawning events, but for a highly fecund species there is still inevitably a substantial escape risk from the combined spawning of the farmed stock. While the use of triploids has been widely adopted in major oyster-producing countries such as China, the United States, and France, its uptake remains uneven across countries and across species. In some regions, adoption is limited by regulatory barriers, lack of triploid technology, and logistical hurdles such as the cost of importing triploid spat (pers. comm., Emily Johns, Hog Island Oysters Co., October 2025; pers. comm., Jorge Chaves, CIBNOR, September 2025). However, the apparent high use of triploids in China indicates that the global use is substantial.

Overall, the broadcast spawning of oysters inherently carries a high escape risk. While the use of triploid stocks greatly reduces fecundity, the naturally high reproductive output of oysters means this reduction may have limited ecological significance; even with a 98% decrease, the cumulative spawning of the farmed stock can still release substantial numbers of offspring into surrounding waters. Therefore, the score for Factor 6.1 is 0 out of 10.

Factor 6.2. Competitive and genetic interactions

The global expansion of oyster aquaculture presents a range of potential competitive and genetic interactions with wild populations. In many regions, native species are farmed; however, hatchery production of spat and selective breeding for traits favorable to aquaculture may alter the genetic integrity of wild populations if farmed oysters successfully spawn (Bishop et al., 2023; Harwell et al., 2010). For oysters cultured within their native range, farmed stocks are typically derived either from natural settlement within the same waterbody or from hatchery-reared spat (MPI, 2013). Although hatchery production is considered the predominant method, passive collection of wild oyster spat remains widely used in many regions. (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025; pers. comm. Wenbo Zhang, Shanghai Ocean University, March 2025; pers. comm., B. Rheault, 2019). The extent to which hatchery-produced spat influence wild genetic diversity remains uncertain and likely varies by species and region (Martinez-Garcia et al., 2021; Anglès d'Auriac et al. 2017; Levinton, Doall and Allam 2013). Additionally, competition and potential displacement of native species, including native oysters, are among the most commonly recognized negative outcomes associated with the establishment of feral oyster populations resulting from the introduction of non-native species. Nevertheless, a global review of cultured oysters found that in some instances, no negative effects of *C. gigas* have been observed, and in certain contexts, despite being non-native species, its presence may offer net benefits, by fulfilling some ecosystem functions once performed by native oysters, whose populations have experienced significant global declines (Martinez-Garcia et al., 2021).

Introductions and Establishments

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The oyster production of 17 commercial species reported by FAO as of 2024 was reported in 36 countries since 2012 (Fishstat, 2024). It has been speculated that oyster introductions began as early as the seventeenth century, when *Crassostrea angulata* (the "Portuguese oyster") was brought from Asia to Europe (Ruesink et al., 2005 and references therein). By the 1950s, oyster translocations for aquaculture were already widespread, often intended to replace declining native oyster stocks or to establish new export commodities. While most introductions of non-native oysters have been associated with aquaculture, others have occurred through intentional restocking efforts, accidental transfers via global shipping (e.g., attachment to vessels, equipment, or transport in ballast water), and, to a lesser extent, for research purposes (Martinez-Garcia et al., 2021). Over the past 150 years, France has received more introduced oyster species than any other country, with at least eight species brought in for aquaculture or research (Ruesink et al., 2005 and references therein). While the current extent of intentional introductions of non-native species for aquaculture is unclear, there are anecdotal reports that, in rare cases, individual producers obtain spat without notification, permits, or certificates for trial grow-out (pers. comm., Jorge Chaves, CIBNOR, September 2025). Even so, the literature suggests this practice has largely ceased, given the impacts outlined in the "Competition" section.

The Pacific oyster is the most widely translocated oyster species. Its establishment is reported in 30 countries; therefore, given its broad global distribution it serves as the most appropriate proxy for assessing the potential escape risks associated with oyster aquaculture (Martinez-Garcia et al., 2021; Herbert et al., 2016). Accordingly, it is used in this assessment to represent escape risks of global oyster production.

Understanding the potential invasiveness of oysters (especially *C. gigas*) requires consideration of its inherent biological traits. This species (native to China, Japan, and South Korea – see Figure 11) exhibits remarkable ecological plasticity, thriving across a broad range of salinities (10–50 psu) and temperatures (–1.8 to 35°C), though successful reproduction occurs within narrower thermal thresholds (Martinez-Garcia et al., 2021). Its habitat versatility allows it to colonize both stable substrates, such as rocks, shells, and rubble, and softer mud and sand-mud bottoms, from mid-tidal zones down to depths of 40 meters. In addition, *C. gigas* demonstrates a highly prolific reproductive capacity (fecundity), as protandrous hermaphroditic females measuring 8–15 cm can release up to 60 million eggs per spawning event (ibid.).

Additionally, oysters are genetically diverse but also carry a high genetic load due to a high rate of deleterious mutations and segregation distortion. In hatchery populations, the combination of high reproductive variance and small effective population sizes can increase the prevalence of harmful recessive mutations, especially affecting survival during early developmental stages like metamorphosis. Although mass selection is a common breeding strategy, it poses risks of inbreeding depression, which has been linked to high early mortality. These biological traits and life-history characteristics can limit the effectiveness of genomic tools in oyster breeding programs (Jiang et al., 2023).

These characteristics collectively contribute to Pacific oysters' capacity to establish self-sustaining populations beyond farming areas when introduced to new environments (Jiang et al., 2023). That potential is strongly shaped by local environmental conditions. For example, in Baja California Sur, Mexico, Pacific oysters were present for roughly five decades without feral records until 2019, when uncultivated, rock-attached adults with mature gonads were detected in the northern peninsula, indicating a prolonged adaptation period before successful reproduction and naturalization (Chávez-Villalba and Alcántara-Razo, 2025).

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As previously noted, a key strategy to mitigate spawning-related escape risks is the use of triploid oysters, which are functionally, though not entirely, sterile (Bishop et al., 2023). While concerns remain due to the exceptionally high fecundity associated with oyster broadcast spawning, it is important to recognize that most larvae produced from triploid crosses are aneuploid and fail to survive beyond the early larval stages. Flow cytometry has shown that spermatozoa from triploid oysters are aneuploid, carrying ~1.5 times the DNA of diploid sperm (Guo & Allen, 1994). Fertilization with such gametes results in irregular ploidy combinations, producing predominantly aneuploid embryos. Guo and Allen (1994) reported that during the first week of larval rearing, 75–90% of these aneuploids died, leaving tetraploid larvae as the dominant survivors by Day 7 post-fertilization. Even so, overall survival remained extremely low: typical larval runs yielded <1% survival, and by three months only 0.07% of fertilized eggs developed into spat.

These findings demonstrate that while triploids can produce gametes, their offspring are overwhelmingly non-viable (Vignier et al., 2024; Chen et al., 2024). In fact, the reproductive potential of triploid × triploid crosses has been estimated at only 0.0008% of that of normal diploids in controlled spawning experiments (Guo & Allen, 1994a). It is therefore highly unlikely that such spawning events would produce any viable contribution to wild populations (in terms of oyster numbers, biomass, or of genetic material) under natural conditions (Vignier et al., 2024; Chen et al., 2024; Guo & Allen, 1994).

With this biological context in mind, it is important to examine the global patterns of *C. gigas* distribution presented in Figure 11, which distinguishes between regions where it remains within its native range (yellow regions), areas where it has been introduced but not established (light purple regions), where they have been successfully established (dark purple regions), and locations where there have been no known introductions (grey regions) (Martinez-Garcia et al., 2021).

Pacific oyster introductions have been most widespread in Europe, where they were introduced to 68% of coastal countries since 1961 (beginning in Germany) and have established self-sustaining populations in 91% of these coastal regions (20 out of 22 regions, with France hosting established populations since 1975) (Martinez-Garcia et al., 2021; Ruesink et al., 2005). In the Americas, introductions date back to 1902 on the U.S. West Coast and 1912 in Canada, and ultimately occurred in 55% of the continent's coastal countries . In Oceania, introductions began in 1947 in Australia and ultimately occurred in 50% of the region's coastal countries. In Asia, excluding the species' native range of China, Japan, and South Korea, introductions have been reported in 33% of coastal countries, though precise dates are unclear. In Africa, introductions date to 1950 and have been recorded in 24% of the continent's coastal countries. Establishment rates in these regions have also been notable, with self-sustaining populations reported in 30% of African coastal countries (3 of 10), 23% in the Americas (5 of 22), 18% in Oceania (2 of 11), and 22% in Asia (2 of 9, excluding native regions) (Martinez-Garcia et al., 2021).

C. gigas establishment rates were highest for early introductions (70% before 1970) but appear to be rare since 2010. As mentioned previously, it remains unclear to what extent these introductions continue to occur, or whether there is evidence confirming that they have ceased entirely. Additionally, establishment success increases with latitude, with 30°N acting as a threshold; no clear decline is seen at higher latitudes. Based on temperature tolerances, *C. gigas* could potentially expand to 100,000 km of global coastline, compared to its current ~40,000 km range (Martinez-Garcia et al., 2021). While this study provides valuable insight into where *C. gigas* is being produced outside its native range, covering the majority of nations that have adopted the species for aquaculture, and where it has successfully established versus where it remains unestablished, it remains challenging to accurately estimate these dynamics for other oyster cultured species. More broadly, significant uncertainties persist regarding how these introductions have altered the diverse ecosystems in which non-native aquaculture occurs, as well

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as how genetic differences between cultured and wild stocks may have impacted regions where the species are considered native.

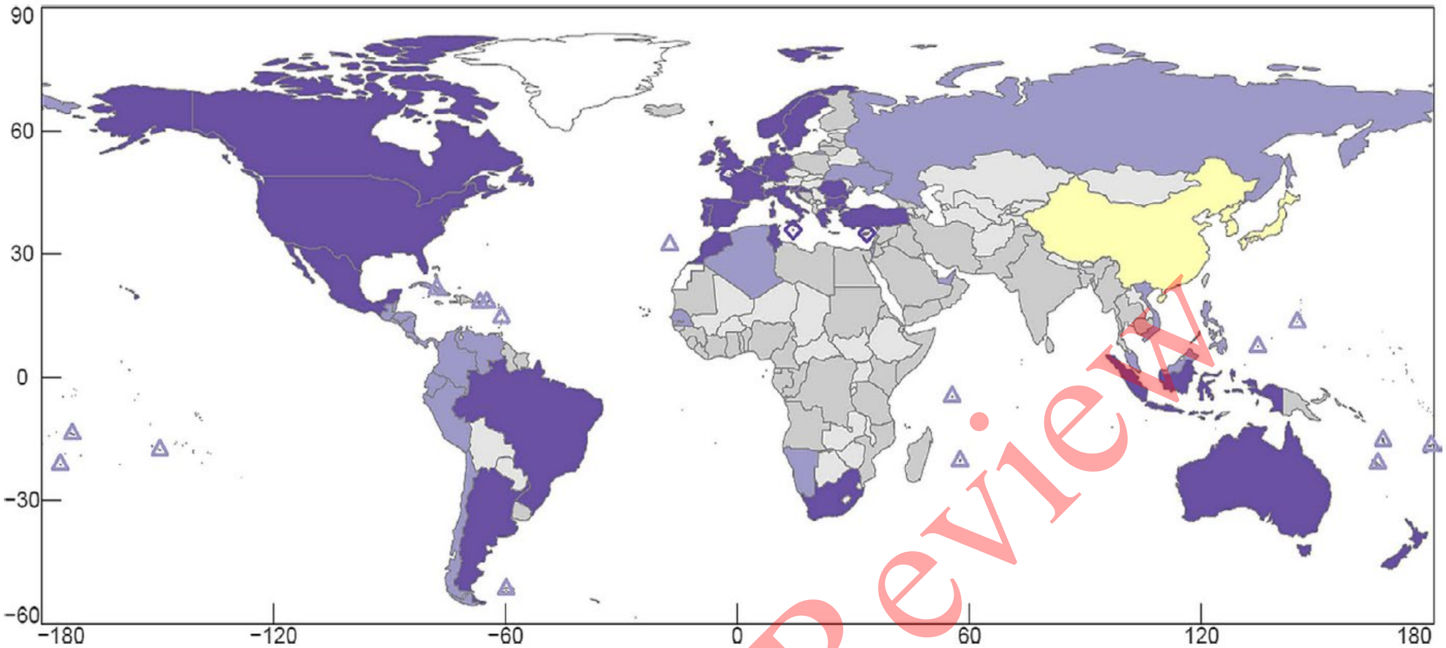

Figure 11. Map of 64 countries and 10 territories with known outcome for introduction and establishment of Pacific oysters (Crassostrea gigas). Yellow: native range, which extends into eastern Russia. Grey: coastal country with no known introduction. Light purple: introduced but not established, including islands marked as triangles. Dark purple: established (self-reproducing populations), including islands marked as diamonds. (Built using R package rworldmap) (Map and figure caption taken from, Martinez-Garcia et al., 2021).

Introgression

While oysters have demonstrated the ability to establish feral populations when introduced outside their native habitats, studies to date within their native ranges have found little evidence of genetic introgression from aquaculture lines into wild oyster populations (Bishop et al., 2023 and references therein; Sutherland et al., 2020). This may reflect the fact that aquaculture strains, typically selected for traits such as fast growth rather than resilience to environmental stressors, may be maladapted to survival in wild conditions (Bishop et al., 2023). Additionally, in many estuaries, the biomass of cultivated oysters remains small relative to remnant wild populations, limiting opportunities for introgression (ibid.). Recent genome-wide studies further support these findings; for example, Sutherland et al. (2020) analyzed over 16,000 genetic markers in naturalized and farmed *C. gigas* populations across Europe, Asia, and North America, and found very low levels of genetic differentiation between wild populations, and limited evidence for introgression from hatchery-farmed stocks. Additionally, oyster samples from China (i.e., farmed and wild), were distinct from Japan–Canada–France translocation lineage, confirming known historical translocation patterns, but again does not suggest farmed oysters have affected wild population genetics significantly. While hatchery populations exhibited some signatures of domestication and private alleles suggestive of non-local origins, there was no evidence of strong within-generation selection or significant gene flow into wild populations (ibid.).

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The AquaVitae survey introduced in Criterion 2 – Effluent (which covered 16 Atlantic-bordering countries and included responses from 18 oyster producers) indicated that at least five producers identified genetic introgression as an environmental risk of low-trophic aquaculture (LTA), for which current monitoring is not mitigating the risk (Hughes et al., 2023; Hughes, Diakos, and Irwin-Moore, 2023). Unlike other biotic risks, genetic introgression showed higher risk magnitude where no monitoring was in place, suggesting a gap in effective mitigation (Hughes, Diakos, and Irwin-Moore, 2023). Monitoring is not widely implemented due to the complexity, cost, and technical requirements involved, such as genomic sequencing, SNP marker development, and sampling of wild populations, which exceed the capacity of most producers, particularly small-medium producers (ibid.).

Competition
In addition to the risks of introgression, the introduction of non-native oyster species, particularly *C. gigas*, has led to competitive displacement of native species (Botta et al., 2020; Harris, 2008). These impacts arise from both resource competition and habitat modification, as the broadcast-spawning nature of *C. gigas* facilitates the establishment of dense oyster reefs, which can significantly alter native biodiversity and ecosystem dynamics (Federal Agency for Nature Conservation, 2018; Herbert et al., 2016; Botta et al., 2020; Wilkie et al., 2013). For example, *C. gigas* has displaced native oyster populations, overgrown benthic species, and altered benthic community structure (GISD, 2019; Ojaveer et al., 2018; Anglès d'Auriac et al., 2017; Padilla et al., 2011; Wilkie et al., 2013). On the other hand, in regions that culture native oysters using passive collection or strong genetic management to avoid gene-pool dilution, their broadcast spawning can enhance recruitment and aid the recovery of local wild stocks (pers. comm., Robert Rheault, ECSGA, October 2025; pers. comm., Emily Johns, Hog Island Oysters Co., October 2025; pers. comm., Jorge Chaves, CIBNOR, September 2025).

Across multiple countries, *C. gigas* feral populations have shown varying degrees of competition with native species. In several European regions (UK, Ireland, France, Germany, Belgium, Norway, Croatia, Romania), *C. gigas* has displaced or competed with native bivalves such as *Ostrea edulis*, *Mytilus edulis*, *Cerastoderma edule*, *Sabellaria spp.*, and other invertebrates, often through overgrowth, spatial exclusion, or food competition (Martinez-Garcia et al., 2021). In some cases, niche differentiation (e.g. intertidal vs. subtidal zones in Croatia) has reduced direct competition, though dietary overlap and larval predation still occur. In France, *C. gigas* was introduced following the collapse of *C. angulata* populations (see Criterion 7 – Disease), with imports from Japan and Canada serving as broodstock for new culture operations (Botta et al. 2020). While this transition revitalized French oyster production and consolidated *C. gigas* as the dominant commercial species in European markets, it also accelerated the marginalization of *O. edulis*, pushing the latter close to extinction in several areas (Botta et al. 2020). Empirical evidence from Denmark further illustrates this competition, where *C. gigas* outcompetes *O. edulis* for food and space (Zhen 2018; Chen 2018; Tang 2018). Similarly, in Australia and New Zealand, Pacific oysters overgrow native oysters (*Saccostrea glomerata* and local species), complicating aquaculture operations and requiring costly removal (Martinez-Garcia et al., 2021). This competitive dynamic extends beyond interactions among oyster species; oysters can also compete with native seagrasses, as both rely on overlapping habitat and environmental resources. Such competition for limited space and resources can directly influence the success and persistence of both groups within shared coastal ecosystems (Gardner et al., 2017).

In Sanggou Bay, oyster farming densities have reached up to 2943 t km^{-2}, roughly three times the ecological carrying capacity of 976 t km^{-2} leading to clear sings phytoplankton and microzooplankton

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depletion. Zooplanktivorous fish are particularly vulnerable, with their biomass dropping to as low as 8.5% of baseline levels under high-intensity farming scenarios. Long-term oyster expansion has also shifted seasonal zooplankton dynamics, largely due to intensified food competition during peak shellfish feeding periods (Gao et al., 2020 and references therein). While, these feeding-related impacts are recognized here as indicators of competition, they are accounted for under Criterion 5 – Feed.

Nonetheless, a similar effect is caused by the presence of fouling species on suspended culture systems and settled escaped oysters, adding additional filtering pressure, and further amplifying resource competition and ecosystem impacts (Gao et al., 2020 and references therein). These impacts are likewise considered a potential competitive effect escapees and are therefore addressed here under Criterion 6 – Escapes. However, the extent to which this competition affects wild species has not been evaluated in the available literature and is recognized only as a potential risk associated with fouling organisms. On the other hand, some regions (e.g. parts of Germany and the UK) report that Pacific oyster reefs can also enhance habitat complexity and support greater species diversity and biomass, partially compensating for the loss of native beds (Kemp and Hansen, 2018). Despite these mixed outcomes, *C. gigas* introductions remain a significant concern for native biodiversity, particularly where high-density oyster reefs alter benthic communities and reduce habitat for local species (ibid.).

In summary, in some regions, oysters cultured within their native range are hatchery-raised, derived either from wild-caught broodstock or from several generations of domesticated hatchery lines. In other regions, spat is passively collected from the environment, originating from both wild and farmed oysters. Elsewhere, non-native oyster species have been introduced as early as the seventeenth century, and in many cases, have become fully ecologically established through aquaculture or unintentional introductions. The establishment of non-native oysters was more common prior to 1970 but appears to have become rare in recent decades, likely due to management measures such as the increasing use of triploid spat. While there is no readily available evidence on whether new introductions are still occurring or to what extent, the adoption of triploids in major producing regions like China, France, and the USA has substantially lowered escape risks despite the species' high fecundity. Even when triploids spawn, their offspring rarely survive beyond early larval stages, making the potential for introgression into wild populations negligible compared to diploid escapees. Although studies to date have found limited evidence of genetic introgression from aquaculture lines into wild oyster populations, the risk remains and is influenced by species, geographic context, and environmental conditions. Additionally, non-native oysters have been shown to compete with native populations for both food and habitat, potentially altering local ecosystem dynamics. Therefore, considering the combination of escapee characteristics, such as high post-escape mortality of triploids, the fact that oysters are non-native yet already well-established in most major production regions, along with the production of native or closely related populations in other regions, and the residual risk of establishment coupled with evidence of competition; an intermediate score is assigned. Accordingly, Factor 6.2 Competitive and Genetic Interactions receives a score of 7 out of 10.

Conclusions and final score

The risk of larval escape in oyster farming is inherently high due to the open nature of grow-out systems and the highly fecund broadcast spawning behavior typical of most cultured oyster species. To mitigate this risk, the use of triploid spat (i.e., functionally sterile oysters) has emerged as a key best management practice. This approach has been widely adopted in major oyster-producing countries such as China, the United States, and France. However, uptake remains uneven across regions and species, and it cannot be considered to be fully adopted across the global industry. It is also noted that while the use of triploid

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spat reduces fecundity to approximately 2% of standard diploid spat (and thereby substantially reduces the numbers of oysters escaping during spawning events), as a single female diploid oyster can release approximately 60 million eggs, even the 98% reduction in triploids still represents a high escape risk from the combined spawning output of the farmed stock The overall risk of escape is high, and the score for Factor 6.1 is 0 out of 10.

Oysters can be highly invasive due to their biological traits, with species like *C. gigas* now established in many regions outside their native range, largely through aquaculture or unintentional introductions. While non-native oysters often compete with native species and alter ecosystem structure, in regions where farming occurs within their native range, ecological risks are generally lower, and genetic introgression from cultured to wild populations has been minimal. Early introductions (pre-1970) often led to establishment, but appears to have become rare in recent decades (although, there is no readily available evidence on whether new introductions are still occurring or to what extent), partly due to management measures such as the widespread adoption of triploid spat. While oysters are highly fecund, triploids produce negligible viable offspring beyond larval stages, making introgression risks from them minimal compared to diploids. Overall, considering high post-escape mortality, widespread historical establishment, limited evidence of genetic impacts, and the remaining risks of competition, an intermediate score is assigned. The score for Factor 6.2 is 7 out of 10.

Factors 6.1 and 6.2 combine to result in a final numerical score of 4 out of 10 for Criterion 6 – Escapes.

Draft for Review

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.*

Disease Risk-based assessment	Score	
C7 Disease Score (0-10)	4	
Critical?	No	YELLOW

Criterion 7 Summary

Without a robust understanding of how on-farm disease impact wild organisms (i.e., Criterion 1 score of 5 out of 10 for the disease category), the Seafood Watch Risk-Based Assessment methodology was utilized. Oysters are vulnerable to disease at all stages of production, leading to variable mortality rates and raising concerns about potential impacts on wild populations through pathogen amplification, retransmission, or increased virulence. Globally, biosecurity strategies, including selective breeding for disease resistance, have been implemented at the farm, national, and international levels to reduce these risks. While these measures have been effective in many cases, there are instances where they have failed or inadvertently exacerbated disease impacts on wild oyster populations. As such, even with the implementation of biosecurity protocols disease outbreaks in farmed oysters remain relatively common. In general, little is known about the extent to which farming practices (such as high stocking densities, or the frequent movement of animals, farming equipment, vessels, and personnel) contribute to the transmission of these pathogens within and between farms. However, specific cases, such as those documented for OsHV-1, clearly demonstrate that aquaculture conditions can increase both pathogen transmission and amplification. Moreover, significant knowledge gaps also persist regarding transmission dynamics between farmed and wild species, and therefore the ecological consequences for wild species. Ultimately, farms experience disease challenges and are fully open to the introduction and discharge of pathogens. The final score for Criterion 7 – Disease is 4 out of 10.

Justification of score

The amplification of pathogens on aquaculture farms and their potential retransmission to wildlife is of primary concern for ecological impact. While farmed species are commonly infected by environmental

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pathogens, they can also be vectors of pathogen discharge into the marine environment, including prior to any notable disease-related mortality (e.g., Shea et al., 2020).

Although useful country-level data on parasites and pathogens affecting oyster aquaculture are readily available, there are limited data with which to robustly understand the impact of on-farm diseases to wildlife in the area. As a result, the data score for disease is 5 out of 10 (in Criterion 1 – Data); therefore, the Risk-Based Assessment option in the Seafood Watch Aquaculture Standard was used.

As discussed below, disease outbreaks continue to pose a major challenge in oyster aquaculture, periodically leading to significant mortality events among farmed stocks, and occasionally impacting wild populations. In some instances, farmed oyster species have been wiped out by disease (e.g., in the case of the introduced Portuguese oyster (*C. angulata*) in France in the 1970s). These events are typically associated with bacterial, viral, or parasitic pathogens, and despite advances in aquaculture practices, effective disease prevention and control remain limited (Ayvazian et al., 2021; Botta et al., 2020). Many of the infectious diseases associated with shellfish in hatcheries, nurseries, and growout systems are caused by opportunistic agents that become pathogenic at high temperatures or salinities (e.g. seasonal environmental stressors) (Cowan et al., 2024; King et al., 2018).

High stocking densities, frequent movement of animals, and the transfer of farming infrastructure such as vessels, gear, and personnel contribute to the rapid transmission of these pathogens within and between farms (Bishop et al., 2023). Since oyster farming takes place directly in natural coastal environments, parasites and pathogens can move freely between farmed and wild populations, with little to no apparent barriers to their transmission (Bouwmeester et al., 2020). However, epidemiological models suggest that the openness of oyster farming methods could reduce disease in nearby wild stocks if farmed oysters act as incompetent decoys and are harvested before infection peaks (Ben-Horin et al., 2018). Therefore, it has been suggested that whether aquaculture serves as a disease source or sink depends on management variables like stocking density, harvest rate, and stock traits (ibid). Intensive, contained culture and shorter harvest schedules may lower risks, but there is no field evidence yet that aquaculture reliably reduces parasitism in the wild.

<u>Diseases associated with oyster aquaculture</u>

Several diseases that affect farmed oysters can cause mortality or decreased flesh quality. Although considerable information is available on diseases, and the management measures in place to control them, significant knowledge gaps remain around disease sources, modes of transmission, and vectors, as well as the impacts of disease to wild populations. The following diseases are known to impact farmed oysters worldwide (See Table 3):

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Table 3. Diseases and parasites associated with oyster aquaculture (Mercer et al., 2024; King et al., 2018; Sweet and Bateman, 2016).

	Disease	Causative Parasite / Pathogen	Susceptible Species	Affected oyster stage	Geographic Distribution	Signs and Pathology	Mortality range (%)	Management Measures
Parasites								
1.	Dermo	*Perkinsus marinus*	*C. virginica*	Adult	Eastern USA, Central America, South America	Emaciation, shell lesions, retarded growth, blockage of circulatory system, mortality	20 - 85	Selective breeding, Timely harvest
2.	Bonamiosis	*Bonamia (roughleyi, perspora; Bonamia exitiosa; Bonamia ostreae)*	*C. gigas, O. edulis, O. Chilensis, O. angasi, S. glomerata*	Adult	Europe, New Zealand, and Australia, USA	Connective tissue disruption, ulcers, necrotic tissues, impaired muscles	9 - 52	NA
3.	Seaside Organism (SSO)/ high salinity disease	*Haplosporidium costale*	*C. virginica, C. gigas* (rare)	Spat, adult	USA, Canada, and parts of China	Rapid mortality	20 - 40[21]	Maintain low salinity, timely harvest, filter/sterilize hatcheries
4.	Multinucleated Sphere Unknown (MSX)	*Haplosporidium nelsoni*	*C. gigas, C. virginica*	Spat, adult	USA, Canada, and in Korea, Japan and France	Respiratory and digestive impacts, eventual mortality	33 - 95	Avoiding infected areas, growout in low salinity areas, and proper timing for movements and growout, selective breeding
5.	Queensland Unknown (QX)	*Marteilia sydneyi*	*S. glomerata*	Spat, adult	Australia	Emaciation, discolored digestive tract, stunted growth, mortality	22 - 99	Selective breeding
6.	Marteiliosis	*Marteilia refringens* (O, M, and C types).	*O. edulis*	NA – likely adults	France, Spain, Portugal, and Greece	Digestive gland infection, impaired growth, starvation	50 - 90	NA

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[21] https://www.dfo-mpo.gc.ca/science/aah-saa/diseases-maladies/hcoy-eng.html

	Disease	Causative Parasite / Pathogen	Susceptible Species	Affected oyster stage	Geographic Distribution	Signs and Pathology	Mortality range (%)	Management Measures
7.	Denman Island Disease	*Mikrocytos mackini*	*C. gigas, C.virginica, O.edulis, O.lurida*	Adult	West coast USA, Canada	Yellow/green pustules within the mantle tissues, labial palps and adductor muscle	17 - 53	NA
				Bacterial and viral				
8.	Pacific Oyster Mortality Syndrome (POMS)	Ostreid Herpes Virus (OsHV-1)	*C. gigas*	Larvae, spat	USA, Japan, Europe, China, Australia and New Zealand	Lesions, pale digestive gland, cessation of feeding and swimming in larvae, summer mortality	40 - 100	Minimize movement, specialized handling procedures and regulate stocking densities, selective breeding
9.	Roseovarius Oyster Disease (ROD)/ Juvenile Oyster Disease (JOD)	*Aliiroseovarius crassostreae*	*C. virginica*	Spat	North Eastern USA and France	Reduced growth, abnormalities in tissues and shell, mortality	54 - 75	Low density of spat, increased flow in nursery systems, selective breeding, and properly timing transplantation
10.	Nocardiosis	*Nocardia crassostreae*	*C. gigas*	Adult	West coast of USA and Canada	Green pustules and lesions on oyster tissue	47 - 50	NA
11.	Vibrosis	*Vibrio* Spp.	*C. gigas, Clam species*	Larvae, spat, adult	Worldwide	Abnormal swimming, necrosis, lesions	76 - 100	Tetracyclines (oxytetracycline)

While all of the diseases listed in Table 3 have presented important challenges for the oyster industry and occasionally in wild oyster, brief details for the most prevalent diseases in oyster aquaculture are briefly discussed below.

Parasites

Dermo

Dermo disease affects mainly *C. virginica* and is caused by protozoan parasite *Perkinsus marinus,* but has been reported in more than 50 shellfish species globally (Mercer et al., 2024). The disease proliferates at high temperatures and high salinities (King et al., 2018). The disease was first observed in the Gulf of Mexico in the 1940s and spread to Delaware Bay by the mid-1950s due to the importation of spat from the Chesapeake Bay (VIMS 2019b). While *Perkinsus marinus* is mainly geographically distributed along the east coast of the US from Maine to Florida, the Gulf of Mexico, and South America (VIMS 2019b, Bower 2013), other species such as *Perkinsus olseni* in Australia, and *Perkinsus atlanticus* and *Perkinsus*

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mediterraneus in Europe are also found to cause disease related issues (Mercer et al., 2024). The geographic range of the disease is increasing with higher winter temperatures and drought conditions which affect salinity, coupled with unintentional introduction of disease through shucking waste (VIMS 2019b). It can take up to three years of infection to kill an oyster, during which time the oyster is able to be harvested as a mitigation strategy (Connecticut Bureau of Aquaculture, 2018). Nonetheless, MSX (i.e., addressed ahead) and Dermo diseases can frequently co-occur in C. virginica and are responsible for significant mortalities within the second year of the gowout phase (Jiang et al., 2023).

Mortalities can be avoided by harvesting oysters within three years before the disease becomes fatal, and by fallowing infected grow areas (Connecticut Bureau of Aquaculture, 2018). For this reason, dermo is less of a concern for oyster farmers than other diseases that cannot be managed through timed harvest (pers. comms., B. Rheault, 2019).

The disease is spread from oyster-to-oyster when dead oysters disintegrate and release water-borne parasites that are then ingested by healthy oysters, or when spread by scavenging hosts such as snails (King et al., 2018; Connecticut Bureau of Aquaculture 2018). While it seems that wild, native oysters are developing resistance to the parasite that is the causative agent (VIMS 2020), recent histological evidence reveals that *P. marinus* has undergone significant phenotypic changes that may enhance its transmissibility and ecological impact (Carnegie et al., 2021). Historically, the parasite infected deeper connective tissues and featured large, multinucleated cells dividing through schizogony. In contrast, the modern form primarily targets digestive epithelia and consists of smaller cells that appear to divide more rapidly, likely via binary fission (Carnegie et al., 2021). This shift in tissue tropism and life cycle suggests an adaptation to reduced oyster abundance and longevity following mass mortality events caused by *Haplosporidium nelsoni*. These changes enable faster infection and earlier transmission, including possible fecal shedding prior to host death, which may be advantageous in sparse or short-lived host populations. As a result, *P. marinus* has become more virulent and persistent, raising concerns about its broader ecological effects, including altered disease dynamics in estuarine systems and potential impacts on native parasite communities (ibid.). Although these findings do not directly assess the transmissibility or amplification of *P. marinus* from farms to wild populations, the parasite's increasing virulence and persistence in the environment, combined with the high stocking densities of oyster farms located within natural ecosystems, can heighten the risk of disease amplification and raise the likelihood of transmission into adjacent wild stocks. Therefore, the impact risk of dermo in wild oysters in the Chesapeake Bay is still considered "significant" (Carnegie et al., 2021; VIMS 2020).

Bonamiosis and Marteiliosis

Bonamia refers to a group of protozoan parasites, which are often called microcells. They affect various oyster species and are a significant concern for oyster aquaculture worldwide. Among them, *Bonamia ostreae* and *Bonamia exitiosa* are the most widely studied, both listed by the World Organisation for Animal Health (WOAH) as notifiable diseases (Mercer et al., 2024; Sweet and Bateman, 2016). *B. ostreae* primarily infects the hemocytes of *O. edulis* and *O. chilensis*, and is widespread across Europe, the U.S., and Canada. Although it can be detected in *C. gigas*, it does not cause mortality in this species. Transmission appears to occur directly from infected to naïve oysters via entry through epithelial tissues such as the gills, after which the parasite spreads through hemocyte circulation impairing cellular functions. *Bonamia exitiosa* affects *Ostrea angasi* and *O. chilensis* and is mainly reported in Australia, New Zealand, and parts of Europe (Mercer et al., 2024). Despite better insights into species diversity, the exact pathogenesis of *Bonamia spp.* remains poorly understood (Sweet and Bateman, 2016).

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Another similar parasite, *Marteilia refringens* (also called *M. maurini*), affects the digestive tract of *O. edulis* during the second year of infestation, often causing significant mortalities (Mercer et al., 2024). Although *M. refringens* has been detected in *C. gigas*, it does not appear to cause disease in them. This parasite likely requires an intermediate host, such as copepods, for transmission, but full transmission pathways are still being investigated (ibid.). As no treatments exist for these parasitic infections, disease prevention relies on surveillance, movement restrictions, and robust biosecurity practices (Mercer et al., 2024; Sweet and Bateman, 2016). Although no studies have directly examined the transmissibility or amplification of these parasites from farms to wild populations, the parasite's broad host range and global distribution, coupled with the high stocking densities of oyster farms situated within natural ecosystems and the absence of effective barriers to transmission, indicate a significant risk to wild populations.

SSO (Seaside Organism, also known as high salinity disease)

SSO is caused by the parasite *Haplosporidium costale* and has been observed in the connective tissue of gills and digestive gland of oysters (Arzul et al., 2022). The disease affects *C. virginica* in the USA from Virginia to Maine (first observed in Virginia), Canada, and *C. gigas* in parts of China, with some detection in California (Stokes and Carnegie, n.d) (Arzul et al., 2022). SSO can cause significant and rapid mortality, within one or two months of histological detection (DFO, 2018c). Peak infections occur in March to June, with most mortalities occurring in May and June (Arzul et al., 2022; Stokes and Carnegie, n.d). The disease is only found in areas of high salinity (>24ppt) (Arzul et al., 2022; DFO Canada, 2018; ICES, 2011). The complete lifecycle and mode of transmission are still unknown, but it is not believed to be directly transmitted from oyster to oyster (DFO Canada, 2018) without an intermediate host. Nonetheless, a 2019 study in France confirmed the presence of SSO in *C. gigas* for the first time, expanding its known host range beyond *C. virginica* . PCR analysis of archived samples revealed the parasite has been present since at least 2008, with detection in 15%–75% of oysters, despite no histological signs. Its presence was not correlated with mortality events, suggesting *C. gigas* may be more resistant to this pathogen, than *C. virginica*. This likely explains the pathogen's previous underreporting in *C. gigas*, though further research is needed to assess transmission and amplification risks associated with this pathogen (Arzul et al., 2022).

Management of disease outbreak and spread can be controlled by maintaining low salinity during the hatchery phase, harvesting prior to mortality, avoiding the transportation of oysters from infected areas into uninfected areas, and filtering/sterilizing water used in hatcheries and nurseries to eliminate infective stages (DFO Canada, 2018; ICES, 2011). High infection rates do not necessarily result in high mortality rates, and the parasite can be eradicated from an area if temperatures increase or salinity decreases (Banrie, 2013). Although no studies have directly addressed the transmissibility or amplification of SSO from farms to wild populations, the parasite's broad host range and global distribution, combined with the absence of clear histological indicators, high stocking densities in farms located within natural ecosystems, and the lack of effective transmission barriers, suggest a significant risk to wild populations.

MSX (Multinucleated Sphere Unknown)

MSX is caused by the spore-forming protozoan *Haplosporidium nelsoni* and affects both *C. gigas* and *C. virginica* (King et al., 2018). It occurs as a co-infection with the SSO (seaside organism – *H. costale*) or with dermo illness parasites (Jiang et al., 2023; VIMS 2019). MSX is found in Pacific oysters in the west coast of the USA, Canada, and in Korea, Japan and France, where it has caused fewer mortalities than in eastern oysters (Mercer et al., 2024; VIMS 2019, DFO Canada 2018). The complete lifecycle and mode of transmission are still unknown, but it is not believed to be directly transmitted from oyster to oyster and instead need an intermediate carrier (VIMS, 2019; King et al., 2018; Connecticut Bureau of Aquaculture,

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2018). MSX affects oysters in nearly every life stage, and transmission is suppressed at low temperature and salinities (VIMS, 2019). Infected oysters can be harvested prior to mortality.

There is growing evidence that both selective breeding and natural adaptation have contributed to increased resistance to *Haplosporidium nelsoni* (MSX) and *Perkinsus marinus* (Dermo) in eastern oyster populations (VIMS, 2020; Connecticut Bureau of Aquaculture, 2018). Hatchery-based selective breeding programs have successfully developed oyster lines with dual resistance, showing significantly lower mortality rates (Jiang et al., 2023). For example, after just three to four generations of selection, the F4-DEBY line exhibited mortality rates ranging from 21.0% to 52.4%, in contrast to over 82% mortality observed in earlier-generation lines such as F1-MB and F1-TS (Jiang et al., 2023; King et al., 2018). Parallel to these efforts, field studies by VIMS have documented increased prevalence of *H. nelsoni* over the decades, yet also observed stable infection outcomes in wild oysters transplanted from disease-free zones into infected areas, which suggests the development of natural resistance over time (VIMS, 2020). In regions with historically high disease pressure (i.e., those with elevated salinity and temperature), wild populations in these areas now show widespread resistance (i.e., it is unclear if this trait is due to natural adaptation or a result of introgression), and cultured stocks have been selectively bred for resistance as well; enabling continued production despite ongoing exposure to both MSX and Dermo pathogens (PEI Aquaculture Alliance, 2024).

Additional mitigation methods include avoiding infected areas for oyster growout, siting growout in low salinity areas, and timing oyster movements and growout to avoid summer infection season (VIMS, 2019). Additionally, holding oysters at salinities of less than 15 ppt appears to suppress the disease (DFO Canada, 2018). While no studies have directly examined the transmissibility or amplification of MSX from farms to wild populations, evidence that both wild and cultured oysters are developing resistance, together with the availability of mitigation strategies, suggests that MSX poses a comparatively lower concern than the previously discussed parasites.

Viruses and bacteria

Ostreid Herpes Virus (OsHV-1)/ Pacific Oyster Mortality Syndrome
Pacific Oyster Mortality Syndrome is a deadly disease caused by viral and bacterial co-infections, initiated by the *Ostreid Herpesvirus* micro-variant-1 (OsHV-1 µVar) infection which causes mass mortality in both wild and cultured *C. gigas* (Adekunle, Bidegain, and Ben-Horin, 2025; Mercer et al., 2024; Jiang et al., 2023). The virus has been recorded in the USA, Japan, Europe (with exceptionally intense outbreaks in France), China, Australia and New Zealand, and was first observed in 2008 in France (Adekunle, Bidegain, and Ben-Horin, 2025; Jiang et al., 2023; Ugalde et al., 2018; NEAC, 2017; Neindorf, 2018). While oysters are susceptible to the disease at any life stage, most mortalities occur in juvenile oysters, with up to 100% mortalities recorded at this life stage, and both wild and farmed populations were affected (Mercer et al., 2024; Jiang et al., 2023). OsHV-1 is not host-specific and has been detected in wild populations, which are often susceptible to outbreaks (Sweet & Bateman, 2016; Pernet et al., 2016). Additionally, concerns also persist about broader species susceptibility, as OsHV-1 has been found to infect other mollusks, including abalone, Manila clams, Mediterranean mussels, Eastern oysters, and scallops (USDA, 2021).

Studies have indicated that oyster farming can amplify and spread OsHV-1 into surrounding environments. High stocking densities within farms, particularly those holding juvenile oysters, create favorable conditions for viral outbreaks and replication (Pernet et al. 2014a,b, 2018). Mortality events have been tightly associated with inshore farming zones of highest oyster density, a pattern consistent with epidemiological principles that link host density to increased transmission (Gandnery et al., 2019

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and references therein). OsHV-1 has been shown to spread beyond farm boundaries, with mortalities observed up to 1 km from farms, while viral DNA has been detected more than 3 km away, likely carried by seawater currents (Pernet et al. 2012, 2018). Hydrodynamic models further support this, demonstrating that connectivity to farming areas is strongly correlated with disease risk, suggesting that farms function as centers of infection pressure. (Gandnery et al., 2019 and references therein). While oysters (i.e., sentential oysters used as disease indicators for experimental purposes) located offshore or outside farming areas often carried subclinical infections, they exhibited lower mortality, likely due to dilution of viral particles, reduced host density, and better feeding conditions that enhance immune responses (ibid.). This contrast reinforces the idea that farms act as amplifiers of infection, with effects that radiate outward. Juvenile oysters appear particularly critical, as their presence increases mortality risk, highlighting their role as viral reservoirs and multipliers within farming systems. Overall, the evidence shows that oyster farming, through high host density and hydrodynamic connectivity, creates hotspots of OsHV-1 amplification and transmission, thereby elevating the risk of infection in adjacent wild populations (ibid.).

Currently, there is no treatment or vaccine available. Management in previously infected farms focuses on reducing movement of shellfish, enforcing biosecurity measures (e.g., use of personal protective equipment), regulating stocking densities, and restricting shellfish importation (USDA, 2021; Ugalde et al., 2018). In response to outbreaks, the European Union implemented Regulation No. 175/2010 to standardize diagnostics and containment protocols for OsHV-1 μvar, aiming to limit its spread to uninfected regions (Sweet & Bateman, 2016). In the United States, producers are working in breeding more disease-resistant lines and increasing Atlantic oyster production, as this species is largely unaffected (pers. comm., Emily Johns, Hog Island Oysters Co., October 2025). Encouragingly, some oyster species, such as the Pacific oyster and the black-lip pearl oyster, have begun to show signs of developing resistance to the virus (Sweet & Bateman, 2016 and references therein).

Vibrio species

Vibrio bacteria are frequently detected in oysters making them highly relevant to the oyster aquaculture industry due to their global prevalence and role as opportunistic pathogens (King et al., 2018). These bacteria are ubiquitous in marine environments and are present in the water column, sediments, vegetation, and associated with other organisms. Some *Vibrio* species, such as *V. aestuarianus* and *V. splendidus*, are believed to be part of the oyster microbiome, typically remaining benign until environmental stressors, such as elevated temperatures, poor water quality, or co-infection with viruses such as OsHV-1, compromise the oyster's immune system. Under such conditions, these bacteria can become virulent, triggering disease outbreaks (Mercer et al., 2024; King et al., 2018).

Globally, *Vibrio*-related mortalities have had significant impacts on oyster production. In Europe, *V. aestuarianus* has been frequently isolated from dying adult oysters, with studies confirming its ability to cause disease under lab conditions (Sweet and Bateman, 2016). Alarmingly, both the prevalence and virulence of certain isolates, such as those from France and Ireland, which have increased from only a few detections between 2009 and 2010 to *V. aestuarianus* detected in 100% of moribund oysters in 2012 (ibid.). While some studies have demonstrated that Vibrio transmission between oysters can occur through cohabitation, outcomes vary depending on the *Vibrio species* involved and environmental conditions (King et al., 2018). In other cases, infected oysters have failed to transmit the disease to naïve individuals, highlighting the complexity and species-specific nature of Vibrio transmission dynamics (ibid.).

Draft for Review

While there are antibiotics available to treat vibriosis during the hatchery phase, once disease signs become obvious it is often too late for any treatment. Therefore, management focuses on monitoring environmental conditions, mainly temperature and salinity. In hatchery settings, changing water sources or pausing spat production during high-risk periods may help reduce outbreaks. However, further research is needed to better understand environmental triggers and improve preventive strategies (Mercer et al., 2024; King et al., 2018).

Summer mortality
Summer mortality events have severely affected *C. gigas* aquaculture worldwide since the 1960s, with outbreaks reported in regions including France, Australia, the U.S., Japan, Canada China, and more recently Sweden and Norway (Ben-Horin et al., 2024; Sweet and Bateman, 2016). Characterized by stock losses exceeding 30% and, in some cases, total mortality, these events are not attributed to a single cause but rather a combination of environmental and biological stressors (Sweet and Bateman, 2016). Rising seawater temperatures, marine heatwaves, eutrophication, and co-infections with pathogens like *Vibrio spp.* and the herpesvirus OsHV-1 are frequently implicated. These factors weaken the oyster's immune system, making them more vulnerable to opportunistic infections. Although OsHV-1 is commonly detected during outbreaks and is considered a major contributor, some events (i.e., such as one in Australia) have occurred without its presence, suggesting other microbial agents and stressors are involved. Additionally, *Roseovarius crassostreae* (i.e., Roseovarius Oyster Disease, ROD) is the etiological agent of juvenile oyster disease in *C. virginica* during the summer (From Jiang et al., 2023). As such, summer mortality is considered a multifactorial syndrome likely involving a range of known and unknown pathogens, with environmental stress acting as a critical trigger (Ben-Horin et al., 2024; Sweet and Bateman, 2016).

Therefore, the evidence that oyster farming has the potential to amplify and transmit OsHV-1 due to high host densities, hydrodynamic connectivity, and the presence of susceptible juveniles, demonstrates how farms act as hotspots of disease pressure. Given that summer mortality in oysters is similarly influenced by density-dependent processes and environmental stressors, it is reasonable to expect that farming activities will also increase the risk of transmission and amplification of summer mortality events into surrounding wild populations.

Disease management

The World Organization for Animal Health (formerly the Office International des Epizooties (OIE)) exists as the international body responsible for setting animal health standards. The WOAH adopted the Aquatic Animal Health Code and the Manual of Diagnostic Tests for Aquatic Animals, inclusive of mollusks (World Organization for Animal Health[22], 2024; Pernet et al., 2016; OIE, 2012). These documents are used by World Trade Organization member country authorities to develop individual country standards for all matters related to aquatic products that carry risk of disease (Manual of Diagnostic Tests for Aquatic Animals, 2018; World Organization for Animal Health, 2024). Furthermore, the WOAH maintains a list of 117 animal diseases that helps to inform country bans and restrictions on aquaculture trade to limit disease spread (Rheault and Kehoe, 2019). Among the diseases affecting oysters, Dermo (*Perkinsus marinus*), Marteiliosis (*Marteilia refringens*), and Bonamiosis caused by *Bonamia ostreae* and *B. exitiosa* are listed as notifiable by the WOAH (WOAH, 2024). These notifiable pathogens have led to severe declines and, in some cases, the collapse of both farmed and wild oyster populations. (Sühnel and Strand., 2020).

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[22] https://www.woah.org/en/what-we-do/standards/codes-and-manuals/

Draft for Review

Import rejections for oysters reported by the FDA (i.e., from 2009 to 2025), that are related to diseases and chemical traces, did not report any detection from those listed in Table 3, but instead reported contamination from pathogens relevant for transmission to human health, including: Norovirus GII, from British Columbia in 2025, and Salmonella from Venezuela in 2024 (FDA[23], 2024).

In some cases, efforts to overcome these challenges, such as introducing non-native oyster species to replace declining native stocks, have inadvertently worsened the situation by introducing new pathogens that further the impacts to native species population status (Bishop et a., 2023 and references therein; Litembu et al., 2023; Botta et al., 2020). For instance, in France, the dramatic decline of the native European flat oyster (*O. edulis*) due to overharvesting and parasites like *Marteilia refringens* and *Bonamia ostreae* led to the introduction of the Portuguese oyster (*C. angulata*). However, this species was later wiped out by a disease outbreak (i.e., gill disease) in the 1970s (Botta et al., 2020). A similar pattern occurred in the United States, where Pacific oysters (*C. gigas*) were introduced to replace declining native *O. lurida* populations on the West Coast. Their apparent success led to their subsequent introduction to the East Coast, but these oysters carried parasites from Japan, which contributed to significant mortality events in native Eastern oysters (*C. virginica*) (Botta et al., 2020). Despite growing awareness, the environmental and farming conditions that trigger disease outbreaks remain poorly understood, and new pathogens are still being identified, underscoring the urgent need for improved surveillance and preventative strategies (Sweet & Bateman, 2016).

In other cases, farming methods have been modified in attempts to avoid disease problems. For example, the US oyster industry has modified production practices to avoid mudworms (*Polydora websteri*); the industry, which initially began with on-bottom and dredge bed culture, has transitioned to an intertidal system that enables oysters to be periodically exposed to air, wind, and sun, which prevents parasitism from mudworms (Morse, Rawson and Kraeuter 2015). The same methods of controlling for immersion are used to reduce proliferation of the herpes virus OsHV-1 on oyster farms in Europe, reducing mortality by up to 50% (Pernet et al. 2016). In addition, genetic improvement of *C. gigas* in resistance to OsHV-1 has been achieved using pedigree selection and marker assisted selection in several countries (Jiang et al., 2023). There is evidence that oysters grown in culture with other species, either other oysters species or other shellfish (e.g. mussels), also have a reduced risk of disease transmission (Pernet et al. 2016). Therefore, it appears the industry continues to move toward standardized adoption of biosecurity strategies, both at the individual producer level and through broader regulatory requirements. (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025).

Other forms of disease management require knowledge of transmission vectors and disease progressions. For some diseases, disease-resistant oysters, bred to withstand outbreaks and mass mortality events, can be an effective method for disease control (Connecticut Bureau of Aquaculture 2018, VIMS 2019, Neindorf 2018, NAEC 2017, Prado-Alvarez et al. 2016, Green et al. 2011). For example, following three to four generations of selective breeding, oyster lines with resistance to both MSX and Dermo were developed. One such line, F4-DEBY, exhibited significantly lower mortality rates (21.0%–52.4%) compared to earlier-generation lines like F1-MB and F1-TS, which experienced cumulative mortalities exceeding 82% (Jiang et al., 2023; King et al., 2018). For diseases and parasites exhibiting density-dependent transmission, culling to eradicate disease is a successful method and has been suggested as a control for OsHV-1 to reduce oyster density (Pernet et al. 2016). Similarly, progressive diseases in which mortality occurs after a period of weeks or months can be less of a concern to farmers

[23] https://www.accessdata.fda.gov/cms_ia/importalert_46.html

because oysters can be harvested prior to mortality which prevents the release of infectious agents into the water (pers. comm., B. Rheault, 2019).

Conclusions and final score

Without a robust understanding of how on-farm disease impact wild organisms (i.e., Criterion 1 score of 5 out of 10 for the disease category), the Seafood Watch Risk-Based Assessment methodology was utilized. Oysters are vulnerable to disease at all stages of production, leading to variable mortality rates and raising concerns about potential impacts on wild populations through pathogen amplification, retransmission, or increased virulence. Globally, biosecurity strategies, including selective breeding for disease resistance, have been implemented at the farm, national, and international levels to reduce these risks. While these measures have been effective in many cases, there are instances where they have failed or inadvertently exacerbated disease impacts on wild oyster populations. As such, even with the implementation of biosecurity protocols disease outbreaks in farmed oysters remain relatively common. In general, little is known about the extent to which farming practices (such as high stocking densities, or the frequent movement of animals, farming equipment, vessels, and personnel) contribute to the transmission of these pathogens within and between farms. However, specific cases, such as those documented for OsHV-1, clearly demonstrate that aquaculture conditions can increase both pathogen transmission and amplification. Moreover, significant knowledge gaps also persist regarding transmission dynamics between farmed and wild species, and therefore the ecological consequences for wild species. Ultimately, farms experience disease challenges and are fully open to the introduction and discharge of pathogens. The final score for Criterion 7 – Disease is 4 out of 10.

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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.

Source of stock parameters	Score	
C8X Independence from unsustainable wild fisheries (0 to -10)	-0.0	
Critical?	No	Green

Criterion 8X Summary

Spat for oyster farming is either passively collected through natural settlement of larva on a provided substrate (i.e., culch) or through the use of broodstock in land-based hatcheries. In regions where there is a reliable and abundant supply of wild spat, passive collection is often used. Land-based hatcheries may utilize wild broodstock, but prioritization (due to the selection of genetic traits) is often given to hatchery raised broodstock. Given the high fecundity of oysters, if wild broodstock are collected, the numbers required are considered to be low. Hence it appears that the global industry uses either passively collected wild spat, farm-raised broodstocks, or small numbers of wild broodstock, none of which is a significant conservation concern. Therefore, the final score for Criterion 8X – Source of Stock is a deduction of 0 out of -10.

Justification of score

Stock for oyster farming is either collected passively via natural settlement of larva or via hatchery and nursery production (Mercer et al., 2024; Laing & Bopp, 2019). In regions where there is a reliable and abundant supply of wild spat, passive collection is typically used (Manley, Power and Walker, 2008). Passive collection techniques rely on larva settlement on different types of material (culch), including sticks, drain pipe, oyster and scallop shells placed in bags and strung on wires, and plastic tubes (Doiron, 2008; Queensland Government, 2018). For instance, in China, which is the largest oyster-producing country, local government regulations permit the collection of both native and non-native oyster larvae, as long as the spawning area has been approved in advance (ASC, 2023). In Zhanjiang, the lack of a local hatchery has led the majority of farmers to depend on wild-collected spat or imported sources. Recent data show that around 1,079 (~71%) of producers use wild-collected spat, 404 producers (~27%) rely on hatchery spat, and a small portion of farmers combine both methods (<2%) (Yu et al., 2023). The use of passively collected (i.e., naturally settled) spat in oyster farming is a low conservation concern, and is not considered in the scoring of this criterion.

While many producers might favor passive collection since it costs far less than sourcing spat from hatcheries, wild spat might not always be a reliable and/or sufficient source, for example, disease outbreaks have compromised much of the spat collection from natural reefs in France (pers. comm., Emily Johns, Hog Island Oysters Co., October 2025; pers. comm., Jorge Chaves, CIBNOR, September 2025;

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Botta et al., 2020). The production of spat in hatcheries using farm-raised or wild broodstock provides an alternative spat supply. For example, in the United States, although a minimal portion of shellfish spat is still obtained from wild larvae through passive settlement, most producers now rely primarily on hatchery-produced spat pers. comm., Emily Johns, Hog Island Oysters Co., October 2025). When choosing spat sources, preference is generally given to stock derived from broodstock that are well suited to the specific environmental conditions of the farming region (ECSGA[24], 2023).

Ultimately, given the global scope of this assessment, and the perceived regional variations in practices, estimating the proportion of global oyster production that comes from wild-collected versus hatchery-raised stocks is challenging. However according to recent consultations with industry experts, and the available peer-reviewed literature, hatchery production is considered the predominant method globally (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025; pers. comm. Wenbo Zhang, Shanghai Ocean University, March 2025; Pers. comm., B. Rheault, 2019; Yu et al., 2023; Ying et al., 2021)..Passive collection of wild oyster spat is still considered to be widely used, and to which degree one method is used over the other will likely vary by region (ibid.).

Broodstock in hatcheries are sometimes selected from wild populations and spawned under controlled conditions to produce spat (Oregon State University, 2019; Helm, Bourne, and Lovatelli 2004; Wallace et al., 2008), however, given the high fecundity of oysters (e.g., an adult *C. gigas* can produce 60 million larvae per spawning; Martinez-Garcia et al., 2021), the number of individuals required is low. As such, the occasional collection of wild oyster broodstock is also considered a low conservation concern. In many operations, the full life cycle is maintained within the hatchery (with an increasing emphasis on selective breeding), thereby eliminating the need for ongoing wild broodstock collection (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025).

Overall, it appears that the global oyster industry uses either passively collected wild spat, farm-raised broodstocks, or small numbers of wild broodstock, none of which is a significant conservation concern (FAO Fisheries & Aquaculture, 2018; Beustel, 2009). Consequently, the overall demand for wild broodstock in global oyster aquaculture is low, and is considered to be less than 9.9%, which corresponds to a score deduction of 0 out of -10 in the Seafood Watch Aquaculture Standard.

Conclusions and final score

Spat for oyster farming is either passively collected through natural settlement of larva on a provided substrate (i.e., culch) or through the use of broodstock in land-based hatcheries. In regions where there is a reliable and abundant supply of wild spat, passive collection is often used. Land-based hatcheries may utilize wild broodstock, but prioritization (due to the selection of genetic traits) is often given to hatchery raised broodstock. Given the high fecundity of oysters, if wild broodstock are collected, the numbers required are considered to be low. Hence it appears that the global industry uses either passively collected wild spat, farm-raised broodstocks, or small numbers of wild broodstock, none of which is a significant conservation concern. Therefore, the final score for Criterion 8X – Source of Stock is a deduction of 0 out of -10.

[24] https://ecsga.org/wp-content/uploads/2023/11/ECSGA-BPs.pdf

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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.

Wildlife and predator mortality parameters	Score	
C9X Wildlife and predator mortality Final Score (0 to -10)	-2.0	
Critical?		Green

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Criterion 9X Summary

Marine aquaculture operations, including oyster farms, inevitably interact with a wide range of wildlife species depending on their location, infrastructure type, and farming practices. Predators such as fish, crabs, birds, gastropods, and starfish can affect farm productivity, and in some cases predator-related mortalities of oysters have led to farm closures. Producers therefore adopt a suite of mostly non-lethal mitigation strategies, including physical exclusion, nursery-based husbandry, and in some cases, predator removal. Most of the primary species of predatory concern (listed above) are abundant, reproduce rapidly, and readily recolonize disturbed areas, and as such are a low conservation concern. While regulatory oversight of predator control practices varies globally, lethal control is increasingly rare, with most farms relying on non-harmful methods that align with animal welfare and conservation goals.

Although a small number of entanglements with cetaceans and sea turtles have been documented in shellfish aquaculture, these cases are rare and typically involve mussel or spat collection lines rather than oyster farming gear. As such, the risk of negative interactions, such as entanglement or behavioral disturbance of marine mammals and seabirds, is generally considered low in oyster aquaculture. Studies from multiple regions further demonstrate that, when farms are sited with ecological considerations in mind, they tend to have minimal or even neutral effects on surrounding wildlife, including shorebirds, seabirds, or otters. Similarly, risks from vessel traffic and underwater noise can be mitigated with best practices. Overall, deliberate lethal control is uncommon, and with widespread implementation of non-lethal exclusion techniques, wildlife mortalities associated with oyster farming are considered to be limited to exceptional cases and are unlikely to have population-level consequences. The final numerical score for wildlife and predator mortalities is a deduction of -2 out of -10.

Justification of score

As Wildlife and predator mortality data quality and availability is high (Criterion 1 score of 10 out of 10), the Seafood Watch Evidence-Based Assessment was utilized.

Marine aquaculture operations, including shellfish farms, often overlap with the habitats of a wide range of wild species, and the extent of these interactions depends on the degree of spatial overlap between farm infrastructure and the distribution of local fauna.

Predatory wildlife interactions
Mercer et al., (2024) note that due to the abundance of nutrients that are contained within them, oysters provide a wholesome and attractive meal for many animals and, depending on the density of the predatory fauna that occupy the same environment, these organisms can consume a substantial amount of farmed oysters. While the predation pressure from wild species tends to be relatively low compared to that experienced in finfish aquaculture operations (Bath et al., 2023; Bevin, Chandroo, and Moccia, 2002), in some cases, the impacts can be severe. For example, Stobart et al. (2025) noted that the closure of oyster farms in the Mediterranean has been linked to fish predation.

While land-based or contained oyster hatcheries and nurseries are a low concern, Mercer et al., (2024) note that the nature and impact of oyster predation is affected by the cultivation (i.e., grow out) system that is used:

- On-bottom culture will be directly exposed to benthic predators
- Intertidal farms will be exposed to predation by birds during low tide
- On-rope production can suffer predation from fish or potentially other predators such as turtles (noting that this typically affects small- to medium-size oysters).

Careful site selection and husbandry practices are therefore critical to minimize negative wildlife interactions. In some cases, farm structures may also indirectly attract seabirds and other predators by concentrating prey such as forage fish around gear or by providing access to fouling organisms, in addition to the direct attraction to the cultured shellfish (Bath et al., 2023). Therefore, the following groups of species and their potential interactions with oyster farms (i.e., considered representative of all oyster species) are summarized below (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025; Mercer et al., 2024; Anderson and Connell, 1999):

- Fish: Species such as sea breams (*Sparidae*), flounders (*Pleuronectiformes*), and sandpipers (*Scolopacidae*) can prey on oysters, particularly juveniles.
- Sponges: Boring sponges like *Cliona spp.* can penetrate the shell's outer layer, weakening structural integrity.
- Gastropods: Muricid snails including *Hexaplex trunculus, Bolinus brandaris,* and *Rapana venosa* bore into oyster shells to feed on soft tissues.
- Flatworms: *Stylochus spp.* enter open oysters and consume internal organs, particularly the adductor muscle.
- Crabs: Shore crabs (*Carcinus maenas*), brown crabs (*Cancer pagurus*), and blue crabs (*Callinectes sapidus*) are common benthic predators. Pea crabs (*Pinnotheres pisum*) also reduce market value by living within oysters.
- Starfish: Asterias rubens is a known predator in colder waters.
- Urchins: *Strongylocentrotus droebachiensis* can graze on oyster beds.
- Birds: Such as sea gulls or crows, prey on exposed oysters during low tide, and diving birds such as eider ducks can prey on submerged oysters.

The variation in predation pressure across different production systems and environments has led to a range of strategies to mitigate oyster mortality (Stobart, Jeffs, and Skelton, 2025; Mercer et al., 2024). These strategies typically involve selecting farming sites with naturally low predator densities, employing protective culture systems, raising oysters in nurseries until they reach sizes less vulnerable to predation, and, in some cases, carrying out predator control efforts (Stobart, Jeffs, and Skelton, 2025). While some

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of these methods have proven highly effective and could be adapted to manage predation risks more broadly, their application is often constrained by high costs, and labor demands (ibid.).

Therefore, it appears that the primary means of exclusion in oyster farming are the very baskets, bags, or cages used to contain the oysters themselves as part of the standard production systems. (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025). Still, it is important to outline the available predator mitigation strategies, which can generally be categorized into four main approaches (Categories and description adapted from Stobart, Jeffs, and Skelton, 2025):

1. Physical exclusion methods: Such as nets, screens, and mesh bags, can offer substantial protection, with reported oyster survival rates reaching up to 94% in protected plots versus less than 9% in unprotected ones. However, these tools are often limited by high installation and maintenance costs, issues with biofouling, and impracticality in dynamic or suspended culture environments. Still, they remain particularly useful in early production stages when oysters are most vulnerable.
2. Predator removal: Historically used to manage invertebrate predators like sea stars, gastropods, and crabs. It can be effective but is generally costly, and labor-intensive. As such, it is often considered a last resort, with preventative strategies favored by most farmers.
3. Husbandry practices: Such as growing spat in nurseries until they reach a more resilient size, are commonly used to reduce predation risk. Innovations in gear design and material selection can also contribute to reducing vulnerability to predators across different farming systems.

Globally, governance around predator control in aquaculture remains highly variable, with notable inconsistencies in regulatory protections and reporting requirements. Many countries lack mandatory reporting on interactions between aquaculture operations and protected wildlife such as marine mammals, resulting in sparse, often qualitative data and significant information gaps regarding the scale and nature of predator-related impacts (Bath et al., 2023). While stricter regulations on aquaculture have been introduced in some countries, though they often focus on marine mammals rather than oyster predators. For example, in the United States the Marine Mammal Protection Act sets stringent standards for wildlife interactions, and since January 2023 seafood-exporting countries must demonstrate comparable programs addressing marine mammal bycatch and intentional kills (Bath et al., 2023). Despite these advancements, oyster aquaculture production may still occur in countries without strong oversight or transparency requirements, data collection, or the adoption of best practices.

Non-predatory wildlife interactions

The risk of negative interactions between shellfish farms and marine mammals or seabirds, such as entanglement or disruption of migratory behavior, is generally considered minimal (MPI, 2013). For instance, a global review by Bath et al. (2023) identified ten recorded cetacean entanglements associated with mussel longline farms between 1998 and 2019, including four confirmed fatalities. These events occurred in New Zealand (3), Iceland (3), and one each in Argentina, Western Australia, South Korea, and South Africa. In addition, at least three entanglements were reported in pearl oyster farms in Western Australia, though no mortalities were noted. While oyster and mussel farms share similar longline systems, oyster culture typically involves baskets or mesh bags suspended from sub-surface lines (e.g., attached to poles on the seabed) rather than directly hanging mussel lines from surface floats (Bath et al., 2023). This configuration should be expected to reduce the likelihood of entanglement, as the gear is more structured and taut, presenting fewer loose lines in the water column. Additionally, since 2009, five entanglement incidents involving leatherback turtles have been reported at shellfish farms in Canada and the U.S., with two resulting in fatalities (Bath et al., 2023), but were linked to mussel spat collection or anchoring lines.

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In contrast, the same review (i.e., Bath et al., 2023) documented 87 marine mammal entanglements related to finfish aquaculture between 1987 and 2019, of which 77 resulted in fatalities across ten countries. This difference suggests that while oyster farms can result in occasional entanglements and fatalities, the wildlife interactions risks appear to be minimal when compared with finfish systems.

With regard to other marine mammals, Criterion 3 – Habitat noted the potential for interactions with sea otters (Enhydra lutris), a protected species. Although it was hypothesized that sea otters might preferentially use oyster farms in Alaska for foraging and resting activities compared to undisturbed habitat areas, Reynolds et al., (2025) showed no discernible differences in overall sea otter activity or foraging behavior in the modified habitats of oyster farms (noting that there were no observations of otters predating on the oysters).

Beyond predator control, other types of farm–wildlife interactions can also pose risks to marine species. Underwater noise generated by aquaculture operations and vessel traffic may disrupt marine mammal behavior, impair acoustic communication and navigation, and, in some cases, cause physical injury or death (Bath et al., 2023). Increased boat activity around farms also raises the likelihood of habitat avoidance, collisions, and stress-related impacts, particularly for cetaceans that rely on echolocation. Globally, vessel strikes are recognized as a major source of injury and mortality for marine mammals.

Another important interaction that has received increasing attention involves seabirds (e.g., cormorants, gulls, terns) using floating oyster gear as resting surfaces (Rheault, 2024; Barnes, 2019). This behavior has raised sanitary concerns for farmers, particularly on the U.S. East Coast. For example, during the summer of 2015, fecal coliform levels at several sampling sites exceeded 16,000 most probable number (MPN/100 g) in oyster meat and 210 MPN/100 mL in seawater—far above the established limits of 230 MPN/100 g and 14 MPN/100 mL, respectively (Rheault, 2024; Barnes, 2019). Elevated bacterial concentrations led to farm closures in 2015 and suspension of harvests procedures again in 2021, when another outbreak of illness was reported in Rhode Island. In the latter case, fecal coliform counts fell below permissible thresholds after 18 days of sinking cages below the water surface to prevent seabirds from roosting.

Although the overall risk to human health is considered low due to pathogen specificity, these outbreaks prompted regulatory responses on the East Coast. States now require harvest suspensions or area closures when fecal coliform levels exceed water-quality standards (Rheault, 2024; Barnes, 2019). Farmers have consequently implemented seabird deterrents, often rotating methods to counter bird adaptation. Common measures include poles with lines and streamers, scare kites, noisemakers, spikes or long zip ties, gullsweeps, and temporary gear submersion prior to harvest (the latter a regulatory requirement in states such as New York) (Rheault, 2024; Lennox, 2024; Barnes, 2019). These deterrents are designed to prevent birds from landing on oyster gear and appear to pose minimal risk of entanglement or harm to seabirds.

Therefore, it is evident that oyster aquaculture operations can lead to interactions with wildlife, including occasional mortalities. Several studies suggest that individual farms typically have limited local impacts and the overall risk of population-level effects is generally low. Most of the primary species of predatory concern (listed above) are abundant, rapidly reproduce, and recolonize areas quickly after disturbance, and as such are a low conservation concern. However, on a precautionary basis, the cumulative effects of multiple farms within a region present risks that cannot be entirely disregarded, especially in areas supporting sensitive or vulnerable species (Bath et al., 2023).

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Conclusions and final score

Marine aquaculture operations, including oyster farms, inevitably interact with a wide range of wildlife species depending on their location, infrastructure type, and farming practices. Predators such as fish, crabs, birds, gastropods, and starfish can affect farm productivity, and in some cases predator-related mortalities of oysters have led to farm closures. Producers therefore adopt a suite of mostly non-lethal mitigation strategies, including physical exclusion, nursery-based husbandry, and in some cases, predator removal. Most of the primary species of predatory concern (listed above) are abundant, reproduce rapidly, and readily recolonize disturbed areas, and as such are a low conservation concern. While regulatory oversight of predator control practices varies globally, lethal control is increasingly rare, with most farms relying on non-harmful methods that align with animal welfare and conservation goals.

Although a small number of entanglements with cetaceans and sea turtles have been documented in shellfish aquaculture, these cases are rare and typically involve mussel or spat collection lines rather than oyster farming gear. As such, the risk of negative interactions, such as entanglement or behavioral disturbance of marine mammals and seabirds, is generally considered low in oyster aquaculture. Studies from multiple regions further demonstrate that, when farms are sited with ecological considerations in mind, they tend to have minimal or even neutral effects on surrounding wildlife, including shorebirds, seabirds, or otters. Similarly, risks from vessel traffic and underwater noise can be mitigated with best practices. Overall, deliberate lethal control is uncommon, and with widespread implementation of non-lethal exclusion techniques, wildlife mortalities associated with oyster farming are considered to be limited to exceptional cases and are unlikely to have population-level consequences. The final numerical score for wildlife and predator mortalities is a deduction of -2 out of -10.

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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.

Escape of secondary species parameters	Score	
F10Xa International or trans-waterbody live animal shipments (%)	5.0	
F10Xb Biosecurity of source/destination	6.0	
C10X Escape of secondary species Final Score (0 to -10)	**-2.0**	**Green**

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Criterion 10X Summary

Historically, the introduction of oysters into new cultivation areas has been associated with the unintentional introduction of a variety of invasive animals, plants, and pathogens, often with serious implications for native organisms. However, since 2010, global reviews have not reported significant new impacts associated with such introductions, a trend attributed to tighter biosecurity requirements for oyster movements. Today, live oyster movements are focused on the transfer of spat from hatcheries and nurseries to grow out farms (in addition to the movements of live oysters from harvest to market which is not assessed here). At the same time, reliance on locally collected spat remains widespread in major oyster-producing regions, reducing the necessity for trans-waterbody movements. Based on this context, it is estimated that less than 50% of the global oyster industry relies on the movement of live oysters across waterbodies. Best management practices for both the source and destination of oysters are established, however due to the global scope of this assessment, it is assumed that their implementation and efficacy are varied. Typically, hatcheries use larval tanks, while growout sites are open systems using BMPs. International and national biosecurity measures vary with regard to oyster aquaculture, however trade and movement of oysters and spat is regulated at state, national and international levels. The final score for Criterion 10X – Escape of unintentionally introduced species is –2.0 out of –10.

Justification of score

This criterion provides a measure of the risk that non-native species, apart from the farmed species, might be unintentionally introduced into a distinct waterbody (i.e., one in which they are not native or present) during the transportation of live oysters. Given the global scope of this assessment, robustly assessing the frequency of international and trans-waterbody movements of live oysters (Factor 10Xa), as well as the evolving biosecurity measures applied at both the source and destination of these movements (Factor 10Xb) is challenging. As such, some assumptions and estimates must be applied to the available information from the major producing regions, as discussed below.

Factor 10Xa International or trans-waterbody live animal shipments

Aquaculture oyster stocks are typically sourced either from natural settlement within the same waterbody or from hatchery-reared spat, which often involves movement between regions and, in many cases, international translocation (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025; MPI, 2013). However, no reliable data exist in the published literature or official statistics to quantify the extent of oyster spat trade from hatcheries to grow-out regions. Instead, historical translocations and current production practices provide indirect indicators of how common such movements may be. For instance, historically, more than 180 introductions of 18 oyster species into 73 countries have been recorded, most occurring in the 1970s for aquaculture purposes. *C. gigas*, the most widely translocated oyster species, has since become naturalized in at least 17 countries and, in several cases, facilitated the unintended introduction of associated species (Bishop et al., 2023; Tan et al., 2023; Ruesink et al., 2005). As noted in Criterion 6 – Escapes (Factor 6.2), oyster translocations have been a common pathway for moving secondary species, and as further discussed below under Factor 10Xb – Biosecurity of source/destination, they have often led to the unintentional spread of secondary animals, plants, and pathogens. Nonetheless, global reviews since 2010 (Tan et al., 2023; Martinez-Garcia et al., 2021) report no new impacts from unintentional introductions, a result linked to tighter rules mandating certification that spat, juveniles, and adults are pathogen-free and free of secondary species (pers. comm., Emily Johns, Hog Island Oysters Co., October 2025; pers. comm., Jorge Chaves, CIBNOR, September 2025).

While the transfer of oysters (e.g., from hatcheries and nurseries to grow-out farms) remains a common aquaculture practice, in major producing regions such as China, Europe, and the United States, the collection of wild spat is still widely practiced and, in some cases, continues to serve as the primary source of spat (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025; Mercer et al., 2024; MPI, 2013). This reliance on local spat collection reduces the need for trans-waterbody transfers, since grow-out typically occurs within the same waterbody. However, hatchery-produced spat is increasingly favored for its advantages, including size uniformity, disease resistance, triploidy, and year-round availability (Mercer et al., 2024). Although the scale and frequency of spat trade remain undocumented, it is well established that when local spat supplies are insufficient to support commercial operations, farmers must source spat from other sites or hatcheries, often requiring trans-waterbody movements (pers. comm., Jorge Chaves, CIBNOR, September 2025; Mercer et al., 2024).

While trans-waterbody movements of oyster spat do occur, the quantity and frequency vary widely depending on the region and the specific needs of each farm. Given this variability, and considering that wild spat collection remains common in several major producing countries and typically takes place within the same waterbody, along with the lack of recent impacts recently reported involving unintentional introduction of secondary species, it is estimated here that less than 50 % of the global oyster industry depends on inter- or trans-waterbody transfers. Therefore, the score for Factor 10Xa is 5 out of 10, representing a moderate (<50%) reliance on animal shipments.

Factor 10Xb Biosecurity of source/destination

The global oyster industry has increasingly prioritized biosecurity, with international, national, and regional regulations now in place to reduce the well-documented spread of secondary species and pathogens associated with oyster translocations (Mercer et al., 2024; King et al., 2018; Sweet and Bateman, 2016; Pernet et al., 2016; Pacific Shellfish Institute 2015; Oidtmann 2011). Best Management

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Practices for biosecurity are widely available and typically include pre-movement pathogen screening of hatchery spat and protocols to limit the transfer of equipment between sites (Tan et al., 2023; Pacific Shellfish Institute, 2015; NOAA, 2019; FAO, 2004-2019b, Oidtmann et al., 2011; ECSGA, 2010). While these measures are essential, they may not fully eliminate the risks associated with trans-waterbody movements of oysters (Tan et al., 2023).

There are well-documented cases where trans-waterbody movements of oysters have facilitated the unintentional spread of invasive species and pathogens. For example, the introduction of *C. virginica* to England brought the predatory whelk *Urosalpinx cinerea*, which caused significant mortality of native *O. edulis* populations in the late 1980s (Tan et al., 2023). In Europe during the 1970s, the introduction of *C. gigas* contributed to the spread of the invasive slipper limpet (*Crepidula fornicata*), which subsequently expanded in abundance and competed with both farmed and native bivalves (*M. edulis* and *O. edulis*). Similarly, mud-blister worms such as *Polydora* spp. and *Boccardia* spp. were introduced via oyster and abalone translocations in Hawaii, Chile, and New Zealand during the 1970s and 1980s (Tan et al., 2023; Radashevsky & Olivares, 2005). Oysters have also acted as vectors for harmful algal species: in the 1880s, shipments from France to Ireland introduced at least 67 phytoplankton species, and imports into Atlantic Canada brought green algae (*Codium* spp.), which displaced local bivalves (Tan et al., 2023). With respect to diseases, *Bonamia* spp. spread from various European regions to Portugal in the 1990s, and *O. edulis* was a vector for *Bonamia* introductions from California to France and Spain around 2004. In addition, the copepod parasites *Mytilicola orientalis* and *M. intestinalis* were introduced to Ireland through Pacific oyster imports in the early 1990s, impacting native *O. edulis* populations (Martinez-Garcia et al., 2021).

The most recent documented impacts associated with oyster translocations appear to have occurred prior to 2010. For example, the invasive tunicate *Didemnum vexillum* was introduced via *C. gigas* spat shipments from UK or Guernsey hatcheries in 2009, affecting sensitive habitats in areas such as Loch Creran, Scotland (Tan et al., 2023). Similarly, pathogen spread has been linked to oyster movements during this period. *C. gigas* translocations were associated with the spread of MSX disease from Canada to the eastern United States around 2010 (Tan et al., 2023; Sanchez et al., 2015), and with the introduction of OsHV-1 around 2009 from France and other European countries to Ireland, New Zealand, and previously unaffected French regions. Likewise, *C. virginica* was linked to the spread of *Perkinsus marinus* from northwestern Mexico to the United States and Brazil in approximately 2008 (Tan et al., 2023). Recent reviews, such as Tan et al. (2023), highlight these historical cases but do not identify more recent examples of invasive species or pathogen introductions associated with oyster translocations. This absence of recent records signals that BMPs and strengthened international and national regulations may be contributing to a reduction in the frequency of such events.

Moreover, as a common source of oyster movements, hatcheries play a critical role in mitigating the risks of introducing secondary species and diseases. While many hatcheries employ well-established biosecurity measures, such as closed or semi-closed recirculating larval systems, filtration, water disinfection, and effluent treatment, the specific strategies applied and their effectiveness may vary across production regions (Mercer et al., 2024; FAO, 2021). Although progress has clearly been made, the global scope of this assessment assumes variability in both implementation and outcomes of these BMPs.

Additionally, there is increasing evidence that biosecurity regulations and disease surveillance have been strengthened across the global oyster industry (Tan et al., 2023). For instance, the WOAH maintains a list of 117 notifiable animal diseases that helps to inform country bans and restrictions on aquaculture trade to limit disease spread, including several of the main diseases that affect oysters, which are discussed in Criterion 7 - Disease; pathogen and parasite interactions (Rheault and Kehoe, 2019). In response, it

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became common practice for national authorities to implement regulations aimed at preventing the movement of oysters from infected to non-infected areas (Bishop et al., 2023). For example, In the UK, restrictions on the movement of oysters from areas with disease outbreaks are in place to limit transmission of disease and pathogens between regions. Similarly, in Australia, a disease response plan and movement restrictions limit the spread of disease (Pernet et al., 2016). Other European countries are more strict; for instance, Sweden enforces a strict application of the precautionary principle by prohibiting the import of oyster spat, aiming to prevent the unintentional introduction and spread of pathogens into its coastal waters (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025). In Canada, the Health of Animals Act outlines reportable diseases in aquaculture and mandates the immediate notification of disease outbreak to the Canadian Food Inspection Agency, which then notifies the WOAH (DFO Canada, 2018).

Overall, while it appears that global oyster trade and translocations are subject to legal controls at both national and international levels to manage the spread of notifiable diseases, along with the implementation of BMPs at the hatchery phase of production; the global nature of oyster production makes it challenging to assess the uniformity of biosecurity implementation in all countries. (World Organisation for Animal Health, 2018; Allshouse et al., 2004). As such, a degree of variability in the application and enforcement of biosecurity measures is acknowledged here. Given this, the Source score for Factor 10Xb is 6 out of 10.

The destination for live animal shipments is the farm grow-out site. At this stage, best management practices appear to be generally applied to reduce the risk of disease transfer. The FAO–WHO Technical Guidance on Bivalve Mollusc Sanitation Programmes provides detailed frameworks for growing area profiling, assessment, monitoring, and classification, offering a structured basis for managing biosecurity risks in grow-out operations (Mercer et al., 2024). These guidelines appear to be widely applied across the oyster industry and incorporated into national regulatory frameworks, making them an increasingly important tool for preventing the spread of disease from infected to uninfected areas(ibid.). However, as with hatcheries, practices vary globally, and grow-out systems, whether on-bottom or off-bottom, remain fully open to the surrounding environment. Therefore, as grow-out sites are open systems which generally employ best management practices, the Destination score for Factor 10Xb is 2 out of 10.

The final score for Factor 10Xb is the higher of the two scores for the source and destination of movements, which is 6 out of 10 for the source of movements.

Conclusions and final score

Historically, the introduction of oysters into new cultivation areas has been associated with the unintentional introduction of a variety of invasive animals, plants, and pathogens, often with serious implications for native organisms. However, since 2010, global reviews have not reported significant new impacts associated with such introductions. Today, live oyster movements are focused on the transfer of spat from hatcheries and nurseries to grow out farms (in addition to the movements of live oysters from harvest to market which is not assessed here). At the same time, reliance on locally collected spat remains widespread in major oyster-producing regions, reducing the necessity for trans-waterbody movements. Based on this context, it is estimated that less than 50% of the global oyster industry relies on the movement of live oysters across waterbodies. Best management practices for both the source and destination of oysters are established, however due to the global scope of this assessment, it is assumed that their implementation and efficacy are varied. Typically, hatcheries use larval tanks, while growout sites are open systems using BMPs. International and national biosecurity measures vary with regard to

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oyster aquaculture, however trade and movement of oysters and spat is regulated at state, national and international levels. The final score for Criterion 10X – Escape of unintentionally introduced species is –2.0 out of –10.

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Scientific review does not constitute an endorsement of the Seafood Watch® program, or its seafood ratings, 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	
Data Category	**Data Quality**
Production	10.0
Management	7.5
Effluent	7.5
Habitat	7.5
Chemical Use	7.5
Feed	10.0
Escapes	7.5
Disease	5.0
Source of stock	7.5
Wildlife mortalities	10.0
Escape of secondary species	5.0
C1 Data Final Score (0-10)	**7.727**
	Green

Criterion 2: Effluent	
Effluent Evidence-Based Assessment	**Data and Scores**
C2 Effluent Final Score (0-10)	**8**
Critical?	NO

Criterion 3: Habitat	
F3.1. Habitat conversion and function	**Data and Scores**
F3.1 Score (0-10)	9
F3.2 – Management of farm-level and cumulative habitat impacts	
3.2a Content of habitat management measure	4
3.2b Enforcement of habitat management measures	4
3.2 Habitat management effectiveness	6.400
C3 Habitat Final Score (0-10)	**8.133**
Critical?	No

Criterion 4: Chemical Use	
All-species assessment	**Data and Scores**

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Chemical use initial score (0-10)	9
Trend adjustment	0
C4 Chemical Use Final Score (0-10)	**9**
Critical?	No

Criterion 5: Feed	
C5 Final Feed Criterion Score	**10.0**
Critical?	**No**

Criterion 6: Escapes	**Data and Scores**
F6.1 System escape risk	0
Percent of escapees recaptured (%)	0.000
F6.1 Recapture adjustment	0.000
F6.1 Final escape risk score	0.000
F6.2 Invasiveness score	7
C6 Escape Final Score (0-10)	**4.0**
Critical?	No

Criterion 7: Disease	**Data and Scores**
Evidence-based or Risk-based assessment	Risk
Final C7 Disease Criterion score (0-10)	**4**
Critical?	No

Criterion 8X Source of Stock	**Data and Scores**
Percent of production dependent on wild sources (%)	0.0
Initial Source of Stock score (0-10)	0.0
Use of ETP or SFW "Red" fishery sources	No
Lowest score if multiple species farmed (0-10)	n/a
C8X Source of stock Final Score (0-10)	**0**
Critical?	No

Criterion 9X Wildlife Mortality parameters	**Data and Scores**
Single species wildlife mortality score	-2
System score if multiple species assessed together	n/a
C9X Wildlife Mortality Final Score	**-2**
Critical?	No

Criterion 10X: Introduction of Secondary Species	**Data and Scores**

Draft for Review

Production reliant on transwaterbody movements (%)	49.99
Factor 10Xa score	5
Biosecurity of the source of movements (0-10)	6
Biosecurity of the farm destination of movements (0-10)	0
Species-specific score 10X score	-2.000
Multi-species assessment score if applicable	n/a
C10X Introduction of Secondary Species Final Score	**-2.000**
Critical?	n/a

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Appendix 2 – Criterion 2: Effluent

A brief overview of the key laws and regulations governing oyster aquaculture in major producing regions, including China, the United States, France, South Korea, and Japan is provided below.

China

China went through a rapid development of mariculture since 1979, and for 30 years there was somewhat of an unrestrained industry development, which resulted in marine ecological issues, including eutrophication of seawater (Yu et al., 2020). However, since the 21st century the Chinese government has prioritized the development of the sustainable aquaculture industry (ibid.). The primary legal framework for managing marine pollution (i.e., including from aquaculture) in China is stipulated in the Marine Environmental Protection Law[25] (People's Republic of China). It sets out provisions on pollutant discharge, environmental monitoring, and the responsibility of enterprises to avoid ecological harm. Specifically, the following chapter relate directly to mitigating effluent risks:

- Chapter VII Prevention and Control of Pollution Damage to the Marine Environment caused by Dumping of Wastes.
  - ➢ It establishes a strict regulatory framework for preventing and controlling pollution caused by waste dumping in marine environments. While it is not specifically tailored to aquaculture, it is relevant to aquaculture effluent management because it defines what types of waste may be discharged into marine areas and under what conditions.
  - ➢ No waste dumping is allowed without a permit from the State oceanic administrative department.
  - ➢ Dumping activities must be logged and reported; failure to comply can result in penalties.

Furthermore, while indirectly covering effluent restrictions, the Sea Area Administration Law[26] requires that sea use (including mariculture) complies with environmental protection standards, including water quality regulations (Yu et al., 2020). Similarly, the Marine Ecological Red Line System, defines ecologically sensitive zones and places strict controls on industrial and aquaculture activities within them, including effluent discharge limitations (Zeng et al., 2024; Yu et al., 2020). The Construction Plan of National Marine Ranching Demonstration Zone[27] (2017–2025) Includes guidelines on sustainable marine ranching, with emphasis on environmental impact control, including waste management and water quality monitoring. This plan also included goals to improve water quality and reduce eutrophication.

Europe

The European Union has relatively strict water-quality standards, regulating aquaculture discharges through an integrated policy framework aimed at protecting water quality and sediment conditions (European Commission, 2021; Ross et al., 2013). Central to this are the Water Framework Directive (WFD - Directive 2000/60/EC), the Environmental Assessment Directive (EAD - Directive 2011/92/EU), the Maritime Spatial Planning Directive (MSPD - Directive 2014/89/EU), Marine Strategy Framework Directive (MSFD - 2008/56/EC), and the Strategic Guidelines for Sustainable Aquaculture (SGSA -2021–2030). It

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[25] https://english.court.gov.cn/2016-04/15/c_761499_2.htm

[26] https://english.mee.gov.cn/Resources/laws/environmental_laws/202012/t20201211_812661.shtml#:~:text=Article%201%20This%20law%20has,development%20and%20sustainable%20utilization%20of

[27] https://www.fao.org/faolex/results/details/fr/c/LEX-FAOC193206/#:~:text=By%202025%2C%20178%20national%20marine,nationwide%3B%20artificial%20fish%20reef%20area

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should be noted that, as discussed further below, implementation of these directives may differ across EU member states.

The WFD establishes legally binding objectives for achieving "good ecological and chemical status" of all EU surface and groundwater bodies. While this provision does not specify monitoring for marine ecosystems, it requires Member States to conduct surveillance monitoring at strategically significant locations to assess overall water quality across river basin districts, including areas where water discharges into marine environments (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025; WFD[28], 2000). For aquaculture, this includes strict oversight of nutrient and organic matter discharges, with national authorities required to include aquaculture as a pressure in their River Basin Management Plans. Specifically, Article 11 and Article 6 - Annex IV of the WFD requires Member States to implement basic and supplementary measures to control pollution from point and diffuse sources, including effluent discharges from aquaculture facilities; but again, nothing specifying shellfish aquaculture, so its applicability to this assessment is not clear.

The SGSA reinforce this by mandating the integration of water-quality standards into licensing and spatial planning. Section 2.2.1 explicitly identifies the need for environmental monitoring of discharges and emissions (including nutrients, veterinary products, plastics, and other pollutants) and calls for management practices that include mitigation strategies and discharge controls. It further promotes the use of lower-impact systems such as integrated multi-trophic aquaculture and recirculating aquaculture systems, and urges Member States to apply life-cycle assessment methods to evaluate and minimize environmental footprints.

The MSPD complements these efforts by requiring Member States to designate suitable areas for aquaculture in a manner that prevents cumulative pollution effects and avoids ecologically sensitive zones. Specifically, Article 6(2)(a–d) mandates that plans consider marine ecosystem dynamics, land-sea interactions, and coherence with relevant EU legislation, including the WFD and MSFD. Alignment with WFD objectives (Art. 4 and Annex V) includes the mapping of pollution sources, evaluation of site-specific carrying capacities (Annex II, 1.4), and protection of water bodies vulnerable to anthropogenic sources.

Finally, the EAD requires an Environmental Impact Assessment (EIA) for aquaculture projects likely to have significant effects on the environment (please refer to Criterion 3 – habitat for more details). Annex II(1)(f) lists "intensive fish farming", which also encompasses shellfish farming, as a project category subject to screening by Member States to determine whether an EIA is required. Screening is based on criteria outlined in Annex III, including project size, cumulative impacts, pollution risk, and proximity to sensitive ecosystems, such as Natura 2000 sites or waters designated under the WFD, which can include areas used by shellfish aquaculture. The EIA must include a detailed assessment of impacts on water quality, sediment characteristics, and benthic habitats, as specified in Annex IV(4) and (5), which require description of the likely significant effects of the project on water and the marine environment, and a description of mitigation measures. Moreover, Article 8a of the Directive mandates that environmental monitoring conditions be included as part of project approval where necessary to avoid significant adverse effects, thus supporting adaptive management during farm operations.

While the EU legislative framework is comprehensive, the 2025 MSFD Evaluation highlights inconsistent enforcement among Member States and regulatory overlaps with the Common Fisheries Policy (CFP) that often delay or weaken effluent-related conservation actions. Additionally, the European Court of Auditors

[28] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32000L0060

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(2020) found that spatial protections for fisheries and aquaculture, though established, are frequently undermined by insufficient monitoring and enforcement to effectively reduce anthropogenic pollution.

For instance, a European initiative - AquaVitae, which spans 16 Atlantic-bordering countries, surveyed 18 oyster producers (i.e., mainly from the U.S., Canada, Ireland, Sweden, Brazil, and Namibia) to understand current practices around environmental monitoring, including effluent impacts in Low Trophic Aquaculture; also supporting the European Court of Auditors (2020) determination that aquaculture monitoring is insufficient(Hughes et al., 2023). Statutory monitoring was largely driven by food safety regulations, with limited focus on water quality; only 14% of producers reported monitoring parameters like total ammonia nitrogen, pH, or dissolved oxygen (ibid.). While all shellfish companies monitored phytoplankton toxins and harmful algal blooms, elective monitoring efforts were more comprehensive, though about 60% of producers did not share the data externally. Key environmental risks, such as genetic introgression, persistent organic pollutants, and microplastic pollution, were under-monitored, revealing significant gaps. Furthermore, although large volumes of data were collected, most were underutilized, illustrating a "Data Rich, Information Poor" dynamic (ibid.). The study suggests that to enhance effluent mitigation, improved data use, strategic risk-focused monitoring, and better coordination between producers and regulators are essential to maximize ecological and operational benefits without incurring diminishing returns (Hughes et al., 2023).

In summary, effluent and sediment management in EU oyster aquaculture is governed by a multilayered regulatory framework that includes directives on environmental assessment, spatial planning, discharge controls, and coordinated licensing. However, enforcement in practice is largely geared toward ensuring that bivalves harvested for human consumption meet strict sanitary (food safety) standards. While water quality monitoring is mandated to protect public health, continuous monitoring of sediment or broader ecological impacts is generally not required for oyster farms (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025). In contrast, fed aquaculture (e.g., salmon farming in Norway) often requires routine benthic and pelagic monitoring and area fallowing between cycles. Such practices and standards, like stocking density limits, are more common in finfish and organic systems than in low-trophic aquaculture (pers. comm. Åsa Strand, Länsstyrelsen i Västra Götalands län, March 2025). As a result, implementation gaps and administrative fragmentation remain key obstacles to achieving Good Environmental Status (GES) in Europe's coastal and transitional waters.

United States

As noted earlier, the United States is home to approximately 900 reported oyster farms, with 63% (565 farms) located in just five states: Massachusetts (21%), Washington (13%), Florida (10%), Virginia (10%), and Maine (9%) (USDA, 2023). Given this concentration, we reviewed the effluent-related regulatory frameworks governing oyster aquaculture in these leading production states. These states all exhibit, to varying degrees, oversight mechanisms aimed at managing potential water quality risks associated with oyster farming. Across the board, coordination among multiple state and federal agencies is necessary to allocate permits and enforce standards (NOAA, 2021). While this report does not delve into the full technical complexity of water quality monitoring and compliance requirements, it provides a general overview of the key effluent management measures and permitting considerations that apply to oyster production in these states (NOAA, 2021).

1. National Pollutant Discharge Elimination System (NPDES) permits (Section 402/403 of the Clean Water Act):
   While not always required, a NPDES permit is mandatory if a facility discharges pollutants such as nutrients, pharmaceuticals, antifouling agents, or disinfectants into U.S. waters. Most oyster

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farms avoid the need for this permit by operating as low-discharge or non-discharge systems (e.g., using filter feeders or recirculating systems).

2. Section 401 Water Quality Certification:
   Activities related to oyster farming must comply with state-level water quality standards under Section 401. Each state evaluates whether aquaculture operations meet these standards, either through general permits or individualized certification processes.
3. Coastal zone management (CZM) Consistency:
   All five states require that oyster aquaculture activities align with their coastal zone management programs. This ensures that farm siting and operation do not conflict with broader coastal protection and land-use goals. Some states, like Massachusetts and Washington, require individual CZM reviews under specific conditions.
4. State-level best management practices (BMPs):
   While the requirements for the application of BMPs vary by state, in general, certified aquaculture operations must implement BMPs to minimize environmental impact. These may include using species that do not require feed or fertilizer, applying low-impact growing methods, or complying with siting restrictions near sensitive habitats or pollution sources.
5. Permit coordination and overlap:
   Multiple agencies at both state and federal levels are often involved in the permitting and oversight process. Coordination ensures that oyster farms comply with overlapping environmental protection statutes, including aquaculture-specific exemptions where applicable.

Overall in the U.S., although regulatory implementation varies by state, the national framework reflects a shared emphasis on pollution prevention, adaptive management, and coordinated oversight to minimize effluent-related risks from oyster farming (NOAA, 2021).

South Korea

Oyster aquaculture in the Republic of Korea is governed under a set of environmental protection and marine management laws aimed at preventing water pollution, regulating wastewater discharge, and protecting marine ecosystems (FAO[29], 2023).

1. Aquaculture Industry Development Act (2019)
   - Article 9 requires that the head of the local government (Si, Gun, Gu) or Governor (Mayors/Do) formulate development plans for licensed fish farms, considering environmental restrictions.
   - Article 20 allows aquaculture businesses to occupy and use public waters, subject to environmental compliance under the Public Waters Management and Reclamation Act.

2. Framework Act on Environmental Policy (2011).
   - Article 1 defines the government's responsibility to prevent environmental pollution and ensure a clean, healthy environment for all citizens.
   - Article 18 mandates local governments to manage and monitor environmental status by category (water, air, natural ecology), using spatial data to guide policy.
   - Article 30 authorizes the government to regulate pollutants, including those discharged into water bodies and the sea.
   - Article 39 introduces zonal environmental management, requiring the Minister of Environment to manage water pollution by watershed and affected zones.

[29] https://www.fao.org/faolex/country-profiles/general-profile/en/?iso3=KOR

Draft for Review

3. Marine Environment Management Act (2007) (Refer to the following articles within the legislation for more details: Articles 3, 9, 14, 18, 22, and 36)
    - Requires regular marine environmental monitoring via official measuring networks.
    - Prohibits unregulated discharge of pollutants in marine spaces (bathing areas, estuaries, etc.).
    - Mandates comprehensive marine environment plans every 10 years.
    - Enforces appointment of marine pollution prevention managers for marine facilities.
    - Supports installation of pollutant control infrastructure.

4. Environmental Impact Assessment Act (2011)
    - Article 1 establishes the Act's goal: to forecast and assess environmental impacts of projects, ensuring environmental conservation and sustainable, citizen-friendly development.
    - Article 22 lists public waters development projects (e.g., reclamation, coastal use, installation of submerged cages, seafloor-altering structures) as subject to EIA.
    - Article 5 mandates that conservation goals must consider existing environmental quality standards under laws such as the Water Quality and Aquatic Ecosystem Conservation Act, which are applicable to effluent discharges from aquaculture (mainly applicable for freshwater systems).
    - Article 28. The Minister of Environment reviews the report with input from relevant ministries, including the Ministry of Oceans and Fisheries, especially if marine pollution is a concern.
    - Article 30. Once terms are agreed upon (e.g., discharge limits, treatment technologies), they must be reflected in the project plan and adhered to during operation.
    - Article 36. A follow-up environmental impact survey is required after project commencement to assess actual environmental outcomes and adjust measures if needed.

While not always specific to shellfish farming, they form the legal basis for controlling effluent impacts. The Ministry of Environment, the Ministry of Oceans and Fisheries, and local governments, including Si, Gun, Gu administrations as well as Mayors and Do Governors are the central coordinating bodies for environmental protection and pollution surveillance, and are responsible for the implementation of these policies.

Japan

In Japan, the mitigation of effluent impacts from oyster aquaculture is supported by two central legislative instruments: the Sustainable Aquaculture Production Assurance Act (1999) and the Basic Environment Law. Together, these laws establish a dual focus on environmental protection and sustainable aquaculture development.

1. Sustainable Aquaculture Production Assurance Act (1999) is specifically designed to promote environmentally responsible aquaculture practices (Refer to the following articles within the legislation for more details: Articles 1, 2, and 3).
    - It mandates that aquaculture areas, such as those used for oyster farming, must be maintained or restored to conditions that support the healthy growth of aquatic organisms.

Draft for Review

- Effluent-related concerns from and to aquaculture farms, are indirectly addressed through the requirement to reduce the accumulation of feed byproducts and sediments that can inhibit farm raised aquatic animals or plants (i.e., including oysters) growth or promote disease.
- It empowers Fisheries Cooperative Associations to prepare and implement Aquaculture Area Improvement Plans, which outline targeted measures (e.g., reducing organic loading, removing bottom sediment, and installing treatment infrastructure) to improve local water quality.

2. Basic Environment Law provides the broader regulatory framework for pollution control and environmental governance across all industries, including aquaculture.
    - Imposes general obligations on corporations (including aquaculture operators) to prevent water pollution, treat wastewater, and comply with national discharge standards.
    - Implementation of Environmental Pollution Control Programs in areas where pollution is or may become a concern.

3. The Environmental Impact Assessment Act of Japan (1997) provides a procedural framework for identifying, assessing, and mitigating environmental risks, including those posed by oyster aquaculture effluent. However, the main focus of this requirement, as it is for the other countries described previously, is when the operations involve structural developments or land modifications in coastal or marine environments (hence covered in more detailed in Criterion 3 – Habitat) (Refer to Chapter II – Section I for more details).
    - Before drafting detailed assessment documents, project proponents must evaluate and report key environmental concerns. While, it does not explicitly require proponents to include potential water pollution from effluents they are required to identify any environmental-related risks, so they would be expected to include potential effluent risks if these were a concern, along with include stage the proposal of mitigation measures.
    - If required, a comprehensive EIS must include data and analysis on the potential for effluent pollution, such as nutrient loading, dissolved oxygen depletion, or harmful algal blooms.

The Ministry of Agriculture, Forestry and Fisheries, along with the Fisheries Cooperative Associations are responsible for the implementation of the Sustainable Aquaculture Production Assurance Act, while the Ministry of the Environment Prefectural Governments share responsibility in implementing the Basic Environment Law and the Environmental Impact Assessment Act.

Overall, the available evidence suggests that management measures addressing effluent risks are in place across major oyster-producing regions. While some gaps in implementation and enforcement may persist, these measures, combined with the natural filter-feeding capacity of oysters, support the conclusion that when the industry is well managed and ecologically planned, it can operate as a low-impact and potentially environmentally beneficial form of aquaculture.

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