Monterey Bay Aquarium
Seafood Watch®

All species

Image courtesy of AKVA Group

Global

Recirculating Aquaculture Systems (indoor, tank-based) operating as grow out facilities

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About Seafood Watch

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

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

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

Guiding Principles

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

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

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

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

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

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

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

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

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

Final Seafood Recommendations

RAS all species (minus eels)

With wastewater treatment

Criterion	Score	Rank	Critical?
C1 Data	7.50	GREEN	
C2 Effluent	8.00	GREEN	NO
C3 Habitat	7.60	GREEN	NO
C4 Chemicals	6.00	YELLOW	NO
C5 Feed	5.69	YELLOW	NO
C6 Escapes	10.00	GREEN	NO
C7 Disease	6.00	YELLOW	NO
C8X Source	0.00	GREEN	NO
C9X Wildlife mortalities	0.00	GREEN	NO
C10X Secondary species escape	-2.40	GREEN	
Total	**48.39**		
Final score (0-10)	**6.91**		

OVERALL RANKING

Final Score	6.91
Initial rank	GREEN
Red criteria	0
Interim rank	GREEN
Critical Criteria?	NO

FINAL RANK

GREEN

Without wastewater treatment

Criterion	Score	Rank	Critical?
C1 Data	7.50	GREEN	
C2 Effluent	6.00	YELLOW	NO
C3 Habitat	7.60	GREEN	NO
C4 Chemicals	6.00	YELLOW	NO
C5 Feed	5.69	YELLOW	NO
C6 Escapes	10.00	GREEN	NO
C7 Disease	6.00	YELLOW	NO
C8X Source	0.00	GREEN	NO
C9X Wildlife mortalities	0.00	GREEN	NO
C10X Secondary species escape	-2.40	GREEN	

Total	**46.39**
Final score (0-10)	**6.63**

OVERALL RANKING

Final Score	6.63
Initial rank	YELLOW
Red criteria	0
Interim rank	YELLOW
Critical Criteria?	NO

FINAL RANK

YELLOW

RAS Eels (European, Japanese)

With wastewater treatment

Criterion	**Score**	**Rank**	**Critical?**
C1 Data	7.50	GREEN	
C2 Effluent	8.00	GREEN	NO
C3 Habitat	7.60	GREEN	NO
C4 Chemicals	6.00	YELLOW	NO
C5 Feed	5.69	YELLOW	NO
C6 Escapes	10.00	GREEN	NO
C7 Disease	6.00	YELLOW	NO
C8X Source	-10.00	CRITICAL	YES
C9X Wildlife mortalities	0.00	GREEN	NO
C10X Secondary species escape	-2.40	GREEN	
Total	**38.39**		
Final score (0-10)	**5.48**		

OVERALL RANKING

Final Score	5.48
Initial rank	YELLOW
Red criteria	1
Interim rank	RED
Critical Criteria?	YES

FINAL RANK

CRITICAL

Without wastewater treatment

Criterion	**Score**	**Rank**	**Critical?**
C1 Data	7.50	GREEN	
C2 Effluent	6.00	YELLOW	NO
C3 Habitat	7.60	GREEN	NO

C4 Chemicals	6.00	YELLOW	NO
C5 Feed	5.69	YELLOW	NO
C6 Escapes	10.00	GREEN	NO
C7 Disease	6.00	YELLOW	NO
C8X Source	-10.00	CRITICAL	YES
C9X Wildlife mortalities	0.00	GREEN	NO
C10X Secondary species escape	-2.40	GREEN	
Total	**36.39**		
Final score (0-10)	**5.19**		

OVERALL RANKING

Final Score	5.19
Initial rank	YELLOW
Red criteria	1
Interim rank	RED
Critical Criteria?	YES

FINAL RANK

CRITICAL

RAS Eels (American)

With wastewater treatment

Criterion	Score	Rank	Critical?
C1 Data	7.50	GREEN	
C2 Effluent	8.00	GREEN	NO
C3 Habitat	7.60	GREEN	NO
C4 Chemicals	6.00	YELLOW	NO
C5 Feed	5.69	YELLOW	NO
C6 Escapes	10.00	GREEN	NO
C7 Disease	6.00	YELLOW	NO
C8X Source	-10.00	RED	NO
C9X Wildlife mortalities	0.00	GREEN	NO
C10X Secondary species escape	-2.40	GREEN	
Total	**38.39**		
Final score (0-10)	**5.48**		

OVERALL RANKING

Final Score	5.48
Initial rank	YELLOW
Red criteria	1
Interim rank	YELLOW

FINAL RANK

Critical Criteria?	NO		YELLOW

Without wastewater treatment

Criterion	Score	Rank	Critical?
C1 Data	7.50	GREEN	
C2 Effluent	6.00	YELLOW	NO
C3 Habitat	7.60	GREEN	NO
C4 Chemicals	6.00	YELLOW	NO
C5 Feed	5.69	YELLOW	NO
C6 Escapes	10.00	GREEN	NO
C7 Disease	6.00	YELLOW	NO
C8X Source	-10.00	RED	NO
C9X Wildlife mortalities	0.00	GREEN	NO
C10X Secondary species escape	-2.40	GREEN	
Total	**36.39**		
Final score (0-10)	**5.19**		

OVERALL RANKING

Final Score	5.19		
Initial rank	YELLOW		
Red criteria	1		
Interim rank	RED		FINAL RANK
Critical Criteria?	NO		YELLOW

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

Summary

The final numerical score for global RAS production of all species (minus eels) with wastewater treatment is 6.91 out of 10, which is in the Green range. With no red criteria and no critical scores, the final recommendation is a Green "Best Choice".

The final numerical score for global RAS production of all species (minus eels) without wastewater treatment is 6.63 out of 10 which is in the Yellow range. With no red criteria and no critical scores, the final recommendation is a Yellow "Good Alternative".

The final numerical score for European and Japanese eels produced in RAS without wastewater treatment is 5.19 out of 10, and 5.48 out of 10 with wastewater treatment. Both are in the

Yellow range, however with one Critical criterion score (Source of stock), the final recommendation is a Red “Avoid”.

The final numerical score for American eels produced in RAS without wastewater treatment is 5.19 out of 10, and 5.48 out of 10 with wastewater treatment. Both are in the Yellow range, and with only one Red criterion score (Source of stock), the final recommendation is a Yellow “Good Alternative”.

Executive Summary

Many aspects of Recirculating Aquaculture Systems (RAS) are similar regardless of the species cultured. Due to the fundamental characteristics of RAS described in this assessment, this Seafood Watch recommendation is considered to apply to all species grown in these systems. In the event that there is a specific Seafood Watch assessment be available for a given species produced in RAS then the final recommendation from that species-specific assessment will take precedent. **These recommendations apply only to seafood products grown exclusively in RAS facilities through harvest at the end of grow out. It does not apply to seafood products that were raised in RAS hatcheries and transitioned to other production systems for the grow out period.**

Data for this assessment are most commonly in the form of peer reviewed articles, current Seafood Watch assessments, and personal communication. Categories such as effluents, habitats, escapes, chemical use, disease, biosecurity and source of stock are relatively thoroughly studied and available in the public domain. Topics such as RAS-specific production statistics and feed formulations are not as readily available, and the authors of this report have relied on extensive personal experience and communications with producers to inform this assessment. Information on predator/wildlife interactions is not as readily available because, with respect to RAS, this is not recognized as not having significant environmental impacts. As the purpose of this assessment is to describe the ecological impact of RAS as a production system, the fact that it is a closed system with minimal discharge is, in many cases, enough to justify a score, even with minimal data. The final numerical score for Criterion 1–Data is 7.5 out of 10.

Commercial recirculating aquaculture systems may use a variety of effluent treatment systems for discharged effluent streams. Freshwater systems often collect solids for further use as fertilizer or compost, and may treat soluble wastes prior to discharging them. However, marine systems often discharge directly into the environment with varying levels of treatment. Management of ecological impacts from wastewater discharge differs globally, however in the countries producing the most in RAS (by volume), regulation generally manages point source impacts from discharge, but may not take into account overall cumulative impacts to the environment.

RAS facilities that employ solids capture and appropriately dispose of it (e.g. constructed wetlands, fertilizer application, municipal waste management, etc.), and implement denitrification or other soluble waste treatment (constructed wetlands, aquaponics systems, etc.) of the effluent discharge stream are considered to sufficiently limit the nutrient concentrations of their effluent such that they do not cause or contribute to cumulative ecological impacts at the waterbody/regional scale. As such, RAS facilities employing these discharge treatments score 8 out of 10 for Criterion 2 – Effluent.

RAS facilities that do not employ solids capture or do not appropriately dispose of captured solids (e.g. dumping), or do not implement denitrification or other soluble waste treatments are considered unlikely to create environmental impacts beyond the immediate vicinity of the discharge point, but have the potential to contribute to cumulative impacts at the waterbody/regional scale. As such, RAS facilities without effective solids capture and disposal, or without denitrification or other soluble waste treatment score 6 out of 10 for Criterion 2 – Effluent.

Many RAS operations utilize previously existing buildings (e.g., warehouse, greenhouses, etc.) or, when purpose-built, are done so on previously converted land; as a result, there is no further habitat conversion or loss of ecosystem functionality. Any habitat impacts that do occur (or have previously occurred) are expected to be minor with no overall loss of habitat functionality. The score for Factor 3.1 is 9 out of 10. Given that this assessment is global in scope and siting regulations are varied, a precautionary approach was taken in the scoring of Factor 3.2. Taking into account the management scores of current Seafood Watch reports for countries where RAS also operates, it is determined that countries operating RAS facilities manage their siting through legislation that accounts for sensitive habitats. Information from existing Seafood Watch assessments of countries also producing RAS were used as a proxy for determining the effectiveness, implementation and enforcement of these regulations. This information yielded a score of 4.8 out of 10 for Factor 3.2 The final score for Criterion 3–Habitat is 7.6 out of 10.

The inherent design of RAS (i.e., the physical isolation from the surrounding environment) in combination with the potential for strict biosecurity protocols lowers the risk of introduction of disease agents and thus the need for chemical treatments. While RAS are considered closed systems, they may have an effluent system that discharges a percentage of wastewater from the system. In some cases this effluent is untreated, and discharged directly into surrounding environments. Specific data on chemical use in RAS is limited, however literature provides insights into commonly used or recommended chemicals for these systems, two of which are considered Highly important, and one Critically important for human medicine by the World Health Organization (WHO). While RAS has demonstrably low need for chemical use, systems can, in theory, allow discharge of up to 10% of daily water flow untreated into the surrounding environment. As such the numerical score for Criterion 4–Chemicals is 6 out of 10.

Feed use and subsequent environmental impacts are highly species-specific, with some species requiring high levels of fishmeal and fish oil in their diets, while others can be grown commercially on a feed containing no animal ingredients. Due to ongoing improvements in aquaculture feeds (particularly reductions in the use of fishmeal and fish oil) and their efficiency of use (i.e., the feed conversion ratio, FCR), the large majority of species assessed by Seafood Watch now have Yellow scores for the feed criterion.

To determine a feed score applicable to all RAS grown species, an average of all feed scores applied to species currently grown in RAS that have coinciding Seafood Watch assessments was determined. There is an assumption that RAS use manufactured dry pellet feeds, and therefore the Seafood Watch assessments in which a species is fed whole fish and/or wet/moist pellets are excluded; as such, RAS facilities that feed whole fish and/or wet/moist pellets are not considered within the scope of this assessment. The average is in the Yellow scoring range, and the final feed score is 5.69 out of 10 for all RAS species globally.

Buildings and tanks ensure physical separation of the culture area and the natural environment, minimizing the risk of escapes from RAS. Additionally, tank-based recirculation systems have multiple screens, water treatment, and secondary capture devices to mitigate the risk of escapes. Given the wide range of RAS operating globally, it is assumed that some are in areas where, in the event of an escape, competitive and/or genetic interactions with wild, native populations could occur, however given the extremely low risk of escape, the numerical score for Criterion 6–Escapes is 10 out of 10.

While disease can be an issue for production in RAS, there is a low risk of transmission to wild populations due to the limited volumes of water discharged, and the ability to treat or otherwise control those discharges. Ozonation and UV irradiation are commonly used to disinfect influent waters, and both are often used as part of the recirculation system to maintain water quality. This combination is effective for managing pathogens, and can be applied to effluent wastewater from RAS prior to discharge as well. The numerical score for Criterion 7–Disease is 6 out of 10.

In the majority of global RAS facilities the farmed population is sourced from hatchery-reared broodstock as opposed to wild-caught individuals. Therefore, for this global multi-species RAS assessment, a score of 0 out of -10 has been applied as a universal score with the exception of RAS eels. Production of European (*Anguilla anguilla*) and Japanese eels (*Anguilla japonica*) is still considered 100% reliant on Endangered and Critically Endangered wild populations for juveniles. This results in an individual Criterion 8X scores for European and Japanese eels (Critical) and American eels (-10 out of -10).

This assessment covers indoor, tank-based RAS facilities. These provide physical separation of the culture area from the natural environment, and do not present any risk of wildlife interactions. As such, the score for Criterion 9X– Wildlife Interactions is 0 out of -10.

Due to the variability in sourcing of grow out stock for RAS, it is assumed that 50% of the global RAS industry relies on international or trans-waterbody movement of animals resulting in a Factor 10Xa score of 4 out of 10. RAS facilities vary in their treatment of effluent prior to discharging it, in some cases directly to surrounding ecosystems. Very few, if any, disinfect wastewater discharge. This results in a Factor 10Xb score of 6 out of 10. The final numerical score for Criterion 10X – Escape of Unintentionally Introduced Species is -2.4 out of -10.

The final numerical score for global RAS production of all species (minus eels) with wastewater treatment is 6.91 out of 10, which is in the Green range. With no red criteria and no critical scores, the final recommendation is a Green "Best Choice".

The final numerical score for global RAS production of all species (minus eels) without wastewater treatment is 6.63 out of 10 which is in the Yellow range. With no red criteria and no critical scores, the final recommendation is a Yellow "Good Alternative".

The final numerical score for eels (American, European, and Japanese) produced in RAS without wastewater treatment is 5.19 out of 10, and 5.48 out of 10 with wastewater treatment. Both are in the Yellow range, however with one Critical criterion score (Source of stock), the final recommendation is a Red "Avoid".

Introduction

Scope of the analysis and ensuing recommendation(s)

Species
All species. Many aspects of Recirculating Aquaculture Systems (RAS) are similar regardless of the species being cultured. Due to the fundamental characteristics of RAS described in this assessment, these Seafood Watch recommendations apply to species grown using these systems as grow out.

Geographic Coverage
Global

Production Method(s)
Indoor, tank based recirculating aquaculture systems used for grow out

Species Overview

Brief overview of the species
While salmonid species comprise the majority of RAS production globally (hatcheries included), other species are also grown in these systems. Bostock et al., (2018) list sea bass, meagre, yellowtail, sole, multiple species of grouper, barramundi, tilapia, catfish, zander, perch, jade perch, eel and sturgeon. Turbot has also been produced in RAS systems. The percentages of these species produced in RAS systems are unknown.

Production system
The key characteristic of RAS is the reuse of between 90-99% of the system's water per day by passing it continuously (i.e., recirculating it) through various treatment components such as solids filters, biofilters and disinfection units. Lane et al., (2014) define RAS as replenishing <5% of the water in a system per day. The technology often utilized in these systems offers several additional environmental advantages over other aquaculture production systems, such as the collection and treatment of wastes, increased biosecurity and control over the water quality of the growing environment, reduced risk of escapes, and limited or no interaction with wild fauna.

While RAS are generally characterized as recirculating 90-99% of water contained within the system, it is important to note the difference between reuse of water volume – a measure of volume exchange – and the reuse of flow, a measure of the degree of recirculation. To calculate the degree of recirculation, the following equation is utilized:

(internal recirculating flow rate)/(internal recirculating flow rate + new water intake) x 100

The internal recirculating flow rate is calculated by multiplying daily water turnover (number of water cycles per day) by the volume of the system.

Consider a system with a volume of 10,000 m^3 with a turnover rate of 1 cycle per hour, or 24 cycles per day; the recirculating flow rate is thus 240,000 m^3 per day. If this system exchanges 10% of its water volume daily, new water intake is 1,000 m^3 per day. Therefore, the degree of recirculation is calculated as:

(240,000 m^3 per day) / (240,000 m^3 per day + 1,000 m^3 per day) x 100 =
(240,000 m^3 per day) / (241,000 m^3 per day) x 100 = 99.58%

Thus, the degree of recirculation or reuse of flow in this system is 99.6%, though the system reuses 90% of its water volume.

For the purposes of this report, RAS under the scope of assessment reuse $\geq$90% of their daily water flow, which is typical of modern RAS; depending on the size of the system, this may result in the discharge of significant volumes of water, potentially equivalent to or more than the volumetric capacity of the system.

Production Statistics

The global RAS industry has been cited as doing a poor job of communicating information, as shown by various authors. There are no databases aggregating production volumes, species produced, monetary values, or number of farms in operation. A study completed in 2019 estimates that in 2018 3,405 mt of seafood was grown in RAS globally for commercial use. While this study attributes volumes to individual countries, the list is not exhaustive, and does not specify which species are produced. Denmark, Iceland and the Netherlands are the top producers (by volume) from RAS, growing Atlantic salmon, Yellowtail, Pike-perch, Hybrid Striped Bass, African catfish (Bostock et al., 2018), trout (Eurofish, 2016a), and eel (Fletcher, 2018). The following table aggregates the available information about species produced by country, and provides production volumes where available.

Table 1 Species and total volumes produced in RAS by country

Country	Species	Total volume (mt)
Canada	Atlantic salmon, coho salmon, sockeye salmon, rainbow trout, steelhead, halibut, arctic char (Bostock et al., 2018)	200 (O'Shea et al., 2019) 960 (current capacity) (Badiola, pers. comm., 2019)
China	Atlantic salmon, eel (Bostock et al., 2018)	200 (O'Shea et al., 2019) 500 (current capacity) (Badiola, pers. comm., 2019)

Denmark	Atlantic salmon, Yellowtail (Bostock et al., 2018; Badiola, pers. comm., 2019), Pike-perch, Hybrid Striped Bass (Bostock et al., 2018), eel (Fletcher, 2018), trout (Eurofish, 2016a)	1,400 (O'Shea et al., 2019) 1,183 (eel in 2015) 5,400 (current capacity) (Badiola, pers. comm., 2019)
Estonia	Trout (Bostock et al., 2018), eel (FAO, 2019a)	>870 (Eurofish, 2016b) 280 (current capacity) (Badiola, pers. comm., 2019)
France	Atlantic salmon, sea bass, meagre (Bostock et al., 2018), turbot (FAO, 2019b)	unknown
Germany	Whiteleg shrimp (Bostock et al., 2018)	unknown
Iceland	Atlantic salmon (Badiola, pers. comm, 2019)	1,000 (O'Shea et al., 2019) 1,500 (current capacity) (Badiola, pers. comm., 2019)
Netherlands	Yellowtail (Badiola, pers. comm., 2019; Bostock et al., 2018), African catfish (FAO, 2019c), eel (Fletcher, 2018)	2,000 (eel) (Kouvelis, 2017) 600 (current Yellowtail capacity) (Badiola, pers. comm., 2019)
Norway	Atlantic salmon (Bostock et al., 2018)	2,000 (current capacity) (Badiola, pers. comm., 2019)
Poland	Atlantic salmon	150 (O'Shea et al., 2019) 1,600 (current capacity) (Badiola, pers. comm., 2019)
Russia	Trout (Bostock et al., 2018)	unknown
Scotland	Atlantic salmon (Bostock et al., 2018)	unknown
Spain	Amberjack (Bostock et al., 2018)	unknown
Switzerland	Atlantic salmon (Bostock et al., 2018)	400 (O'Shea et al., 2019) 600 (current capacity) (Badiola, pers. comm., 2019)
United Arab Emirates	Sturgeon, tilapia (Bostock et al., 2018)	unknown
United States	Atlantic salmon, Rainbow trout, steelhead, sea bass (Bostock et	30 (O'Shea et al., 2019)

	al., 2018), tilapia (Blue Ridge Aquaculture, 2019), Pompano (Badiola, pers. comm., 2019)	2,674 (current capacity) (Badiola, pers. comm., 2019)

In contrast to the above figures, it has also been estimated that in 2012 approximately 9,180 mt of coldwater marine fish, and 340 mt of warmwater marine fish were produced in the EU in RAS facilities (Bostock et al., 2016). This study also uses a figure from a 2014 source (using 2012 data) which shows freshwater fish production in the EU in indoor recirculating tanks (salmon and trout are both separately included in this figure with 0 mt of production) including catfish production at 3,790 mt, eel at 4,960 mt, tilapias 450 mt, and "freshwater other" at 290 mt. (Bostock et al., 2016).

It is not clear why estimated volumes vary so significantly, however given that there is variation in the definition of RAS, it is not entirely surprising. It is also often not stated in the data whether figures are based on volumes of whole, harvested fish or juveniles produced in RAS that are then transported to other types of on-growing systems. This may account for inconsistencies in the definitions of RAS volumes from one source to another. In addition to this, given the fragmented nature of the global RAS industry, and the lack of any organization or database aggregating reported volumes it is unsurprising that figures presented by different researchers vary highly.

Import and Export Sources and Statistics

Import and export statistics generally fail to differentiate between grow out systems, often with volumes given specific only to species. Bostock et al (2018) state that the most "important" countries for RAS include Norway, Canada and Chile, however it is unclear whether these countries export RAS products from grow out systems to the United States, and if so, in what volume.

Common and Market Names

Scientific Name	n/a
Common Name	n/a

Product forms

It is assumed that RAS products available in the United States market are available in all forms, given that there are multiple species from all over the world.

Criterion 1: Data quality and availability

Impact, unit of sustainability and principle

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

Criterion 1 Summary

Data Category	Data Quality	Score (0-10)
Industry or production statistics	2.5	2.5
Management	7.5	7.5
Effluent	7.5	7.5
Habitat	7.5	7.5
Chemical use	7.5	7.5
Feed	5	5
Escapes	10	10
Disease	7.5	7.5
Source of stock	7.5	7.5
Predators and wildlife	10	10
Introduced species	5	5
Other – (e.g. GHG emissions)	Not Applicable	n/a
Total		**82.5**

C1 Data Final Score (0-10)		**7.5**

Brief Summary

Data for this assessment are most commonly in the form of peer reviewed articles, current Seafood Watch assessments, and personal communication. Categories such as effluents, habitats, escapes, chemical use, disease, biosecurity and source of stock are relatively thoroughly studied and available in the public domain. Topics such as RAS-specific production statistics and feed formulations are not as readily available, and the authors of this report have relied on extensive personal experience and communications with producers to inform this assessment. Information on predator/wildlife interactions is not as readily available because, with respect to RAS, this is not recognized as not having significant environmental impacts. As the purpose of this assessment is to describe the ecological impact of RAS as a production system, the fact that it is a closed system with minimal discharge is, in many cases, enough to justify a score, even with minimal data. The final numerical score for Criterion 1–Data is 7.5 out of 10.

Justification of Rating

Industry and production statistics

Data describing the size of the global RAS industry are non-aggregated, and often contradictory. It is unclear what percentage of the global RAS industry is hatchery production, and what is grow out. It is also unclear what percentages are for research and commercial production. A variety of studies and country level agency data offer production volumes by country or by species, but data describing production volumes of a given species in a given country are not available, and the contradictory nature of much of the available research renders educated estimates impossible. Given this, the data that are available are not sufficient to give confidence in the size of the global industry, species grown using RAS, or production volumes of these species. The Data score for Industry and production statistics is 2.5 out of 10.

Management

As this is a global assessment, management scores from available Seafood Watch assessments of countries producing from both RAS and other production systems were used as a proxy for overall management of RAS globally. In general, countries producing RAS tend to provide public access to national and state/province/ regulations, as well as some forms of company level management information. The average of the available scores fell directly between scores of 7.5 and 10. Given that this is proxy information, the Data score for management was rounded down to 7.5 out of 10.

Effluent

Data describing the types of filtration and treatment systems used by RAS globally are readily available in peer reviewed articles as well as personal communications. Information detailing the process, treatment, and ecological impact of wastewater effluents that are discharged from RAS is not nearly as readily available. Information is available regarding management measures regulating effluent impacts from the producing countries from the FAO as well as individual country agency documents. The data score for Effluent is 7.5 out of 10.

Habitat

Data describing the ecological impacts of siting of RAS facilities is relatively scarce, besides showing that often they are in buildings that were constructed for other purposes originally. While not directly describing the ecological impacts of RAS, this allows assumptions to be made about the ongoing functionality, and the degree of planning for cumulative impacts. The data score for Habitat is 7.5 out of 10.

Chemical use

Data describing the most common chemicals used in RAS are available in non-aggregated and non-comprehensive form in literature, as are data and information regarding the fate of effluents after they've been discharged. Information describing whether or how chemicals are treated prior to discharge is less available. Given the closed nature of RAS, and the readily available data describing types of treatment systems commonly used, it is logically concluded that there are, at most, minor ecological impacts from chemical use in RAS. The data score for Chemical use is 7.5 out of 10.

Feed

Data describing the ecological impacts of feeds used in RAS are collected using Seafood Watch assessments of species grown in both RAS and other production systems as a proxy. Given this use of data, it requires that an assumption is made that feeds, and subsequently the ecological impacts of those feeds, are the same between RAS and non-RAS production. Given this discrepancy, the data used provide some useful information, but leave questions as to whether they accurately describe impacts from RAS facilities. Exceptions are made for Yellowtail, which relies on literature to provide evidence that FCR values for Yellowtail grown in RAS are better than those presented in the table in Criterion 5. These data are supported by further studies showing that better FCR values are common in RAS production. The data score for Feed is 5 out of 10.

Escapes

The design and inherent characteristics of RAS as closed systems are, in themselves, data that describe the likelihood of escapes, and subsequent ecological impacts. The data score for the Escapes criterion is 10 out of 10.

Disease

While data describing the most common diseases in RAS are available in non-aggregated and non-comprehensive form, data describing the types of treatment systems used by RAS globally are readily available in peer reviewed articles as well as through personal communications, as are data and information regarding the fate of effluents after they've been discharged. Information describing effectiveness of treatment systems for water prior to discharge from the system (rather than recirculation back through the system) are less available. The data score for Disease is 7.5 out of 10.

Source of stock

Data describing the ecological impacts of sourcing of stocks used in RAS are collected using Seafood Watch assessments of species grown in both RAS and other production systems as a proxy. Given this use of data, it requires that an assumption is made that sources of stock, and subsequently the ecological impacts of that sourcing, are the same between RAS and non-RAS production. Given this discrepancy, the data used provide some useful information, but leave questions as to whether they accurately describe impacts from RAS facilities. One exception is made for Yellowtail, which is scored using data collected from the website of one RAS Yellowtail producer, as well as personal communication with an expert in RAS Yellowtail production. The data score for Source of stock is 7.5 out of 10.

Wildlife interactions

The design and inherent characteristics of RAS as indoor, closed systems are, in themselves, data that describe the likelihood of interactions with wildlife, and subsequent ecological impacts. The data score for the Wildlife interactions criterion is 10 out of 10.

Escape of secondary species

Global RAS production uses a wide variety of strategies for obtaining stock, and maintaining biosecurity on the farm. Given the lack of standardization, data describing biosecurity measures at the source and destination of animal movements are scarce, however personal communication indicates that disinfection of wastewater discharge is not common. The data score for Escape of secondary species is 7.5 out of 10.

Conclusions and Final Score

While data and information about some individual RAS facilities and research projects are available, there is no global, aggregated data set describing any ecological impacts from RAS. Data and information are largely drawn from literature, and proxy information from other Seafood Watch reports. Personal communication provided information as well. In many cases, this information is enough to allow confidence that ecological impacts of RAS are thoroughly understood. The final numerical score for Criterion 1 – Data is 7.5 out of 10.

Criterion 2: Effluent

Impact, unit of sustainability and principle

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

Criterion 2 Summary

Effluent Evidence-Based Assessment: Wastewater treatment

C2 Effluent Final Score	**8.00**	**GREEN**

Effluent Evidence-Based Assessment: No wastewater treatment

C2 Effluent Final Score	**6.00**	**YELLOW**

Brief Summary

Commercial recirculating aquaculture systems may use a variety of treatment systems for discharged effluent streams. Freshwater systems often collect solids for further use as an additive to soils, or compost, and may treat soluble wastes prior to discharging them. However, marine systems often discharge directly into the environment with varying levels of treatment. Management of ecological impacts from wastewater discharge differs globally. In the countries producing the most in RAS (by volume), regulation generally manages point source impacts from discharge, but may not take into account overall cumulative impacts to the environment.

RAS facilities that employ solids capture and appropriately dispose of it (e.g. constructed wetlands, fertilizer application, municipal waste management, etc.), and implement denitrification or other soluble waste treatment (constructed wetlands, aquaponics systems, etc.) of the effluent discharge stream are considered to sufficiently limit the nutrient concentrations of their effluent such that they do not cause or contribute to cumulative ecological impacts at the waterbody/regional scale. As such, RAS facilities employing these discharge treatments score 8 out of 10 for Criterion 2 – Effluent.

RAS facilities that do not employ solids capture or do not appropriately dispose of captured solids (e.g. dumping), or do not implement denitrification or other soluble waste treatments are considered unlikely to create environmental impacts beyond the immediate vicinity of the discharge point, but have the potential to contribute to cumulative impacts at the waterbody/regional scale. As such, RAS facilities without effective solids capture and disposal, or without denitrification or other soluble waste treatment score 6 out of 10 for Criterion 2 – Effluent.

Justification of Rating

As effluent data quality and availability is good (i.e. Criterion 1 score of 7.5 or 10 of 10 for the effluent category), the Evidence-based assessment was utilized.

Effluent from RAS is the waste flow emanating from different components of the recirculation loop that is discharged from the facility. This report covers systems that reuse ≥90% of the water flow, which is typical of modern RAS; while this degree of reuse is high, discharge volumes can be high and in larger systems may reach millions of gallons per day.

Several different types of filters are generally used in RAS in order to maintain sufficient water quality to support aquatic life within the culture system: mechanical filters, biological filters, and trickling (degassing) filters. These filters enable the high levels of daily water flow recirculation (≥90%) for systems under the scope of this report. Mechanical filters remove relatively large organic solid wastes, such as feces and uneaten feed, though some particles are too small to be removed and pass through alongside dissolved or soluble organic wastes. These soluble wastes consist of nitrogen (in the form of ammonia, nitrite, and nitrate) and phosphate; biological filters containing bacteria are used to breakdown small organic matter particles via oxidation, as well as transforming toxic free ammonia (NH_3) into harmless nitrate (NO_3^-) via nitrification. Sludge and carbon dioxide are produced as a result of these mechanical and biological processes. While carbon dioxide is removed from the water using degassing or aerating filters (alongside nitrogen gas), the sludge is backwashed into the wastewater stream. Wastewater may be discharged directly, or further treated to remove solids and/or soluble nitrogenous compounds.

Treatment of Effluent

<u>Solid waste</u>
In many cases, the solids fraction of the wastewater stream is separated prior to discharge using a settlement tank or basin. This sludge is roughly 90-98% water and is generally dewatered, a process by which excess water is removed from captured sludge in order to minimize the volume of solid waste leaving a facility (Summerfelt et al, 1999). This is achieved via technologies such as belt filters, together with other methods such as coagulation/flocculation, to produce a final effluent with a solids content of 9–22% (Sharrer et al, 2010) and decreased phosphorous concentrations (Danaher et al., 2011; Ebeling et al., 2003; Ebeling et al., 2006; Sharrer et al., 2010). While solid wastes from freshwater systems can be disposed of via land application as fertilizer, compost production, or industrial/municipal waste management centers (Bregnballe et al., 2015; Matias del Campo, 2010; Turcios & Papenbrock, 2014), it is more difficult to dispose of solid wastes in this way when they are from a recirculating marine system, given the salinity (Boxman et al., 2018; van Rijn, 2013). In marine

systems, solid wastes are generally not useable without extensive treatment, and effluents containing solid wastes are commonly discharged into marine waterbodies (van Rijn 2013). While treatment options are available, they are extremely costly (S. Summerfelt, personal communication, 2019).

Anaerobic digestion of sludge is also used as a means of decreasing the volume of solid waste leaving a facility, and converting nutrients in the sludge to energy through bacterial processing (Bregnballe 2015; van Rijn 2013). Anaerobic digestion involves biological degradation via microbes in external reactors known as sludge digesters. This process occurs after solids have been filtered out of the system, and are no longer part of the effluent stream. Anaerobic treatment decreases the volume of solid waste leaving a facility, and converts nutrients in the sludge to energy through the production of methane gas. The resulting products are methane, and a solid material that can be spread on soil to increase its quality (Matias del Campo et al., 2010).

Soluble waste

Soluble wastes, such as dissolved nitrogenous and phosphate compounds, are present in the discharge stream from RAS facilities; often times, most phosphate is removed from the discharge via solids removal, but high concentration of nitrogen is common (Bregnballe et al., 2015). This nutrient-rich discharge stream is often discharged directly to the environment but can be further treated to reduce the nutrient content should effluent discharge regulations require it; this may be through the use of constructed wetlands, aquaponics systems (hydroponic vegetables using the nutrient rich discharge as fertilizer), or through anaerobic denitrification filters which convert nitrate into nitrogen gas (Bregnballe et al., 2015).

Management of waste water

Management and regulation of wastewater discharges from RAS facilities varies from country to country. Many countries have water quality regulations in place to manage ecological impacts from wastewater. This assessment includes management measures taken by some of the top RAS producers as identified in Table 1 above, and cited literature.

In Denmark discharges of waste water must be permitted, and permit regulations include discharge limits are prescribed for nitrogen and phosphorus from freshwater (MEFD, 2019) and marine aquaculture (FAO, 2019da) (FAO, 2019db), although it is unclear whether these also apply to marine RAS. Requirements for design and installation of “cleansing systems” are in place for freshwater aquaculture systems (FAO, 2019d).

In the Netherlands water quality is regulated by different levels of management from national to local municipalities. There is an overall strategic water management policy set forth by the central (federal) government which is implemented through provincial water management policies. Provinces are responsible for maintaining water quality with the exception of “state-waters” which are maintained by a central government agency. Provinces are given authority to grant discharge permits, but often delegate it to municipalities. Every wastewater discharge into surface waters must be permitted by the appropriate authority (FAO, 2019da).

In Canada regulations are in place that manage ecological impacts from aquaculture, and prohibit the "deposit of deleterious substances" except as authorized. Regulation sets waste discharge limits for un-ionized ammonia, suspended solids, carbonaceous biological oxygen demand, and total residual chlorine, and includes monitoring and reporting requirements (Canadian Water Network, 2018). All aquaculture farms are required to register, and provide a management plan for an operating license (FAO, 2019d).

In Chile, there are specific limits set for contaminants, and any discharge must be done with a permit. Aquaculture operations have to ensure they do not dump solid or liquid wastes that can impact aquatic areas (FAO, 2019d).

In Norway water bodies have designated environmental statuses, and discharge permits for aquaculture are given or declined in accordance with the likely impact the operation will have. Permits include specific discharge limits based on the receiving waterbody. Regulations also include requirements for disinfection of waste water prior to discharge (FAO, 2019da).

In the United States effluent discharge from aquaculture operations is regulated at the federal level by the Environmental Protection Agency (EPA) through the Clean Water Act (CWA) (Jensen & Zajicek, 2008). The CWA mandates that states designate specific uses for waterbodies, and assign site-specific water quality standards (can include nitrogen, phosphorous, etc.) that will maintain those uses (US EPA**,** 2019). If the water quality of a given waterbody is not meeting quality standards, the waterbody must be designated as "water quality limited," and specific total maximum daily loads (TMDL) are put in place in order to restore water quality to a level that achieves state water quality standards (US EPA, 2015).

Conclusions and Final Score

Effluents from RAS are in the form of solid and soluble wastes. While the majority of water is treated and recirculated through the system, up to 10% of a system's daily flow (in some cases this is millions of gallons per day) leaves the system as nutrient-rich discharge. Solids from freshwater RAS are generally filtered and collected for further use as fertilizer or compost, though solids from marine RAS are typically more difficult and costly to treat for further use. The remaining soluble wastes in the discharge may be significant, and this effluent is generally discharged directly into the surrounding environment unless further treatment is required for compliance with regulations. Management of effluent discharges varies globally, however typically there are regulations in place that manage impacts to the environment from wastewater discharges.

RAS facilities that employ solids capture and appropriately dispose of it (e.g. constructed wetlands, fertilizer application, municipal waste management, etc.), and implement denitrification or other soluble waste treatment (constructed wetlands, aquaponics systems, etc.) are considered to sufficiently limit the nutrient concentrations of the effluent discharge stream such that they do not cause or contribute to cumulative ecological impacts at the waterbody/regional scale. As such, RAS facilities employing these discharge treatments score 8 out of 10 for Criterion 2 – Effluent.

RAS facilities that do not employ solids capture or do not appropriately dispose of captured solids (e.g. dumping), or do not implement denitrification or other soluble waste treatments are considered unlikely to create environmental impacts beyond the immediate vicinity of the discharge point, but have the potential to contribute to cumulative impacts at the waterbody/regional scale. As such, RAS facilities without effective solids capture and disposal, or without denitrification or other soluble waste treatment score 6 out of 10 for Criterion 2 – Effluent.

Criterion 3: Habitat

Impact, unit of sustainability and principle

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

Criterion 3 Summary

Habitat parameters	Value	Score
F3.1 Habitat conversion and function		9
F3.2a Content of habitat regulations	3	
F3.2b Enforcement of habitat regulations	4	
F3.2 Regulatory or management effectiveness score		4.8
C3 Habitat Final Score (0-10)		**7.6**
Critical?	NO	**GREEN**

Brief Summary

Many RAS operations utilize previously existing buildings (e.g., warehouse, greenhouses, etc.) or, when purpose-built, are done so on previously converted land; as a result, there is no further habitat conversion or loss of ecosystem functionality. Any habitat impacts that do occur (or have previously occurred) are expected to be minor with no overall loss of habitat functionality. The score for Factor 3.1 is 9 out of 10. Given that this assessment is global in scope and siting regulations are varied, a precautionary approach was taken in the scoring of Factor 3.2. Taking into account the management scores of current Seafood Watch reports for countries where RAS also operates, it is determined that countries operating RAS facilities manage their siting through legislation that accounts for sensitive habitats. Information from existing Seafood Watch assessments of countries also producing RAS were used as a proxy for determining the effectiveness, implementation and enforcement of these regulations. This information yielded a score of 4.8 out of 10 for Factor 3.2 The final score for Criterion 3–Habitat is 7.6 out of 10.

Justification of Rating

The construction and operation of a RAS, similarly to other types of production systems and industries, inherently implies a habitat conversion due to the utilization of land by building a new farm. However, the physical footprint of a RAS is relatively small due to intensive production volumes (i.e., less physical space than is needed to produce the same amount of fish if compared to other systems).

Factor 3.1. Habitat conversion and function

Many RAS operations utilize previously existing buildings (e.g., warehouse, greenhouses, etc.) or, when purpose-built, are done so on previously converted land. RAS facilities are most often located on land that was previously used for agriculture or other industrial activities. Given that RAS facilities are often located in already existing structures, or occupy a small footprint if they are new construction, no more than minor habitat impacts are expected from the construction and operation of a RAS, with no overall loss of habitat functionality. The score for Factor 3.1 Habitat conversion and function is 9 out of 10.

Factor 3.2. Farm siting regulation and management

Factor 3.2a: Content of habitat management measures

It is unlikely that a RAS facility would be built in an environmentally sensitive location or high value ecological habitat (e.g., coastal intertidal, estuaries, freshwater wetlands) as these vulnerable habitats are often covered by relevant regional and international policies. For example, Canada uses an integrated resource planning process that includes ecological sustainability considerations to identify land that is suitable and capable of supporting aquaculture, and Norway has regulation that can ban aquaculture sites from being located in areas of special importance to aquatic life (FAO, 2019da). In Denmark counties maintain Regional Plans that designate aquaculture zones, and large facilities must have an EIA (FAO, 2019d). The Netherlands maintains land use plans that delegate tasks to National, provincial and municipal governments, and identify Nature Protection Areas. Anyone cultivating animals must also obtain an environmental protection act permit (FAO, 2019da). In Chile, concessions are granted for aquaculture operations, although they are not required if operations are carried out on privately owned land. All aquaculture is subject to an EIA (FAO, 2019d). While RAS operation in itself is not expected to contribute to cumulative habitat impacts, given the global scope of this assessment, and the variation in regulations globally, the precautionary principle is used to draw the assumption that while it is likely that siting is based on ecological principles, cumulative impacts were not taken into account when these sites were originally converted. This results in a Factor 3.2a score of 3 out of 5.

Factor 3.2b: Enforcement of habitat management measures

Enforcement of regulations relating to RAS siting is varied given the global scope of this assessment. Information for scoring is taken from current Seafood Watch assessments of countries where RAS production is most common as identified in Table 1 above[2], and cited literature (Norway Atlantic salmon, 2017; British Columbia Atlantic salmon, 2017; Chile Atlantic and Coho salmon, 2017; Iceland/Canada/US Arctic char, 2014). This information is used as a proxy for determining the level of enforcement of habitat regulations in the top RAS producing countries.

[2] All Seafood Watch reports can be found at www.SeafoodWatch.org

In Norway enforcement measures are considered highly effective with some minor limitations including the applicability to area-based or habitat-scale impacts, evidence of fines or penalties, and as-yet unknown consideration of sensitive habitats such as deep-water corals. This scores 4 out of 5.

In British Columbia there is active enforcement at the site level with effective control of benthic impacts at peak production and prior to restocking. With limited area-based regulation other than site separation distances, enforcement does not appear to be fully active at an area or regional cumulative impact level at present. This scores 4 out of 5.

In Chile farm-level regulatory enforcement is generally effective, but there are concerns regarding the scale of production, and protection of unique habitats in Chile. Given this, enforcement on a national scale has some limitations. Ultimately, enforcement organizations are identifiable and active, but these limitations mean that cumulative habitat impacts may not be fully addressed. This scores 3 out of 5.

The Iceland/Canada/US Arctic char assessment indicates that enforcement organizations are identifiable and appropriate for the scale of the industry; siting and permitting “mostly” function according to zoning plans, and “moderately” takes account of cumulative impacts. It states that the enforcement process is transparent, and that there is evidence that restrictions included in regulations are being followed. This scores 4.25 out of 5 (rounded to 4 out of 5).

When averaged together, these Factor 3.2b scores result in a 3.75 out of 4, which is rounded to a final score of 4 out of 5 for Factor 3.2b.

Conclusions and Final Score

RAS operations have a small footprint relative to other types of commercial aquaculture, and are often sited in areas that were previously converted for other industries. New construction is often sited in areas that are not designated as sensitive habitat. Since this assessment is global in scope, it is assumed that regulations generally ensure that sites are not located in sensitive habitats, but likely did not take cumulative impacts into account when the area was first converted from its natural state. Based on scores from current Seafood Watch assessments of countries where RAS production is most common, it is assumed that enforcement is generally effective. This results in a Factor 3.2 score of 3.6 out of 10. Factors 3.1 and 3.2 combine to give a final Criterion 3 – Habitat score of 7.2 out of 10.

Criterion 4: Evidence or Risk of Chemical Use

Impact, unit of sustainability and principle

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

Criterion 4 Summary

Chemical Use parameters	Score	
C4 Chemical Use Score (0-10)	**6**	
Critical?	NO	**YELLOW**

Brief Summary

The inherent design of RAS (i.e., the physical isolation from the surrounding environment) in combination with the potential for strict biosecurity protocols lowers the risk of introduction of disease agents and thus the need for chemical treatments. While RAS are considered closed systems, they can discharge up to 10% of their water flow daily, in some cases untreated, and directly into surrounding environments. Specific data on chemical use in RAS is limited, however literature provides insights into commonly used or recommended chemicals for these systems, two of which are considered Highly important, and one Critically important for human medicine by the World Health Organization (WHO). While RAS has demonstrably low need for chemical use, systems can, in theory, allow discharge of up to 10% of daily water flow untreated into the surrounding environment. As such the numerical score for Criterion 4–Chemicals is 6 out of 10.

Justification of Rating

Due to the ability of RAS to manage biosecurity, the risk of introduction of pathogens and parasites is largely mitigated, which minimizes the need for chemical use. These systems often exhibit effective treatment of the limited volumes of incoming water, as well as physical isolation from the surrounding environment and subsequent pathogens. While biosecurity practices minimize the risk of entrance of pathogens and disease agents into the system, RAS are still vulnerable to disease, and can discharge up to 10% of their daily water flow. In the case of marine RAS, this discharge may be untreated (van Rijn, 2013).

In situations where parasites are introduced, parasiticides recommended and commonly used include: salt, Formalin (formaldehyde), Hydrogen peroxide, Praziquantel, Flubendazole, and Chloramine-T (Bregnballe et al., 2015; Murray, Bostock, & Fletcher, 2014). When bacterial infections arise and treatment is necessary, antibiotics recommended for use include Sulfadiazine, Trimethoprim, and Oxolinic acid (Bregnballe et al., 2015). Of these antibiotics, Sulfadiazine and Trimethoprim are considered Highly Important antimicrobials, and Oxolinic acid is considered a Critically Important antimicrobial by the World Health Organization (WHO) (WHO, 2019). It is generally considered that the use of hydrogen peroxide in aquaculture does not cause any notable ecological impact (Lillicrap, Macken, & Thomas, 2015), nor does salt (Sipauaba Tavares & Boyd, 2007), however use of the other listed chemotherapeutants can have a negative impact if not properly treated prior to discharge.

While these chemicals are used in some cases, many RAS do not rely on their use (Bregnballe et al., 2015), due to strict biosecurity measures minimizing introductions of pathogens and parasites. As discussed in Criterion 2 – Effluent, wastewater treatments vary for RAS, but in general solid wastes (which may contain chemicals if they have been adsorbed) are collected and used for land application or compost production if they are from a freshwater system, while solid wastes leaving marine RAS are generally discharged along with soluble wastes directly into the surrounding environment without treatment. Soluble effluent wastes from freshwater RAS (which may contain chemicals) may go through a process of nutrient treatment prior to discharge, most often into natural waterways or agricultural irrigation, though there is limited information to suggest that any remaining active chemicals are degraded or treated. Given the variability of treatment and sterilization techniques used globally it is unclear whether the majority of chemicals that may be present in soluble effluent wastes are removed prior to entry into natural waterbodies. However, given that there are many examples of RAS operating without disease issues (or subsequent antibiotic or parasiticide use), and the ability of these systems to be completely separated from pathogens (Bregnballe et al., 2015), it is assumed that the majority of RAS do not rely on chemical use.

Conclusions and Final Score

RAS have the ability to prevent the introduction of pathogens and parasites through the treatment of incoming water and the physical isolation of the system from environmental pathogens. Therefore, the risk of disease or parasite outbreaks, as well as the subsequent need for chemical treatments, is considered to be low. While some of the chemicals used or recommended for use in RAS are considered Highly or Critically Important by the WHO, it is unlikely that this is common practice for RAS globally. The final numerical score for Criterion 4– Chemicals is 6 out of 10.

Criterion 5: Feed

Impact, unit of sustainability and principle

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

Criterion 5 Summary

RAS all species

C5 Feed Final Score (0-10)	5.69	
Critical?	NO	**YELLOW**

Brief Summary

Feed use and subsequent environmental impacts are highly species-specific, with some species requiring high levels of fishmeal and fish oil in their diets, while others can be grown commercially on a feed containing no animal ingredients. Due to ongoing improvements in aquaculture feeds (particularly reductions in the use of fishmeal and fish oil) and their efficiency of use (i.e., the feed conversion ratio, FCR), the large majority of species assessed by Seafood Watch now have Yellow scores for the feed criterion.

To determine a feed score applicable to all RAS grown species, an average of all feed scores applied to species currently grown in RAS that have coinciding Seafood Watch assessments was determined. There is an assumption that RAS use manufactured dry pellet feeds, and therefore the Seafood Watch assessments in which a species is fed whole fish and/or wet/moist pellets are excluded; as such, RAS facilities that feed whole fish and/or wet/moist pellets are not considered within the scope of this assessment. The average is in the Yellow scoring range, and the final feed score is 5.69 out of 10 for all RAS species globally.

Justification of Rating

Many of the ecological impact risks of RAS are similar regardless of the species being cultured (e.g., effluent, disease, or escape risks), and can therefore be assessed somewhat universally to generate a broad multi-species RAS recommendation. However, feed composition and use, and subsequent environmental impacts, can vary considerably between species.

To determine a feed score applicable to all RAS grown species, an average of all feed scores applied to species currently grown in RAS that have coinciding Seafood Watch assessments was determined. Table 2 provides a list of these assessments. There is an assumption that RAS use manufactured dry pellet feeds, and therefore the Seafood Watch assessments in which a species is fed whole fish and/or wet/moist pellets are excluded from Table 2; as such, RAS facilities that feed whole fish and/or wet/moist pellets are not considered within the scope of this assessment. The average is in the Yellow scoring range (see Table 2 below). Nearly all feed criterion scores are Yellow or Green, with the exception of Almaco jack (*Seriola rivoliana*) farmed in the United States.

Table 3 includes studies to provide further confidence that lower FCR results for any given species are likely in a RAS situation, as compared to the values assessed in the existing suite of Seafood Watch reports. In RAS, feed intake by the species being grown is more easily tracked than it is in other production systems such as net pens and ponds. This leads to less wasted feed, and lower FCR values (Bregnballe et al., 2015; van Rijn, 2013). Characteristics of the RAS system such as pH, salinity and temperature can be monitored and managed to ensure optimal efficiency for feeding and growth, whereas other production systems generally do not have the ability to exercise this level of control (Bregnballe et al., 2015; van Rijn, 2013).

Table 2. Feed scores for current Seafood Watch aquaculture assessments of species also produced in RAS

Species	Region	Production method	Feed score	Feed rating
Almaco jack (*S. rivoliana)*	United States	Net pens	2.91	RED
Almaco jack	Mexico	Net Pens	5.11	YELLOW
Almaco jack average			4.01	YELLOW
Atlantic salmon	Norway	Net pens	4.86	YELLOW
Atlantic salmon	Scotland & Orkney	Net pens	3.58	YELLOW
Atlantic salmon	Chile	Net pens	4.70	YELLOW
Atlantic salmon	British Columbia	Net pens	5.08	YELLOW
Atlantic salmon	Faroes	Net pens	4.49	YELLOW
Atlantic salmon	Maine & E. Canada	Net pens	6.59	YELLOW
Atlantic salmon	Skjerstadfjorden, Nordland, Norway	Net pens	6.89	GREEN
Atlantic salmon average			5.17	YELLOW
Arctic char	Canada	Net pens	5.52	YELLOW
Arctic char	Iceland	Net pens	6.1	YELLOW
Arctic char	United States	Net pens	5.52	YELLOW
Arctic char average			5.71	YELLOW
Coho salmon	Chile	Net pens	5.62	YELLOW
Eel (American, European, Japanese)	China, South Korea, Taiwan, Japan	Ponds	5.26	YELLOW
European seabass	Mediterranean	Net pens	4.05	YELLOW

Hybrid striped bass	United States	Ponds	4.47	YELLOW
Hybrid striped bass	United States	Tanks	5.39	YELLOW
Hybrid striped bass average			4.93	YELLOW
Rainbow trout	United States	Net pens	5.22	YELLOW
Rainbow trout	United States	Raceways, Pond	5.81	YELLOW
Rainbow trout	Canada	Tanks, net pens	6.95	GREEN
Rainbow trout	Chile	Net pens	4.54	YELLOW
Rainbow trout	Colombia	Net pens	6.38	YELLOW
Rainbow trout	Colombia	Raceways	6.52	YELLOW
Rainbow trout average			5.9	YELLOW
Sturgeon	United States	Tanks (non-RAS)	3.59	YELLOW
Tilapia	Peru	Raceways	6.57	YELLOW
Tilapia	Ecuador	Ponds	8.25	GREEN
Tilapia	Taiwan	Ponds	7.56	GREEN
Tilapia	Colombia	Net pens	8.24	GREEN
Tilapia	Honduras	Net pens	8.00	GREEN
Tilapia	Indonesia	Net pens	7.25	GREEN
Tilapia	Mexico	Net pens	7.90	GREEN
Tilapia	China	Ponds	8.16	GREEN
Tilapia average			7.74	GREEN
Whiteleg shrimp	US	Ponds	3.87	YELLOW
Whiteleg shrimp	Ecuador	Ponds	7.70	GREEN
Whiteleg shrimp	Honduras	Ponds	8.74	GREEN
Whiteleg shrimp	Thailand	Ponds	4.00	YELLOW
Whiteleg shrimp	China	Ponds	3.44	YELLOW
Whiteleg shrimp	India	Ponds	4.59	YELLOW
Whiteleg shrimp	Nicaragua	Ponds	6.19	YELLOW
Whiteleg shrimp	Malaysia	Ponds	5.05	YELLOW
Whiteleg shrimp	Indonesia	Ponds	5.14	YELLOW
Whiteleg shrimp	Vietnam	Ponds	5.78	YELLOW
Whiteleg shrimp	Mexico	Ponds	3.50	YELLOW
Whiteleg shrimp average			5.30	YELLOW
Yellowtail (*S. lalandi*)	Mexico	Net pens	5.11	YELLOW
Average total			**5.69**	**YELLOW**

Table 3. Peer-reviewed studies comparing the FCR between RAS and other aquaculture production systems

Species	RAS	Other systems	Reference
Sea Bream	1.8–3.0	4-7	(Ökte, 2002)
Trout	0.8	1.1 (FTS)	(Roque d'Orbcastel, Blancheton, & Aubin, 2009)
Salmon	1.05	1.27 (net-pen)	(Boulet, Struthers, & Gilbert, 2010)
Salmon	0.8	1.2 (open flow system)	(Matias del Campo et al., 2010)

Salmon	1.09	1.27 (net-pen)	(Vinci, Summerfelt, Rosten, Henriksen, & Hognes, 2013)
Yellowtail	0.88-1.26	n/a	(Abbink et al., 2012)
	1.75		(Orellana, Waller, & Wecker, 2014)
	0.9, 2.6		(Sicuro & Luzzana, 2016)
	1.2, 1.1		(Buentello, Jirsa, Barrows, & Drawbridge, 2015)
Rainbow Trout	0.8-1.1	1.1-1.3	(Bureau, Gunther, & Cho, 2003; Roque d'Orbcastel et al., 2009)
Barramundi	0.8-1.1	1.5-2.2 (pond), 1.6-2.0 (cage)	(FAO, 2012; Schipp, Bosmans, & Humphrey, 2007)
Tilapia	1.0-2.2	0.8-3.5 (pond), >1.5 (cage)	(Leenhouwers, Ortega, Verreth, & Schrama, 2007; Little et al., 2008; Martins, Ochola, Ende, Eding, & Verreth, 2009; Perschbacher, 2007)
Gilthead seabream	0.9-1.9	1.4-2.2 (cage)	(Kogeler et al., 2003; Zohar et al., 2005)
Cobia	1.0	1.5 (pond), 1.5-2.0 (cage)	(Bennetti et al., 2008; Kaiser & Holt, 2005)

Conclusions and Final Score

To determine a feed score applicable to all RAS grown species, an average of all feed scores applied to species currently grown in RAS that have coinciding Seafood Watch assessments was determined. There is an assumption that RAS use manufactured dry pellet feeds, and therefore the Seafood Watch assessments in which a species is fed whole fish and/or wet/moist pellets are excluded; as such, RAS facilities that feed whole fish and/or wet/moist pellets are not considered within the scope of this assessment. The average is in the Yellow scoring range, and the final feed score is 5.69 out of 10 for all RAS species globally.

Criterion 6: Escapes

Impact, unit of sustainability and principle

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

Criterion 6 Summary

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

Brief Summary

Buildings and tanks ensure physical separation of the culture area and the natural environment, minimizing the risk of escapes from RAS. Additionally, tank-based recirculation systems have multiple screens, water treatment, and secondary capture devices to mitigate the risk of escapes. Given the wide range of RAS operating globally, it is assumed that some are in areas where, in the event of an escape, competitive and/or genetic interactions with wild, native populations could occur, however given the extremely low risk of escape, the numerical score for Criterion 6–Escapes is 10 out of 10.

Justification of Rating

Factor 6.1 Escape Risk

Recirculating aquaculture systems can be located practically anywhere, because their design and operation do not require the facility to be located near a water body for either water supply or effluent discharge (Martins et al., 2010). RAS grow fish in “relative isolation from the surrounding environment” (van Rijn, 2013). Consequently, when designed and operated correctly, there is no risk of escapement from RAS (Labatut & Olivares, 2004; Leung & Dudgeon, 2008).

In addition to containing fish within solid wall tanks, RAS install multiple barriers along the discharge water stream in order to prevent any animal escapement. The water treatment components, filters, and screens all represent physical barriers that allow water to pass through while retaining any particles and potential escapees. From a design perspective, land-based recirculating systems effectively eliminate the risk of escapes when appropriate (multiple) and properly maintained screens, water treatment, or secondary capture devices are put in place. As such, the score for Factor 6.1 is 10 out of 10.

Factor 6.2. Competitive and genetic interactions

Factor 6.2 evaluates the likelihood of escaped fish to compete with wild populations for food or habitat, as well as the likelihood of genetic interactions with wild populations that may influence their fitness. Given the variability of habitats in which RAS operate globally, a precautionary assumption is made that in some cases the species grown in these systems would have a high risk of impact to wild, native, populations, and is farmed in an area where it is either not yet established or could increase the range of established, escaped, farmed fish. The Factor 6.2 score is 0 out of 10.

Conclusions and Final Score

The low risk of escapes from RAS (Factor 6.1 score of 10 out of 10) coupled with a potentially high risk of competitive and genetic interaction (Factor 6.2 score of 0 out of 10) results in a Criterion 6– Escape score of 10 out of 10.

Criterion 7: Disease; pathogen and parasite interactions

Impact, unit of sustainability and principle

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

Criterion 7 Summary

Risk-Based Assessment

Pathogen and parasite parameters	Score	
C7 Disease Score (0-10)	6	
Critical?	NO	YELLOW

Brief Summary

While disease can be an issue for production in RAS, there is a low risk of transmission to wild populations due to the limited volumes of water discharged, and the ability to treat or otherwise control those discharges. Ozonation and UV irradiation are commonly used to disinfect influent waters, and both are often used as part of the recirculation system to maintain water quality. This combination is effective for managing pathogens, and can be applied to effluent wastewater from RAS prior to discharge as well. The numerical score for Criterion 7–Disease is 6 out of 10.

Justification of Rating

RAS are relatively closed to the introduction of pathogens and parasites due to their ability to treat incoming water, the physical isolation they offer against the environmental pathogens, and biosecurity protocols practiced. However, despite this environmental control and biosecurity, numerous pathogens (e.g., vibrio bacteria) are ubiquitous in all aquatic systems, or can be introduced into RAS by any number of vectors, including, but not limited to live fish, feed, incoming water, and/or employees.

Pathogens can present a challenge in RAS when introduced due to high stocking densities, stress levels, and the rapid spread in recirculating systems (Bregnballe et al., 2015; Murray et al., 2014). Opportunistic bacteria can affect stressed fish, and all RAS have opportunistic pathogens living among the microbial populations in a typical biofiltration unit. Controlling these pathogens to maintain healthy growing conditions for fish is a constant challenge, and systems must be designed to manage an outbreak in the event that one does occur (Bregnballe et al., 2015).

As is discussed in Criterion 2 – Effluent, RAS recirculate 90-99% of their daily water flow, yet in large systems, 10% discharge can be millions of gallons daily (O'Shea et al., 2019). Water leaving a system as effluent wastewater discharge may be treated to remove solid and soluble nutrient wastes, though discharged effluents are rarely disinfected (S. Summerfelt, personal communication, 2019), and in the case of marine RAS, are often discharged directly to the surrounding environment (van Rijn, 2013). Given this, in the case of a disease event, a system may discharge wastewater directly into surrounding ecosystems with no disinfection.

A list of diseases encountered in rainbow trout cultured in RAS was published in 1996, concluding that disease concerns for each farm are unique due to different protocols and management practices (Noble & Summerfelt, 1996). The list includes the following:

Bacterial	**Parasites**	**Fungus**	**Viral**
Bacterial gill disease	Gyrodactylus	Saprolegnia	Infectious pancreatic necrosis
Furunculosis	Chilodonella		Viral hemorrhagic septicemia
Bacterial kidney disease	Trichodina, Epistylis, and Trichophyra		Infectious hematopoietic necrosis
Fin rot	Icthyopthirius		
	Icthyobodo		
	Proliferative kidney disease		
	Amoebic gill infestation		
	Coleps		

Masser, Rakocy, & Losordo, (1999) listed particularly problematic diseases in RAS in general:

- Protozoal diseases Ich (*Ichthyophthirius*) and *Trichodina*
- Bacterial diseases columnaris, *Aeromonas, Streptococcus,* and *Mycobacterium*
- *Trichodina* and *Streptococcus* diseases especially with tilapia
- *Mycobacterium* with hybrid striped bass

Murray et al., (2014) cite examples of parasites that have been problematic in trout RAS in Europe, as well as individual cases of pathogenic and parasitic outbreaks elsewhere.

Disease	**Region**	**Citation**
Parasitic		
Trichodina spp.	Europe	(Jørgensen, Larsen, & Buchmann, 2009)
Apiosoma sp.	Europe	
Ambiphrya sp.	Europe	
Epistylis sp.	Europe	
Chilodonella piscicola	Europe	
Icthyobodo necator	Europe	

Spironucleus salmonis (Diplomonadida)	Europe	
Gyrodactylus derjavinoides (monogenean platyhelminthe)	Europe	
Displostomum spathaceum (digenean)	Europe	
Luciella masanensis	Europe	(Murray et al., 2014)
Pfiesteria shumwayae	Europe	
Amyloodinium ocellatum	Europe	
Ichthyophthirius multifiliis	Most climatic zones	(Heinecke & Buchmann, 2009)
Bacterial		
Aeromonas spp.	All	(Yanong, 2009)
Vibrio spp.	All	
Mycobacterium spp.	All	
Streptococcus spp.	All	
Flavobacterium spp.	All	
Fransicella asiatica	UK	(Jeffery, Stone, Feist, & Verner-Jeffreys, 2010)
Virus		
Infectious pancreatic necrosis virus	All	(Murray et al., 2014)
Fungi	All	(Murray et al., 2014)

It should be noted that while disease events in RAS have been documented, many of these incidents are from ≥5 years ago. Personal communication indicates that of the large RAS companies operating currently, only one has had a disease event (furunculosis) that resulted in a die-off of the majority of fish (S. Summerfelt, personal communication, 2019). Given this information, it is considered that in global RAS fish health management measures result in infrequent occurrences of infections or mortalities at a "typical" RAS facility.

Conclusions and Final Score

While disease can be an issue for production in RAS, there is a low risk of transmission to wild populations due to the limited volumes of water discharged, and the ability to treat or otherwise control those discharges. Ozonation and UV irradiation are commonly used to disinfect influent waters, and both are often used as part of the recirculation system to maintain water quality (Ebeling et al., 2003). This combination is effective for managing pathogens (Murray et al., 2014), and can be applied to effluent wastewater from RAS prior to discharge as well, though this is not considered to be common (van Rijn, 2013). Because of this, global RAS fish health management measures are said to result in infrequent occurrences of infections or mortalities at a "typical" RAS facility, and the numerical score for Criterion 7 – Disease is 6 out of 10.

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

Impact, unit of sustainability and principle

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

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

Criterion 8X Summary

RAS All species (minus eel)

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

RAS eel (European, Japanese)

Source of stock parameters	Score	
C8X Independence from unsustainable wild fisheries (0-10)	Critical	
Critical?	YES	CRITICAL

RAS eel (American eel)

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

Brief Summary

In the majority of global RAS facilities the farmed population is sourced from hatchery-reared broodstock as opposed to wild-caught individuals. Therefore, for this global multi-species RAS assessment, a score of 0 out of -10 has been applied as a universal score with the exception of RAS eels. Production of European (*Anguilla anguilla*) and Japanese eels (*Anguilla japonica*) is still considered 100% reliant on Endangered and Critically Endangered wild populations for juveniles. Production of American eel (*Anguilla rostrata*) is also 100% reliant on wild populations, but the species is not considered endangered. This results in an individual Criterion 8X scores for European and Japanese eels (Critical) and American eels (-10 out of -10).

Justification of Rating

The majority of the aquaculture industry globally has closed the lifecycles of species being grown commercially, and are no longer reliant on wild populations for grow out stock or broodstock. Table 4 below shows the Seafood Watch assessment scores from non-RAS Seafood Watch assessments of species also produced in RAS.

It should be noted that while Yellowtail from Japan is listed in Table 4 as having a Red Seafood Watch Source of stock rating for production in net pens, further research has indicated that while some net pen production of Yellowtail may rely on wild populations, RAS production of Yellowtail has closed the lifecycle and now relies only on juveniles bred in captivity (Abbink, W. personal communication, 2019). The same cannot be said for the majority of eel RAS production, which continues to rely on wild populations for juveniles (Fletcher, 2018; University of Maine, 2019); this drove the previous Red score in Criterion 8X – Source of Stock for eels farmed in ponds in China, South Korea, Taiwan, and Japan, also seen in Table 4. Japanese eels (*Anguilla japonica*) are currently listed as Endangered by the IUCN (Jacoby, Cassleman, DeLucia, & Gollock, 2017; Jacoby & Gollock, 2014), and European eels (*Anguilla anguilla*) are listed as Critically Endangered (Jacoby & Gollock, 2010). The American eel (*Anguilla rostrata*), however, is not considered endangered for the purposes of the report; while the IUCN listed this species as endangered in 2017 as a result of a 2013 assessment, a more recent (2015) assessment by the United States Fish and Wildlife Service (USFWS) found that while the population is depleted, it is stable, and does not warrant protection under the Endangered Species Act. Further details regarding the population status of the American eel can be found in the Seafood Watch assessment of American eel caught in the United States in pots, barriers, fences, weirds, corrals, etc. (SFW 2020). Overall, the endangered status of Japanese and European eels results in a Critical score for Criterion 8X – Source of Stock, and drives an overall Red rating for RAS production for these species. The final Criterion 8X – Source of Stock score for American eels is -10 out of -10, given 100% reliance on wild fisheries, and drives an overall Yellow rating for RAS American eel production. All other species score 0 out of -10 for Criterion 8X – Source of Stock.

Table 4. Source of stock ratings for current Seafood Watch aquaculture assessments of species also produced in RAS

Species	Region	Production method	Source of stock rating
Almaco jack (*S. rivoliana*)	United States	Net pens	GREEN
Almaco jack (*S. rivoliana*)	Mexico	Net pens	GREEN
Atlantic salmon	Norway	Net pens	GREEN
Atlantic salmon	Scotland & Orkney	Net pens	GREEN
Atlantic salmon	Chile	Net pens	GREEN
Atlantic salmon	British Columbia	Net pens	GREEN
Atlantic salmon	Kvaroy	Net pens	GREEN
Atlantic salmon	Faroes	Net pens	GREEN
Atlantic salmon	Chile -Verlasso	Net pens	GREEN
Atlantic salmon	Maine & E. Canada	Net pens	GREEN
Atlantic salmon	Chile - Nova Austral	Net pens	GREEN
Arctic char	Canada	Net pens	GREEN
Arctic char	Iceland	Net pens	GREEN
Arctic char	United States	Net pens	GREEN

Coho salmon	Chile	Net pens	GREEN
Eel (American, European, Japanese)	China, South Korea, Taiwan, Japan	Ponds	RED
European seabass	Mediterranean	Net pens	GREEN
Hybrid striped bass	United States	Ponds	GREEN
Rainbow trout	United States	Net pens	GREEN
Rainbow trout	United States	Raceways, Pond	GREEN
Rainbow trout	Canada	Tanks, net pens	GREEN
Rainbow trout	Chile	Net pens	GREEN
Rainbow trout	Colombia	Net pens	GREEN
Rainbow trout	Colombia	Raceways	GREEN
Sturgeon	United States	Tanks (non-RAS)	GREEN
Tilapia	Peru	Raceways	GREEN
Tilapia	Ecuador	Ponds	GREEN
Tilapia	Taiwan	Ponds	GREEN
Tilapia	Colombia	Net pens	GREEN
Tilapia	Honduras	Net pens	GREEN
Tilapia	Indonesia	Net pens	GREEN
Tilapia	Mexico	Net pens	GREEN
Tilapia	China	Ponds	GREEN
Whiteleg shrimp	US	Ponds	GREEN
Whiteleg shrimp	Ecuador	Ponds	GREEN
Whiteleg shrimp	Honduras	Ponds	GREEN
Whiteleg shrimp	Thailand	Ponds	GREEN
Whiteleg shrimp	China	Ponds	GREEN
Whiteleg shrimp	India	Ponds	GREEN
Whiteleg shrimp	Nicaragua	Ponds	GREEN
Whiteleg shrimp	Malaysia	Ponds	GREEN
Whiteleg shrimp	Indonesia	Ponds	GREEN
Whiteleg shrimp	Vietnam	Ponds	GREEN
Whiteleg shrimp	Mexico	Ponds	GREEN
Yellowtail (*S. lalandi*)	Japan	Net pens	RED
Yellowtail (*S. lalandi*)	Mexico	Net pens	GREEN

Conclusions and Final Score

The vast majority of global aquaculture production originates from hatchery-raised seed/juveniles from hatchery-raised broodstock, which includes RAS production. Seafood Watch has assessed a number of species using production systems other than RAS. The Criterion 8X Source of stock scores from these assessments have been used as a proxy in this report, as it is assumed that sources of stock for RAS and other grow out systems are often the same. These data result in a deduction of 0 out of -10 for all species grown in RAS, with the exception of Eels (American, European, and Japanese). Production of European (*Anguilla anguilla*) and Japanese eels (*Anguilla japonica*) is still considered 100% reliant on Endangered and Critically Endangered wild populations for juveniles. Production of American eel (Anguilla rostrata) is also 100% reliant on wild populations, but the species is not considered endangered. This results in an individual Criterion 8X scores for European and Japanese eels (Critical) and American eels (-10 out of -10).

Criterion 9X: Wildlife and predator mortalities

Impact, unit of sustainability and principle

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

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

Criterion 9X Summary

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

Brief Summary

This assessment covers indoor, tank-based RAS facilities. These provide physical separation of the culture area from the natural environment, and do not present any risk of wildlife interactions. As such, the score for Criterion 9X– Wildlife Interactions is 0 out of -10.

Justification of Rating

The scope of this assessment includes only indoor RAS, as outdoor systems may have higher risk of wildlife interactions. Interaction with wildlife is not a concern, as all operations are physically separated from the surrounding environment, which eliminates the risk of wildlife and predator interactions that can be common with other types of production systems (Sea Choice, 2019).

Conclusions and Final Score

The final numerical score for Criterion 9X – Wildlife Mortalities is 0 out of -10.

Criterion 10X: Escape of secondary species

Impact, unit of sustainability and principle

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

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

Criterion 10X Summary

Escape of secondary species parameters		Score	
F10Xa International or trans-waterbody live animal shipments (%)		4	
F10Xb Biosecurity of source/destination		6	
C10X Escape of secondary species Final Score		**-2.40**	**GREEN**

Brief Summary

Due to the variability in sourcing of grow out stock for RAS, it is assumed that 50% of the global RAS industry relies on international or trans-waterbody movement of animals resulting in a Factor 10Xa score of 4 out of 10. RAS facilities vary in their treatment of effluent prior to discharging it, in some cases directly to surrounding ecosystems. Very few, if any, disinfect wastewater discharge. This results in a Factor 10Xb score of 6 out of 10. The final numerical score for Criterion 10X – Escape of Unintentionally Introduced Species is -2.4 out of -10.

Justification of Rating

Factor 10Xa: International or trans-waterbody animal shipments

Because not all RAS facilities rear every life stage (i.e., from egg to adult, including broodstock), animals need to be transported into, out of, or between different facilities. This shipping and transportation of animals can pose a significant biosecurity risk (Timmons & Ebeling, 2013). Due to the variability in the global RAS industry, RAS is considered to be 50% reliant on the international and/or trans-waterbody movement of animals. The score for Factor 10Xa is 4 out of 10.

Factor 10Xb Biosecurity of source/destination

Given the wide potential variability in sources of animals subsequently transported to RAS facilities, the Biosecurity of source score in Factor 10Xb is 0 out of 10.

RAS facilities employ a variety of treatment components in order to minimize the likelihood of a disease outbreak within the system (Bregnballe et al., 2015). Treatment of wastewater for solid and soluble waste prior to being discharged varies, and discharge is most commonly to natural waterbodies (van Rijn, 2013). While some systems use ozonation and UV irradiation prior to discharging effluents, this is not the case for all RAS (van Rijn, 2013). As such, the Biosecurity of destination score in Factor 10Xb is 6 out of 10.

Due to the potential variability of biosecurity in sources of animals transported for the global RAS industry, the source of transported animals scores 0 out of 10. While it can be assumed that globally the majority of RAS employ multiple screens, water treatment systems, and secondary capture devices, there is evidence that biosecurity measures differ, with increased levels of risk in some cases. In some cases, effluent treatment may include ozonation and UV irradiation, but it cannot be assumed that this is a common trait of RAS. Given this, the destination of the transported animals scores 6 out of 10. Therefore, the score for Factor 10Xb is 6 out of 10 (the higher of the two scores).

Conclusions and Final Score

It is assumed that 50% of the global RAS industry relies on international or trans-waterbody movement of animals. RAS facilities vary in their treatment of effluent prior to discharging it, in some cases directly to surrounding ecosystems. Very few, if any, disinfect wastewater discharge. The final numerical score for Criterion 10X – Escape of Unintentionally Introduced Species is -2.4 out of -10.

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Appendix 1 - Data points and all scoring calculations

Criterion 1: Data quality and availability

RAS all species

Data Category	Data Quality (0-10)
Industry or production statistics	2.5
Management	7.5
Effluent	7.5
Habitats	7.5
Chemical use	7.5
Feed	7.5
Escapes	10
Disease	7.5
Source of stock	7.5
Predators and wildlife	10
Secondary species	7.5
Other – (e.g. GHG emissions)	n/a
Total	**82.5**

C1 Data Final Score (0-10)	**7.5**	**GREEN**

Criterion 2: Effluents

RAS all species

With wastewater treatment

Effluent Evidence-Based Assessment

C2 Effluent Final Score (0-10)	**8**	**GREEN**
Critical?	NO	

RAS all species

Without wastewater treatment

Effluent Evidence-Based Assessment

C2 Effluent Final Score (0-10)	**6**	**GREEN**
Critical?	NO	

Criterion 3: Habitat

All species with or without wastewater treatment

Factor 3.1. Habitat conversion and function

F3.1 Score (0-10)	9

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

3.2a Content of habiat management measure	3
3.2b Enforcement of habitat management measures	4
3.2 Habitat management effectiveness	**4.8**

C3 Habitat Final Score (0-10)	**8**	**GREEN**
Critical?	NO	

Criterion 4: Evidence or Risk of Chemical Use

All species with or without wastewater treatment

Chemical Use parameters	Score	
C4 Chemical Use Score (0-10)	**6**	
C4 Chemical Use Final Score (0-10)	**6**	**YELLOW**
Critical?	NO	

Criterion 5: Feed

All species with or without wastewater treatment

Feed Final Score (average of all scores)

C5 Feed Final Score (0-10)	**5.69**	**YELLOW**
Critical?	**NO**	

Criterion 6: Escapes

All species with or without wastewater treatment

6.1a System escape Risk (0-10)	10	
6.1a Adjustment for recaptures (0-10)	0	
6.1a Escape Risk Score (0-10)	**10**	
6.2. Competitive and genetic interactions score (0-10)	**0**	
C6 Escapes Final Score (0-10)	**10**	**GREEN**
Critical?	**NO**	

Criterion 7: Diseases

All species with or without wastewater treatment

Disease Evidence-based assessment (0-10)		
Disease Risk-based assessment (0-10)	6	
C7 Disease Final Score (0-10)	**6**	**YELLOW**
Critical?	NO	

Criterion 8X: Source of Stock

All species (except eel) with or without wastewater treatment

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

Eels (European, Japanese) with or without wastewater treatment

C8X Source of stock score (0-10)	Critical	
C8 Source of stock Final Score (0-10)	**Critical**	**RED**
Critical?	YES	

Eels (American) with or without wastewater treatment

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

Criterion 9X: Wildlife and predator mortalities

All species with or without wastewater treatment

C9X Wildlife and Predator Score (0-10)	**0**	
C9X Wildlife and Predator Final Score (0-10)	**0**	**GREEN**
Critical?	NO	

Criterion 10X: Escape of secondary species

All species with or without wastewater treatment

F10Xa live animal shipments score (0-10)	4.00	
F10Xb Biosecurity of source/destination score (0-10)	6.00	
C10X Escape of secondary species Final Score (0-10)	**-2.40**	**GREEN**
Critical?	n/a	