Monterey Bay Aquarium Seafood Watch®

# Recirculating Aquaculture Systems (RAS)

Image courtesy of AKVA Group

## Global
## All Species

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Brian Albaum, Seafood Watch Staff
Maddi Badiola, Consulting Researcher
Diego Mendiola, Consulting Researcher

# Final Seafood Recommendation

**Tank-Based Recirculating Aquaculture Systems (RAS)**
**All Species**
**Global**

| Criterion | Score (0-10) | Rank | Critical? |
|---|---|---|---|
| C1 Data | 7.00 | GREEN | |
| C2 Effluent | 9.00 | GREEN | NO |
| C3 Habitat | 6.83 | GREEN | NO |
| C4 Chemicals | 6.00 | YELLOW | NO |
| C5 Feed | 4.00 | YELLOW | No |
| C6 Escapes | 7.00 | GREEN | NO |
| C7 Disease | 8.00 | GREEN | NO |
| C8 Source | 10.00 | GREEN | |
| | | | |
| C9X Wildlife mortalities | -2.00 | GREEN | NO |
| C10X Introduced species escape | -2.00 | GREEN | |
| **Total** | **53.83** | | |
| **Final score** | **6.73** | | |

OVERALL RANKING

| | |
|---|---|
| Final Score | 6.73 |
| Initial rank | GREEN |
| Red criteria | 0 |
| Interim rank | GREEN |
| Critical Criteria? | NO |

FINAL RANK

**GREEN**

**Summary**
This Seafood Watch assessment evaluates the environmental impacts of aquaculture in tank-based Recirculating Aquaculture Systems (RAS). This evaluation is based on a precautionary approach with respect to variations between RAS facilities and the wide variety of species that can be cultured in them, and therefore, the resulting recommendation is valid for any species grown in RAS in any country. The final numerical score is 6.73, and with no red criteria, the final ranking for seafood produced in RAS is Green–Best Choice. If a species-specific Seafood Watch report is available with a red criterion, that evaluation shall take precedent over this global multi-species ranking.

# Executive Summary

Many aspects of recirculating aquaculture systems (RAS) are similar regardless of the species being cultured and 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; however, should 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 and be used rather than the generic results of this assessment[1]. Although this assessment applies to all species produced in RAS, this report can also be used as a template should a species-specific RAS assessment be desired (for example, where the species or the specifics of the system would generate substantially different scores than those presented here).

Recirculating aquaculture systems (RAS; also known as “closed-containment systems”) are an emerging method of fish production which, due to their contained nature, have the potential to mitigate or eliminate many of the environmental concerns associated with other more “open” aquaculture production systems (e.g., net pens, ponds, flow-through systems, etc.). Typically operating at high stocking densities and utilizing tank-based systems with a limited total volume, the key characteristic of RAS is the reuse of between 90-99% of the water by passing it continuously (i.e., recirculating it) through various treatment components such as solids filters, biofilters and disinfection units. The technology utilized in these systems offers several additional environmental advantages over other aquaculture production systems, for example 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.

The Seafood Watch criteria relate to ten distinct categories of environmental impact (or risk of impact), including effluents, habitats, chemical use, feed and marine resource utilization, escapes, disease, source of stock, wildlife and predator interactions, introduction of non-native organisms (other than the farmed species), and general data availability for these topics. The following assessment evaluates the environmental impacts of a generic RAS facility culturing any species and operating in any country around the world. As this assessment is intended to be global and apply to multiple species, a precautionary approach has been adopted to demonstrate how such a system would score numerically when assessed using the Seafood Watch Aquaculture Criteria.

While recirculation technology has been utilized in many industries, commercial indoor RAS facilities for ongrowing of finfish are a relatively new development when compared with other aquaculture production systems. As such, much of the scientific literature available on RAS is quite specific, focusing study on individual species in certain life stages with given characteristics; this is not always representative of commercial scale units and thus scientific

[1] For example, the Seafood Watch farmed eel assessment has a red final recommendation when cultured in RAS and this should be used as the final recommendation for this species.

studies of commercial production are generally limited. Nevertheless, consideration of the fundamental nature of these systems, in addition to a wide literature review, numerous personal communications, and the authors' extensive international RAS experience has provided the information presented in the following report- the score for Criterion 1–Data is 7 out of 10.

Commercial recirculating aquaculture systems have small total water volumes in comparison to other aquaculture production systems, and as such only small volumes of effluent are generated and discharged. The production system also allows for all waste materials (i.e., sludge and wastewater) to be collected and treated on site prior to discharge. Concentrated sludge is treated and disposed of via municipal wastewater treatment plants, land application, or compost production. While post-treatment wastewater from some RAS facilities is known to be discharged into nearby water bodies, all RAS facilities require a permit to discharge wastewater, which is regulated and frequently monitored under respective regional regulations. Due to the small volume, treatment and regulatory oversight of these effluents the risk of negative impact is very low. As such, Criterion 2–Effluents scores 9 out of 10.

RAS have the ability to be built and operated anywhere, and national legislation often ensures that sensitive habitats are avoided. Since RAS are considered "closed" systems, there is little to no interaction with surrounding habitats. Many RAS operations utilize previously existing buildings (e.g., warehouse, greenhouses, etc.) or, when purpose-built, are done so on previously converted land; as such there is typically little or no habitat conversion or loss of ecosystem functionality as a result of RAS construction or operation. Any habitat impacts that do occur are expected to be minor with no overall loss of habitat functionality. It is unlikely that national or regional regulations would permit deleterious habitat effects to occur as a result of RAS activity, however, because this is a global assessment valid for all species and countries, a precautionary approach is warranted. The numerical score for Criterion 3–Habitat is 6.83 out of 10.

The inherent design of RAS (i.e., the physical isolation from the surrounding environment) in combination with strict biosecurity protocols minimizes the risk of introduction of disease or parasitic agents and thus the need for chemical treatments. All wastewater leaving the facility has the potential to be treated and sterilized prior to discharge, and sludge is disposed of according to relevant regional regulations, indicating that the risk of active chemical compounds being released into the environment is low. Therefore, while disease outbreaks do occur in RAS, and some select chemicals are known to be used, there is no evidence to suggest these compounds have deleterious effects on the environment. Specific data on chemical use in RAS is typically limited; however, the production system has a demonstrably low risk of impact from chemical use, and as such the numerical score for Criterion 4–Chemicals is 6 out of 10.

Feed use and the indirect environmental impacts of ingredient sourcing 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 feeds containing no animal ingredients. Due to ongoing global 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 (or even green) scores for the feed criterion. Therefore, for this global multi-species RAS assessment, a low-moderate score of 4 out of 10 has been applied as a universal score to cover all species. If a species-specific Seafood Watch assessment is available with a red feed criterion score, the species-specific score will supersede this global recommendation and Criterion 5–Feed will be considered to be red for the ranking of this species in RAS. This RAS report can also be used as a template to accompany a species-specific feed assessment that results in a new species-specific report.

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. While some species may be cultured in regions in which they are non-native, regulations in developed nations restrict the culture of non-native species: as such, RAS culturing non-native species are expected to be either located in areas where escapees will not survive or alternatively have no connections to natural water bodies. The numerical score for Criterion 6–Escapes is 7 out of 10.

The opportunity for filtration or sterilization of incoming waters coupled with strict biosecurity protocols mitigates the risk of introduction of a disease agent into recirculating aquaculture systems. Furthermore, when applied, treatment of effluents limits the risk of the release of diseases from a RAS facility into the natural environment. While disease outbreaks in RAS have occurred and continue to pose challenges from a production perspective, the majority of outbreaks are shown to occur as a result of improper implementation of quarantine procedures. Despite the practical production challenges of disease in RAS, there is a low risk of environmental impact from the pathogens due to the limited connectivity of a land-based RAS with potentially vulnerable wild populations. As such, even though disease is a production issue within RAS, there is a low environmental concern and a high score. The score for Criterion 7–Disease is 8 out of 10.

For the overwhelming 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 10 out of 10 has been applied as a universal score to cover all species. However, there are some select examples of wild-caught juveniles being reared to market size in RAS: one notable example is RAS eel aquaculture in Europe and Asia. Therefore, if a species-specific Seafood Watch assessment is available with a red source of stock criterion score, the species-specific score will supersede this global recommendation and Criterion 8–Source of Stock will be considered to be red for the ranking of this species in RAS.

Tank-based RAS facilities provide physical separation of the culture area from the natural environment. While indoor RAS do not present any risk of wildlife interactions, outdoor facilities may present minor concerns in exceptional cases. As such, the score for Criterion 9X–Wildlife Interactions is -2 out of -10.

International shipment of animals is common in the RAS industry- this represents a significant biosecurity risk and has been the cause of several disease outbreaks in RAS. However, these outbreaks are shown to be caused by lack of adherence to proper biosecurity and quarantine practices. Additionally, as all effluents have the capacity to be treated and sterilized prior to discharge, the risk of unintentionally introducing a live organism into the surrounding environment is low. As such, Exceptional Criterion 10X–Escape of Unintentionally Introduced Species is -2 out of -10.

RAS require the continuous operation of extensive life-support technologies and pumps to move water through the different system components – these pumping costs are recognized as the main energy cost associated with RAS. Overall, RAS facilities are highly energy-dependent, and energy use remains one of the principal costs (both economic and environmental) associated with RAS.

Overall, Recirculating Aquaculture Systems are shown to mitigate many of the environmental impacts associated with other aquaculture production systems (e.g., net pens, ponds, flow-through systems). Energy use remains one of the principal concerns and the authors of this report indicate that energy consumption should be the focus of further study. However, in general, as RAS reduce or eliminate many of the environmental concerns associated with commercial aquaculture, the final score is 6.73 out of 10, and the final recommendation for all species grown in these systems is a “Green–Best Choice.”

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# Introduction

**Scope of the analysis and ensuing recommendation**

**Production System**
Tank-based recirculation systems. Although ponds can be (and increasingly are) operated as recirculation or zero exchange systems, this Seafood Watch assessment applies only to tank-based recirculation systems.

**Species**
All species. If a Seafood Watch species-specific assessment is available, the species-specific report and ranking supersedes this global, multi-species assessment.

**Geographic Coverage**
Global

## Overview

The farming of animals for human consumption is known to have significant environmental impacts worldwide (Dumont et al. 2012), and aquaculture is no exception. Various scientific disciplines that emerged in the United States during the 1980s (most notably agroecology and industrial ecology) focus on designing farming systems that minimize their environmental impacts (Wezel and Soldat 2009; Frosch 1992). Since their inception, these disciplines have highlighted recirculating aquaculture systems (RAS) as one possible way for reducing the environmental footprint of aquatic animal production, and mitigating many of the impacts associated with traditional commercial fish culture technologies (i.e., net pens, ponds, flow-through systems).

Recirculating aquaculture systems (RAS, also known as “closed-containment systems”) are an emerging method of fish production that mitigate or eliminate many of the environmental concerns associated with other forms of traditional aquaculture (Dalsgaard et al. 2013; Daniels 2014). RAS inherently reduce these impacts because as opposed to discharging large volumes of untreated effluent directly into the environment, such as in net pen and flow-through production, RAS retain (via treatment and recycling) between 90–99% of the water in the system, passing it through various treatment components such as solids filters, biofilters and disinfection units. While up to 10% of the system volume may be discharged on a daily basis at commercial RAS facilities, the majority of water remains within the system and hence does not impact the surrounding environment.

Many pond aquaculture operations exchange more than 10% of the system volume per day; however, there is an emerging trend in pond aquaculture that involves retaining pond water as opposed to exchanging it. While both ponds and RAS produce concentrated solid wastes (in the form of sludge), how these wastes are handled after being discharged dictates the relative environmental impact of the effluents from each production system. Pond aquaculture may dispose of raw sludge in a variety of manners, and while some disposal methods involve treatment (settling ponds, discharge to wetlands, application as agricultural fertilizer, etc.) and subsequently lower impacts (or risk of impacts), there have also been instances of significant impacts from effluents (e.g., illegal dumping of sludge directly into natural waterways). In contrast, RAS sludge is treated (to remove as much water as possible and concentrate the solids) and sterilized prior to discharge to reduce as much as possible the risk of environmental impact. Additionally, all discharges from RAS must be in compliance with regional regulations; compliance with and enforcement of effluent discharge regulations is shown to be high for RAS facilities around the world. The small total system volume in RAS, combined with lower exchange rates as compared to other aquaculture production systems, results in lowered environmental impact from RAS effluents.

Global freshwater supplies are limited and availability is scarce worldwide. While some aquaculture production methods utilize little or no freshwater (i.e., marine net pens), other systems can utilize significant amounts of freshwater. For example, traditional flow-through systems (FTS) can use up to 22–95 $m^3$ of water per kg of fish produced (Bergheim et al. 2013), whereas RAS systems use approximately 0.005 $m^3$ of water per kg of fish produced (Timmons and Ebeling 2013). The low water use in RAS is made possible by cycling up to 99% of the water through a variety of treatment and sterilization technologies. As such, RAS offer several advantages over other aquaculture production systems, principally increased control over the water quality of the growing environment, and thus the opportunity to create optimal conditions for fish welfare and growth (Heinen et al. 1996).

By design, flow-through daily exchanging or open systems, such as raceways, ponds, and net pens, are intimately connected with their surrounding environments and thus have risks of inherent environmental impacts (e.g., the escape of farmed stock into the wild as shown by Buschmann et al. 2006). By producing fish in tank-based RAS, as Labatut and Olivares (2004) concluded and Zohar et al. (2005) corroborated, there is very limited or no connectivity to surrounding ecosystems. The structure/building in which the RAS is located represents a physical separation of the culture area and the natural environment, indicating that there is no interaction with wild fauna and little opportunity for the escape of farmed animals.

Despite these benefits, there are also some significant challenges to greater adoption of RAS. Common issues include difficulty in treating diseases (Schneider et al. 2006) and a requirement for careful overall management (Badiola et al. 2012); however, the main barriers to success are high capital and operational costs (Timmons and Ebeling 2013). The economic cost associated with the construction and operation of a RAS is often the principal factor in the failure of these endeavors: an average of 8 years is necessary before these facilities become profitable (Badiola et al. 2012).

Due to the heavy reliance on pumping and water treatment technologies, the principal operational cost associated with RAS is energy use. Energy consumption in RAS has been studied extensively (Aubin et al. 2009; Ayer and Tyedmers 2009; Roque d´Orbcastel et al. 2009; Jerbi et al. 2012) and the conclusions of these studies indicate that RAS are much more energy-intensive than other aquaculture production systems. For example, RAS have energy requirements of 17.55 to 22.6 kWh/kg fish as compared to traditional flow-through systems (FTS) that require between 9.75 and 13.4 kWh/kg fish (Ayer and Tyedmers 2009; Roque d´Orbcastel et al. 2009).

## Production System Description

In RAS, water quality is maintained by recirculating water continuously throughout several technological components prior to re-entering the culture tanks. These components can differ depending on the water (i.e., marine or freshwater), species (i.e., cold- or warm-water species) and feed ingredients (i.e., if the species is carnivorous or herbivorous). The most common RAS components are mechanical filtration (to remove solid wastes), biofiltration (to remove liquid nitrogenous wastes), disinfection (i.e., ozone and/or ultra-violet [UV] treatment), gas management ($CO_2$ removal and oxygenation), and protein skimming. With respect to these components, there are many different equipment manufacturers and styles, and their order within the water treatment loop can also vary (depending on the designer, species, and production volume). The design and engineering of RAS has been extensively studied (e.g., Piedrahita et al. 1996; van Rijn 1996; Cripps and Bergheim 2000; Summerfelt and Penne 2005, Eding et al. 2006; Summerfelt 2006; Morey 2009, Timmons and Ebeling 2013), and it is not this report´s aim to analyze RAS engineering in further detail.

Ideally, a recirculating aquaculture system allows the operator to maintain optimal water quality parameters for the species being cultured, although in reality it can often be a management challenge (Badiola et al. 2012). Recirculating aquaculture systems are complex biology-technology interactions, and a wide variety of issues can pose significant challenges to RAS operations. For example, frequent disease problems as a result of high animal densities, and difficulty in treating diseases (e.g., antibiotics are not used because they would destroy the microbial populations in the biofilter, which are necessary to break down liquid nitrogenous wastes) are consistent challenges facing RAS operations. Additionally, difficulty in maintaining all water parameters (e.g., nutrient levels, pH, alkalinity, etc.) at optimal levels is common; for many of these parameters, recirculation systems have much greater fluctuations and are less stable than large water bodies such as ponds or coastal waters. The need for experienced managers who are able to respond to issues and maintain healthy growing conditions for the animals is a vital component to the successful operation of a RAS (Badiola et al. 2012).

With respect to water treatment, mechanical screen filtration captures and removes any particulate wastes and other solids that leave the tank in the effluent stream (mainly uneaten feed and produced feces). As stated by Han et al. (1996), the efficiency of this solids filtration component is essential for the efficient performance of the entire system. If solids are not adequately captured, it may negatively impact the function of the downstream components (e.g., biofilter; Jokumsen and Svendsen 2010) as well as several other water quality parameters such as oxygen, carbon dioxide, and ammonia, leading to potential fish stress and disease outbreaks (Malone and Pfeiffer 2006; Emparanza 2009). Timmons and Ebeling (2013) claim that the most critical component in a RAS is the solids removal, because all other unit processes are compromised or fail when this component does not perform effectively.

Whereas mechanical filtration removes the solid wastes, biofiltration is designed to break down the liquid nitrogenous wastes into less toxic compounds. Biofilters contain populations of living bacteria that play an important role in the water treatment loop: *Nitrosomonas* bacteria oxidize toxic ammonia ($NH_3$) wastes from the fish into nitrite ($NO_2$-), which is also relatively toxic to fish. Then, *Nitrobacter* bacteria oxidize nitrite into nitrate ($NO_3$-), which is relatively non-toxic. Nitrate is able to accumulate in the system in much higher concentrations than ammonia or nitrite without impacts to fish health or welfare; however, they must at some point be removed via denitrification (i.e., the reduction of nitrate into nitrogenous gas).

Carbon dioxide ($CO_2$) is a metabolic waste that represents another limiting factor in a RAS. Especially at high fish densities, $CO_2$ can build up in the system, resulting in a reduced capacity of the fish's blood to transport oxygen, as well as an increase in water acidity. $CO_2$ removal must be rapid and effective, and is accomplished in a RAS through a gas exchange process (via components such as trickle towers, blowers, etc.). These components also help to oxygenate the water, although other methods such as aeration or liquid oxygen may be employed.

Though RAS are usually highly biosecure, bacteria, viruses, and/or parasites may enter the system through a variety of vectors. As such, disinfection processes are necessary to remove disease agents and protect the culture animals from infection. Exposure to ultra-violet (UV) irradiation and/or ozone ($O_3$) are two effective methods that are commonly applied for disinfection in RAS, and may be utilized for either (or both) of the incoming waters as well as discharged wastewaters.

The financial cost associated with a RAS is one of the major constraints and limits for further implementation (e.g., Martins et al. 2010) because high capital costs and energy inputs are required for construction and daily operations. Several studies suggest that energy use in a RAS is the most significant environmental concern associated with these production systems (Bostock et al. 2010; Martins et al. 2010; Dalsgaard et al. 2013).

## Production Volumes

During the last two decades, RAS production has increased significantly around the globe. While the driving factors of this increased production have not been thoroughly studied, potential contributing components may include new stringent regional environmental policies and/or consumers' increased awareness and concern of the environmental impacts of other aquaculture production systems.

Despite this growth, the global RAS industry has been cited as doing a poor job of communicating information, as shown by various authors (Martins et al. 2010; Badiola et al. 2012; Dalsgaard et al. 2013) and international organizations (FAO 2012). Thus, no official worldwide data exist regarding exact production volumes, monetary values, or number of farms in operation. A global census of commercial recirculation aquaculture facilities would represent a valuable resource with respect to production volumes, market information, and a continuation of the study of the environmental impacts associated with this production.

## ***Europe***

Many European fish hatcheries have been operating as closed-containment systems since the early 1900s (Blancheton 2000). In 1986, RAS production was concentrated in the Netherlands with 300 MT, while in 2009 RAS production was spread over the continent, reaching a total volume of nearly 24,000 MT (Martins et al. 2010). This increase was mostly due to new strategy documents developed by the European Commission encouraging RAS use for reduced environmental impacts in aquaculture (COM 2002; 2009), as well as the market's acceptance and encouragement of seafood produced in RAS. Today, there are around 360 farms operating throughout Europe (personal communication through LinkedIn; EPI, Ecoplan International, 2008; aquaoptima.com; billund-aqua.dk).

Atlantic salmon is currently the highest-value species farmed in Europe (European Commission 2011). Norway, Scotland, and the Faroe Islands produce all their Atlantic salmon juveniles in RAS facilities and are increasing ongrowing production levels of Atlantic salmon in RAS (Bergheim et al. 2009; Dalsgaard et al. 2013). In Denmark, one company successfully brought RAS-raised Atlantic salmon to market in 2014, with several other companies on track to do the same in the next 12–24 months. Danish eel production (1500 MT in 2011; Dalsgaard et al. 2013) utilizes closed-containment tanks, and rainbow trout (representing 93% of total Danish aquaculture production; FAO, 2003) is increasingly being raised in RAS (Roque d`Orbcastel et al. 2009; Jokumsen and Svedsen 2010). In the Netherlands RAS finfish production began significant growth in 1980, and today there are 90 companies operating high-tech, temperature-controlled closed-containment farms. Principal species include European eel (*Anguilla anguilla*—44 farms, 4,800 MT/year), African catfish (*Clarias gariepinus*—33 farms, 4,000 MT/year) and tilapia (*Oreochromis niloticus*—5 farms, 600 MT/year).

## **North America**

According to the USDA 2013 Census of Agriculture, in the United States there are 360 closed-containment farms representing 46,503,715 gallons of water. The states with the top numbers of operating RAS include Florida (86), California (25), Virginia (19), North Carolina, Ohio and Wisconsin (16), and Texas and Hawaii (15). There is a great variety of species produced, including channel catfish, tilapia, and sturgeon, among others.

Canada has the $4^{th}$-largest production of Atlantic salmon (behind Norway, the United KIngdom and Chile; CAIA 2012), representing 67% of total aquaculture production in the country. While most Atlantic salmon smolts are produced in RAS before being sent to marine net-pen growout sites, several RAS facilities for ongrowing of Atlantic salmon are currently being planned or constructed. One RAS facility in Canada is currently in operation and successfully brought

Atlantic salmon to market in April 2014. This facility has an estimated annual production of 470 MT and plans to expand capacity to 2500 MT in the next few years. Although small in production volume, the following species are also reared in RAS in Canada: trout, coho salmon, sturgeon, halibut, Arctic char, seabass, seabream, and tilapia.

***South America***

Most of the South American countries´ aquaculture, i.e., Argentina, Colombia, and Brazil, utilizes production systems that experience high water exchange rates. The exception is Chile, where several RAS produce trout, abalone, and turbot (249 MT in 2004). According to a RAS expert in Chile, Claudio García–Huidobro, 141 million salmon smolts are produced in Chile, 76 million of which are produced in RAS (mispeces.com 2013).

***Asia***

While RAS has not yet been as widely embraced in Asia, these systems are gaining popularity as the technology develops more rapidly and the economic costs decrease as a result. Moreover, regional pollution and other environment problems caused in the past are now being treated as more serious issues; therefore, it is expected that new policies will more strongly regulate industries' environmental impacts in the near future. Countries currently operating RAS include China, Saudi Arabia, Taiwan, and Malaysia; eel and shrimp are the main species produced in RAS (FAO 2001). As an example, in 2013, Asmak, the international fish farming holding company, announced salmon farming in Abu Dhabi, also cultivating barramundi and subaiti in an area of 500,000 square meters and producing 4,000 MT yearly (The National 2013).

# Analysis

Production systems analyzed in this assessment are tank-based recirculation systems culturing any species in any country. Although many pond systems currently operate as recirculating or zero-exchange systems, this Seafood Watch assessment applies only to tank-based recirculation systems. If a species-specific SFW assessment is available, that report will take precedent over this multi-species global RAS report.

## Scoring guide

The table below outlines the criteria that are assessed in the following report.

Table 1. Specific Seafood Watch criteria that are assessed in this report.

| | |
|---|---|
| Criterion 1 | Data Quality and Availability |
| Criterion 2 | Effluent |
| Criterion 3 | Habitat |
| Criterion 4 | Evidence or Risk of Chemical Use |
| Criterion 5 | Feed |
| Criterion 6 | Escapes |
| Criterion 7 | Disease, Pathogen, and Parasite Interactions |
| Criterion 8 | Source of Stock |
| Exceptional Criterion 9X | Wildlife and Predator Mortalities |
| Exceptional Criterion 10X | Escape of Unintentionally Introduced Species |
| Additional Criterion (unscored) | Energy Use |

- With the exception of the Exceptional Criteria (9X and 10X), all sections result in a 0 to 10 final score for the criterion and the overall final rank. A 0 score indicates poor performance, while a score of 10 indicates high performance. In contrast, the two Exceptional Criteria result in negative scores from 0 to -10, and in these cases 0 indicates no negative impact.
- The full Seafood Watch Aquaculture Criteria that the following scores relate to are available here http://www.montereybayaquarium.org/cr/cr_seafoodwatch/content/media/MBA_SeafoodWatch_AquacultureCriteraMethodology.pdf
- The full data values and scoring calculations are available in Appendix 1.

# 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: Robust and up-to-date information on production practices and their impacts is available to relevant stakeholders.*

**Criterion 1 Summary**

| Data Category | Relevance (Y/N) | Data Quality | Score (0-10) |
|---|---|---|---|
| Industry or production statistics | Yes | 5 | 5 |
| Effluent | Yes | 7.5 | 7.5 |
| Locations/habitats | Yes | 10 | 10 |
| Chemical use | Yes | 5 | 5 |
| Feed | Yes | 5 | 5 |
| Escapes, animal movements | Yes | 10 | 10 |
| Disease | Yes | 5 | 5 |
| Source of stock | Yes | 10 | 10 |
| Predators and wildlife | Yes | 5 | 5 |
| Other–(e.g., energy use) | Yes | 7.5 | 7.5 |
| **Total** | | | **70** |

| | | |
|---|---|---|
| **C1 Data Final Score** | **7.00** | **GREEN** |

**Brief Summary**

Overall data availability for recirculating aquaculture systems is good. Categories such as effluents, locations and habitats, escapes, source of stock, and energy use are thoroughly studied and widely 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 chemical use, disease, and predator/wildlife interactions is not as readily available because, with respect to RAS, these topics are recognized as not having significant environmental impacts. The final numerical score for Criterion 1–Data is 7.0 out of 10.

**Justification of Ranking**

Recirculating aquaculture systems are relatively young operations when compared with other aquaculture production systems. As such, much of the scientific literature available is quite narrow in scope, focusing study on specific species in certain life stages with given characteristics; this is often not representative of commercial scale production. Additionally, various authors (Martins et al. 2010; Badiola et al. 2012; Dalsgaard et al. 2013) note that global production statistics for RAS are currently not available in a central location, and thus industry and production information is limited, resulting in a score of 5 out of 10 for the production/ industry statistics category.

While extensive literature reviews as well as numerous personal communications have gathered the information necessary to complete this assessment of a generic RAS facility, it is recognized that a global census of RAS operations (including species, production volumes, management regimes, and environmental concerns) would be an valuable resource not only for the global aquaculture industry but also governments, environmental groups, and academia.

There are many studies that examine the environmental effects of effluents from RAS, resulting in a data score of 7.5 for the effluent category. Notable studies that this assessment relies heavily on include Martins et al. (2010), "Review. New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability." This study is the latest comprehensive review regarding RAS environmental impacts and covers such aspects as: (1) effluent treatment, (2) energy consumption and possible future solutions, (3) system viability in terms of habitat requirements and site selection, and (4) feed requirements and impacts. Timmons and Ebeling (2013), "Recirculating Aquaculture" (book, 3$^{rd}$ edition) is one of the premier resources for RAS and is cited heavily within this report. Van Rijn (2013), "Waste treatment in recirculating aquaculture systems," is the latest publication of a prominent RAS scientist that deals with overall water treatment in RAS. Additional relevant scientific literature on effluent characteristics include e.g., Bergheim et al. 1993; Chen et al. 1993, 1997; Ebeling et al. 2003; Sharrer et al. 2009. Lastly, personal communications with several RAS managers also provided valuable input to inform this assessment.

For the habitat criterion (Criterion 3), a global overview of legislative regulation and enforcement is not practical because each nation follows different criteria for evaluation and management (e.g., EPA and NDPE in the United States, Norwegian Authority of Food Safety and Directorate of Fisheries in Norway, NSDFA and DFO in Canada, etc.). Nevertheless, information on habitats in which RAS occur is robust; the locations of operations, as well as data on country-specific regulations governing habitat impacts, are publically available. As such, the Criterion 1 score for the habitat category is 10 out of 10.

RAS have little or no need for chemical use because strict biosecurity protocols ensure minimal entrance of pathogens or diseases. Additionally, although chemicals could be used within a RAS, water is effectively treated and sterilized before discharge to avoid the release of active compounds and their impact on the outflow surroundings. Many of the consulted farm managers openly shared information on chemical use with the author of this report. Despite the demonstrably low frequency of chemical use in RAS, there are limited published scientific studies on this topic. As such, the data score for the chemical category (Criterion 4), is 7.5 out of 10.

The feed category (Criterion 5) analyzes what is often considered one of the most significant environmental concerns for all aquaculture systems, including RAS. Feed is highly-species specific and a wide range of species are cultured in RAS around the world. However, this category has received a data score because data pertaining to feed impacts in RAS are presented in this report. The following relevant literature illustrates the potential environmental effects of feed use in aquaculture: Tyedmers and Pelletier 2007; Ayer and Tyedmers 2009; and Bostock et al*.* 2010. Also, as the feed conversion ratio (FCR) is one of the mains indicators of use of resources, and therefore environmental impact, the following studies are valuable in informing this assessment: Papatryphon et al*.* 2004; Roque d´Orbcastel 2009; and Sintef & Conservation Fund 2013. However, due to the proprietary nature of feed formulations (including ingredients and inclusion levels), farm managers and feed manufacturers are hesitant to release this information, and as such published data on feed are often aggregated and based on global trends. Therefore, the data score is 5 out of 10 for the Feed category.

Relevant literature on escapes from RAS include Labatut and Olivares 2004; Zohar et al*.* 2005; Martins at al. 2010; and van Rijn 2013. This data is publically available, and all of these sources reach the same conclusion that the risk of the escape is significantly reduced or completely eliminated in RAS. Therefore, the data score for the escapes category is 10 out of 10.

The source of stock is known for RAS operations, with the majority of the global industry relying on hatchery-reared juveniles. One notable exception is RAS production of eels, which are heavily dependent on the capture of wild juveniles from threatened populations. However, because the source of stock for all RAS operations is known, the data score for source of stock category is 10 out of 10.

Regarding Criterion 7–Disease, Exceptional Criterion 9X–Wildlife Interactions, and Exceptional Criterion 10X–Unintentionally Introduced Species, a score of 5 has been given for all these categories. Although there is not a large volume of data available, RAS are recognized as reducing or altogether eliminating these impacts, and as such not a large amount of data is expected. The lowered risks and subsequent reduced environmental impacts in these areas are based on management procedures and protocols as outlined in Yanong 2012; Badiola et al*.* 2012; and Timmons and Ebeling 2013.

In addition to feed, energy use is one of the principal environmental factors associated with the sustainability of RAS. While few studies have explored this topic, the relevant ones are cited within this report. Life cycle assessments (LCA) seem to be the most widely-used method to evaluate the energetic costs of RAS. Several authors have published studies utilizing this method, including Papatryphon et al*.* 2004; Aubin et al*.* 2006; Ayer and Tyedmers 2009; Roque d´Orbcastel et al*.* 2009; and Jerbi et al*.* 2012. As a relatively small amount of literature is currently available, and even fewer studies of commercial-scale systems, the data score for the energy category is 5 out of 10.

The final numerical score for Criterion 1–Data is 7 out of 10.

# Criterion 2: Effluents

***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: Aquaculture operations 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 beyond the immediate vicinity of the farm.*

**Criterion 2 Summary**

Effluent Evidence-Based Assessment

| | | |
|---|---|---|
| **C2 Effluent Final Score** | **9.00** | **GREEN** |

**Brief Summary**

Commercial recirculating aquaculture systems have small total water volumes in comparison to other aquaculture production systems, and as such only small volumes of effluent are generated and discharged. The production system also allows for all waste materials (i.e.. sludge and wastewater) to be collected and treated on site prior to discharge. Concentrated sludge is treated and disposed of via municipal wastewater treatment plants, land application, or compost production. While post-treatment wastewater from some RAS facilities is known to be discharged into nearby water bodies, all RAS facilities require a permit to discharge wastewater, which is regulated and frequently monitored under respective regional regulations. Due to the small volume, treatment, and regulatory oversight of these effluents the risk of negative impact is very low. As such, Criterion 2–Effluents scores 9 out of 10.

**Justification of Ranking**

This criterion aims to assess the direct ecological impact that aquaculture farm effluents have on the environment downstream of the farms (i.e., outside the immediate proximity of the farm or an allowable zone of effect—environmental impacts in the immediate farm area are considered in Criterion 3–Habitat).

**General Effluent Definitions**

Effluent: The waste flow emanating from different components of the recirculation loop and that is discharged from the facility. Total effluent is formed by two parts: sludge (feces and uneaten feed) and liquid wastes (backwash flow and wastewater). For the majority of RAS facilities around the world, sludge is disposed of via municipal wastewater treatment plants, land application, or compost production. Wastewater is sterilized via UV-irradiation and/or ozone prior to being discharged into natural water bodies, dry ground infiltration systems, or utilized as irrigation for agricultural crops.

Sludge: Solid wastes (feces and uneaten feed) that are captured via mechanical filtration, dewatered to concentrate solids, and treated prior to disposal.

Wastewater: Backwash flow from mechanical filtration and any additional water that is in the effluent stream.

**Origin of Effluent**

Fish in RAS produce a similar amount of waste as those in other production systems, and despite the high level of water recirculation through the RAS, there remains a substantial quantity of effluent waste that must be disposed of.

First, it is important to differentiate between two separate water loops in RAS: (1) the recirculation loop (contains the culture tanks as well as all water being treated and recirculated, also known as the "online treatment") and (2) the effluent stream and its subsequent treatment and disposal (also known as "final effluent"). The effluent stream is further broken down into two waste streams: (a) sludge waste (i.e., solid wastes, including uneaten food and feces) and (b) liquid waste (including backwash flow and wastewater).

Sludge wastes are captured via mechanical filtration components (e.g., drum filter, sand filter, belt filter, etc.), held and dewatered on-site (see "Treatment of Effluent" below) and then disposed of via a variety of methods, including municipal wastewater treatment plants, land application, and/or compost production. These disposal methods have been extensively studied by numerous authors (e.g., Bergheim et al. 1993; Adler and Sikora 2004; Danaher et al. 2011; Summerfelt et al. 2013), as well as corroborated via personal communications with RAS operators (P. Blancheton personal communication; A. Bergheim, personal communication).

Liquid wastes are also treated via a variety of methods. Typical treatments include mechanical filtration, biological filtration, oxygenation, UV disinfection and/or chlorination and dechlorination. This treatment occurs prior to wastewater being discharged into a nearby water body, a dry ground infiltration system, or utilized as agricultural irrigation (Summerfelt et al. 2013). All RAS facilities require a permit to discharge wastewater, which is regulated and frequently monitored under respective regional legislation.

While some pond production systems may operate at the same water reuse rates as RAS (i.e., 90–99% recirculation), the smaller total volume of tank-based systems as compared to large pond or raceway operations indicates that effluent volumes in RAS are significantly lower. Additionally, because solids are captured and removed from the water stream, effluents from RAS are more concentrated than those from other production systems, making the collection and reutilization (e.g., as agricultural fertilizer) more cost effective and logistically easier to handle (Martins et al. 2010; Timmons and Ebeling 2013).

**Treatment of Effluent**

Wastes (both solid and liquid) are a result of normal metabolic processes, and these wastes must be removed from the system in order to avoid the deterioration of water quality and animal health. The design and sizing of the waste treatment components, as well as their position within the loop, are important considerations in order to minimize toxic ammonia levels and capture as many solids as possible. If not designed correctly, low percentages of these wastes will be removed, resulting in adverse effects on the system (e.g., Chen et al. 1993; 1997; Suzuki et al. 2003; Timmons and Ebeling 2013).

**Sludge**

Sludge waste produced in RAS can be treated onsite via a variety of methods: examples of sludge treatment include (1) sludge thickening, (2) sludge digestion, (3) denitrification, and/or (4) polyculture. All of these treatments are discussed in further detail below:

1) Sludge thickening involves the removal of as much water as possible to achieve a higher concentration of solids in the sludge effluent stream. 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 5–22% (Sharrer et al. 2009) and decreased phosphorous concentrations (Danaher et al. 2011; Ebeling et al. 2003, 2006; Sharrer et al. 2009).
2) Sludge digestion involves biological degradation via microbes in external reactors known as sludge digesters. The residence time in the digesters is the limiting factor causing or preventing anoxic periods and thus more or less sludge decay (Timmons and Ebeling 2013). Regardless, when properly sized, 30–40% degradation can be achieved with sludge digestion; however, the decay is slow compared to other methods (Klas et al. 2006).
3) Denitrification (i.e., reduction of nitrate into nitrogenous gas) is employed to remove nitrates from the system. The process is carried out in denitrifying reactors by heterotrophic bacteria that utilize organic carbon as a food source. The food source can be made available in one of two ways: either internally (i.e., treatment of digested sludge within the treatment loop as demonstrated by van Rijn et al. 2006) or externally (i.e., treatment of effluent wastewater prior to discharge).
4) Polyculture involves combining the cultured fish with the culture of other organisms (e.g., additional species of fish, invertebrates, algae, or plants). The wastes from the cultured fish are utilized as nutrition for lower trophic level organisms; these are also known as integrated systems (e.g., aquaponic systems, bio-floc technologies, peryphiton systems, and constructed wetlands). The type and amount of effluent discharged from these systems is heavily dependent on the combination of organisms cultured.

**Wastewater**
Liquid wastes include backwash from mechanical filtration components, as well as any additional water in the effluent stream. This liquid waste will typically go through some form of treatment prior to being discharged into a nearby water body, a dry ground infiltration system, or utilized in irrigation for agriculture (Summerfelt et al., 2013). Typical wastewater treatments include mechanical filtration, biological filtration, oxygenation, and carbon dioxide stripping; sterilization via UV disinfection and/or chlorination and dechlorination may also occur. All discharged wastewater must be in compliance with guidelines set by operational permits as well as relevant regional legislation. This indicates that any effluent impacts from the discharge of wastewater are minimal.

Wastewater emanating from freshwater systems can be treated off-site in municipal waste water treatment plants (WWTP) or on-site by any of the methods described above. Sterilization of wastewater (via exposure to UV or ozone) indicates that the risk of releasing detrimental microbial agents from a RAS facility is minimal. Finally, as mentioned previously, aquaculture´s water characteristics are vastly different compared with other livestock production or public wastes, making their application in other industries a potential alternative to traditional disposal (e.g., land application, compost production, and/or irrigation for agricultural crops) (Bergheim et al*.* 1993; Adler and Sikora 2004; Danaher et al*.* 2011).

**<u>Evidence of Effluent Management</u>**
Although the effluent volume emanating from RAS is low (compared with other aquaculture production systems), its quality needs to be within certain limits in order to comply with the policy requirements of the respective region where the operation is occurring. As RAS require several operating permits and licenses, all of which involve evidence of compliance with regional regulations governing the discharge of wastewater and subsequent potential effluent impacts, it is likely that RAS effluents have no more than a minimal impact on receiving waters and downstream ecosystems.

An example of strong regulation governing the management and treatment of RAS effluent is found in the United States. In the United States, industrial facilities, i.e., fish farms, must obtain permits if their discharges go directly into surface waters. These permits are granted by the National Pollutant Discharge Elimination System (NPDES) permit program, which is administered in most cases by authorized states (NPDES, 2003). Hatcheries and fish farms are considered concentrated aquatic animal production (CAAP) facilities and thus, if they satisfy the criteria described by the Environmental Protection Agency (EPA; 40 CFR 122 Appendix C) are required to apply for an NPDES permit. Moreover, if a RAS facility produces 100,000 pounds or more per year, the required permit would be different (40 CFR 451).

Additionally, in 2004 the US EPA finalized a new rule regarding effluent limitation guidelines (ELGs) concerning Aquatic Animal Production industries discharging water to any water body of the United States (http://www.epa.gov/fedrgstr/EPA-WATER/2004/August/Day-23/w15530.htm).

**Final Score for Criterion 2–Effluent**

The relatively small total water volume of RAS compared to pond or raceway operations, coupled with a low daily water exchange rate, indicates that effluent volumes discharged from RAS are smaller than those discharged from other production systems. Additionally, because solids are captured and removed from the water stream, sludge waste from RAS are more concentrated than those from other production systems, allowing for the collection, treatment, and proper disposal of this waste. While wastewater may be allowed to enter natural water bodies after being treated and sterilized, wastewater discharge must be in compliance with the permits and licenses required to operate a RAS, indicating that facilities are in compliance with regional legislation governing effluent impacts. As such, RAS effluents are extremely unlikely to have any detrimental impacts on surrounding ecosystems—the score for Criterion 2–Effluent is 9 out of 10.

# 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: Aquaculture operations are located at sites, scales, and intensities that cumulatively maintain the functionality of ecologically valuable habitats.*

**Criterion 3 Summary**

| Habitat parameters | Value | Score | |
|---|---|---|---|
| F3.1 Habitat conversion and function | | 9.00 | |
| F3.2a Content of habitat regulations | 2.50 | | |
| F3.2b Enforcement of habitat regulations | 2.50 | | |
| F3.2 Regulatory or management effectiveness score | | 2.50 | |
| **C3 Habitat Final Score** | | **6.83** | **GREEN** |
| Critical? | NO | | |

**Brief Summary**

RAS have the ability to be built and operated anywhere, and national legislation often ensures that sensitive habitats are avoided. Since RAS are considered "closed" systems, there is little to no interaction with surrounding habitats. 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 habitat conversion or loss of ecosystem functionality. Any habitat impacts that do occur are expected to be minor with no overall loss of habitat functionality. It is unlikely that national or regional regulations would permit deleterious habitat effects to occur as a result of RAS activity; however, because this is a global assessment valid for all species and countries, a precautionary approach is warranted. The numerical score for Criterion 3–Habitat is 6.83 out of 10.

**Justification of Ranking**

Beveridge (2001) describes several ways in which aquaculture activities interact with surrounding habitats, including (1) utilizing land by building new farms, (2) occupying seabeds with net cages, (3) exacerbating pressure on already over-exploited natural resources for fish meal and fish oil production. Regarding the utilization of land, 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. At the same time, and differing from other systems, 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).

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. Some countries are converting existing flow-through farms into RAS systems (e.g., Bergheim et al. 2009; Jokumsen and Svendsen 2010; Martins et al. 2010). In any case, the construction of a RAS must be on land designated for commercial development according to broader zoning and permitting policies. As such, 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.

Proper site selection for the construction and operation of a RAS is vital. Problems stemming from inappropriate site selection are diverse (CEFAS 2011; Lekang, O. I. 2013); however, all of these challenges would affect production and not habitat impacts. Improper site selection does not result in a direct ecological loss when the system is operated correctly (i.e., appropriate and effective effluent treatment, barriers against escapes, etc.).

It is extremely unlikely that a RAS facility would be built in an environmentally sensitive location (e.g., mangroves or protected areas) as these vulnerable habitats are covered by relevant regional and international policies. Additionally, the presence and operation of a RAS is not expected to result in the conversion of ecosystems of the loss of habitat functionality. However, because this is a global assessment valid for all species and countries, a precautionary approach is warranted—the score for Factor 3.2 Regulatory or management effectiveness is 2.5 out of 10, which represents a precautionary “realistic worst-case scenario.”

Factors 3.1 and 3.2 combine to result in a final numerical score for Criterion 3–Habitat of 6.83 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: Aquaculture operations by design, management, or regulation avoid the discharge of chemicals toxic to aquatic life, and/or effectively control the frequency, risk of environmental impact, and risk to human health of their use.*

**Criterion 4 Summary**

| | | |
|---|---|---|
| **C4 Chemical Use Final Score** | **6.00** | **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 minimizes the risk of introduction of disease agents and thus the need for chemical treatments. All wastewater leaving the facility has the potential to be treated and sterilized prior to discharge, and sludge is disposed of according to relevant regional regulations, indicating that the risk of active chemical compounds being released into the environment is low. While some select chemicals are known to be used in RAS, there is no evidence to suggest these compounds have deleterious effects on the environment. Specific data on chemical use in RAS is limited: however, the production system has a demonstrably low need for chemical use—as such the numerical score for Criterion 4–Chemicals is 6 out of 10.

**Justification of Ranking**

Within all aquaculture production systems, chemicals can be used for many different purposes, including (1) to control, prevent, and treat diseases and parasites, (2) for daily fish management procedures (e.g., reduce stress during transport, grading, and harvesting) and (3) to clean and disinfect the system itself. These chemicals can be broadly classified into several different groups: disinfectants (e.g., malachite green, hydrogen peroxide), parasiticides (e.g., benzoate, cypermethrim), anesthetics (e.g., isoeugenol, benzocaine), and antibiotics (e.g., oxytetracycline). Among these, disinfectants and anesthetics are considered to be of little risk to the environment—the main environmental concerns about chemical use in aquaculture focus on antibiotics and pesticides.

Due to the inherent isolation from the surrounding environment, RAS mitigate the risk of introduction of pathogens and parasites and thus minimize the need for chemical use. These systems exhibit effective treatment of the limited volumes of incoming water, as well as physical isolation from the surrounding environment and subsequent pathogens. RAS also have the ability to control pathogens using UV and/or ozone, and effluent can be treated and sterilized before being discharged. While these practices minimize both the risk of entrance of pathogens and disease agents into the system, as well as the release of active chemicals that may be used, RAS are still vulnerable to disease, and some minor chemical use is known to occur. All indications are that this use is low; however, robust data are not publically available. The following examples of chemical use in RAS have been gathered from farm managers through personal communications:

- Sodium chloride to reduce stress and control fungus during production.
- Hydrogen peroxide in the incubation and fry culture stages to control fungus.
- Chlorine for sterilizing tanks when empty and neutralized effluent prior to discharge.
- Very few instances of antibiotic use (e.g., oxytetracycline).

When utilizing chemicals in RAS, extreme caution should be practiced because water quality (i.e., dissolved oxygen, alkalinity, and amount of organic material in the water) could influence the toxicity of certain chemicals and vice versa. Additionally, chemical use may have significant consequences for the living bacteria population of the biofilter, and thus the use of chemicals is often a last resort when other management and husbandry protocols fail to address disease issues.

All wastewater leaving RAS can be treated prior to discharge, most commonly via ultraviolet (UV) filtration. This treatment serves to break down any active chemical compounds and thus minimizes the risk of releasing active chemicals (should they be used) into the environment.

RAS have a much greater 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. The limited volumes of discharge from RAS in addition to the capability to collect, treat, or otherwise control the discharge indicates that active chemicals are most likely not discharged, and as such the risk of environmental impacts from chemical use is low. While specific data on chemical use is limited, the production system has a demonstrably low need for chemical use, and therefore, the 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: Aquaculture operations source only sustainable feed ingredients, convert them efficiently and responsibly, and minimize and utilize the non-edible portion of farmed fish.*

**Criterion 5 Summary**

| | | |
|---|---|---|
| **C5 Feed Final Score** | **4.00** | **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 (or even green) scores for the feed criterion. Therefore, for this global multi-species RAS assessment, a low-moderate score of 4 out of 10 has been applied as a universal score to cover all species. If a species-specific Seafood Watch assessment is available with a red feed criterion score, the species-specific score will supersede this global recommendation and Criterion 5–Feed will be considered to be red for the ranking of this species in RAS. This RAS report can also be used as a template to accompany a species-specific feed assessment that results in a new species-specific report.

**Justification of Ranking**

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

The existing suite of Seafood Watch recommendations (Table 1) provides a list of data points for a variety of species that can be considered to be applicable to this assessment should that species be produced in a RAS. Due to ongoing global 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 (or even green) scores for the feed criterion as shown in Table 1.

Table 2. Feed scores for a variety of current Seafood Watch aquaculture assessments.

| Species | Region | Production Method | Feed Score | Feed Ranking |
|---|---|---|---|---|
| Atlantic Salmon | Norway | Net Pens | 5.2 | YELLOW |
| Atlantic Salmon | Chile | Net Pens | 4.2 | YELLOW |
| Atlantic Salmon | Scotland | Net Pens | 5.9 | YELLOW |
| Atlantic Salmon | British Columbia | Net Pens | 5.8 | YELLOW |
| Branzino | Canada | RAS | 6.75 | GREEN |
| Halibut | Canada | RAS | 2.98 | RED |
| Perch | United States | RAS | 5.41 | YELLOW |
| Pompano | United States | RAS | 5.09 | YELLOW |
| Pompano | Asia/ Dominican Republic | Net Pens | 2.38 | RED |
| Red Drum | United States | Ponds | 4.17 | YELLOW |
| Red Swamp Crawfish | China | Ponds | 9.75 | GREEN |
| Red Swamp Crawfish | United States | Ponds | 10.00 | GREEN |
| Shrimp | United States | Ponds | 3.35 | YELLOW |
| Sturgeon | United States | RAS | 3.59 | YELLOW |
| Tilapia | United States | RAS | 8.10 | GREEN |
| Tilapia | China | Ponds | 9.39 | GREEN |
| Tilapia | Ecuador | Ponds | 8.25 | GREEN |
| Tilapia | Taiwan | Ponds | 8.22 | GREEN |
| Tilapia | Canada | RAS | 6.55 | YELLOW |
| Trout | US | Net Pens | 5.22 | YELLOW |

Furthermore, the ability to highly control the culture conditions and feed application in RAS also results in a typical improvement in FCR over other commercial aquaculture production systems. For example, Losordo et al. (1998) concluded that tank systems generally yield better FCRs than pond systems. The table below shows several other scientific studies that demonstrate the improvement of FCR in RAS.

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 E. (2002) |
| Trout | 0.8 | 1.1 (FTS) | Roque d´Orbcastel et al. (2009) |
| Trout / Sturgeon | 0.43–0.80 | 0.73-0.84 (FTS) | Buric et al. (2010) |
| Salmon | 1.05 | 1.27 (net-pen) | Fisheries and Ocean Canada (2010) |
| Salmon | 0.8 | 1.2 (open flow system) | Aguila and Silva (2008) |
| Salmon | 1.09 | 1.27 (net-pen) | Sintef & Conservation Fund (2013) |

These studies give further confidence that poorer feed results for any given species are unlikely in a RAS situation, as compared to the feed results assessed in the existing suite of Seafood Watch reports.

Therefore, for this global all-species RAS assessment, a low-moderate score of 4 out of 10 has been applied as a universal score to cover all species. If a species-specific Seafood Watch assessment is available with a red feed criterion score, the species-specific score will supersede this global recommendation and Criterion 5–Feed will be considered to be red for the ranking of the species in RAS. If this is the only red criterion, the final overall ranking for this species in RAS will be “Yellow–Good Alternative” instead of “Green–Best Choice.”

# 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: Aquaculture operations pose no substantial risk of deleterious effects to wild populations associated with the escape of farmed fish or other unintentionally introduced species.*

**Criterion 6 Summary**

| Escape parameters | Value | Score | |
|---|---|---|---|
| F6.1 Escape risk | | 8.00 | |
| F6.1a Recapture and mortality (%) | 0 | | |
| F6.1b Invasiveness | | 6 | |
| **C6 Escape Final Score** | | **7.00** | **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. Any escapes that do occur are expected to have minor ecosystem impacts. While some species may be cultured in regions in which they are non-native, regulations restrict the culture of non-native species; as such, RAS culturing non-native species are expected to be either located in areas where escapees will not survive, or alternatively in facilities that have no connections to natural water bodies. The numerical score for Criterion 6–Escapes is 7 out of 10.

**Justification of Ranking**

**Factor 6.1a. Escape risk**

Recirculating aquaculture systems can be located 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). Because these systems operate with closed containments, they successfully isolate both water (see below) and fish from the surrounding environment (Summerfelt et al. 2013). Consequently, when designed and operated correctly, there is no risk of biological pollution or escapement from RAS (Labatut and Olivares 2004; Zohar et al. 2005; Leung and Dudgeon, 2008). This has been corroborated by several culturists and researchers (e.g., Bergheim, A., Blancheton, J., Henderson, T., personal communication), as well as in several published Seafood Watch assessments.

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. Nevertheless, from an operational perspective, natural disasters (e.g., floods), human errors and overflows, coupled with some systems' known connection to natural water bodies, indicate that escapes do occur in exceptional circumstances. As such, the score for the escape risk (Factor 6.1a) is 8 out of 10.

**Factor 6.1b. Species status and impact**

Factor 6.1b evaluates the native/non-native status of the farmed animals, as well as any ecosystem impacts of escapes. In order to be applicable to all species grown in RAS anywhere in the world, this assessment has adopted a realistic worst-case scenario of a non-native species. Regulations often restrict the culture of non-native species; consequently, non-native RAS farm stock is expected to be either (a) grown in an area where escapees will not survive or (b) in facilities that do not have connections to natural water bodies. For the purposes of this assessment, the farm stock is considered "highly unlikely to survive or establish viable populations." The numerical score for Factor 6.1b Part B is 2 out of 2.5.

Farmed fish that escape to the wild from aquaculture operations may have a variety of direct and indirect environmental impacts. These may include competition for food or habitat (i.e., predator pressure on native populations), competition for breeding partners (i.e., interbreeding with wild species or disturbing their breeding behavior), and the potential genetic modification of native wild stocks.

As a realistic worst-case scenario, escapes from RAS are expected to compete to some extent with native populations for food or habitat, as well as add some additional predation pressure on wild native populations. The score for Factor 6.b Part C is 4 out of 5.

A low escape risk (Factor 6.1a score of 8 out of 10) coupled with moderate invasiveness based on a realistic worst-case scenario (Factor 6.1b score of 6 out of 10) results in a Criterion 6–Escape score of 7 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: Aquaculture operations pose no substantial risk of deleterious effects to wild populations through the amplification and retransmission of pathogens or parasites.*

**Criterion 7 Summary**

| | | |
|---|---|---|
| **C7 Disease: pathogen and parasite Final Score** | **8.00** | **GREEN** |

**Brief Summary**

The opportunity for sterilization of incoming waters coupled with strict biosecurity protocols mitigates the risk of introduction of a disease agent into recirculating aquaculture systems. Furthermore, when applied, treatment of effluents limits the risk of the release of diseases from a RAS facility into the natural environment. While disease outbreaks in RAS have occurred and continue to pose challenges from a production perspective, the majority of outbreaks are shown to occur as a result of improper implementation of quarantine procedures. Despite the practical production challenges of disease in RAS, there is a low risk of environmental impact from the pathogens due to the limited connectivity of a land-based RAS with potentially vulnerable wild populations. As such, even though disease is a production issue within RAS, there is a low environmental concern and a high score. The score for Criterion 7–Disease is 8 out of 10.

**Justification of Ranking**

Disease outbreaks in aquaculture are a significant problem for the industry (Newaj-Fyzul et al. 2014), both from an economic perspective (losses due to mortalities and reduced marketability) as well as from an environmental perspective (spread of disease from farmed to wild populations). Nevertheless, RAS are relatively closed to the introduction of pathogens and parasites due to their ability to treat incoming water and the physical isolation they offer against the environmental pathogens compared to other systems that (1) are vulnerable to horizontal infection from wild fish (e.g., net pens systems), and/or (2) exchange large volumes of untreated water (e.g., open ponds). As such, RAS are considered to be more sheltered from the introduction of pathogens. Therefore, the likelihood of amplification or transmission to the wild is minimized.

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 (1) live fish, (2) feed, (3) incoming water, (4) employees. The treatment and filtration of incoming water, as well as the quarantine of new fish prior to introduction to the system, minimizes the potential introduction of pathogens.

These pathogens represent a continuous challenge in RAS, and in fact, may be a bigger challenge than in other production systems due to the very high stocking densities, stress levels, and the rapid spread of any pathogens that do enter recirculating systems. Opportunistic bacteria can affect stressed fish, and all RAS have opportunistic pathogens living among the host of microbial populations in a typical biofiltration unit. Controlling these pathogens to maintain healthy growing conditions for fish is a constant challenge, necessitating the use of components such as UV and ozone within the treatment systems, as well as other engineering requirements, such as the need for double pipework systems that allow specific sections of the system to be shut down and disinfected.

When properly managed, RAS reduce overall water consumption and improve control of many aspects of culture, such as nutrition, water quality, and health management (Yanong 2012). RAS allows producers to control the rearing environment and minimize potential introduction of pathogens by using water treatment and filtration, as well as rigorous husbandry techniques. However, improper management or other technical issues can create unstable water conditions and environmental fluctuations that often lead to suppressed animal immune systems and greater susceptibility to pathogens and disease outbreaks (Yanong 2012).

If a pathogen were to be introduced, both high fish stocking densities and favorable microbial growing conditions within the system can result in a rapid spread of disease (Thune and Schwedler 1991; Timmons and Ebeling 2013). Therefore, not allowing the pathogen to enter the system, followed by good health management procedures (i.e., stock containment, effluent treatment, disinfection/ hygiene practices, stock monitoring, record keeping, controlling staff movements, post-translocation quarantine, etc.) serve to reduce, but never completely eliminate, the risk of a disease outbreak. The design and engineering of the system can also inherently reduce the risk of the introduction of a pathogen; using a reliable water supply (groundwater when possible), treatment of the incoming water, and sterilization of the wastewater all work to reducing the risk of disease impacts.

Moreover, there are other general management practices that should be followed to mitigate the risk of disease: (1) if eggs or juveniles are purchased, they should be certified as “specific-pathogen free”; (2) feed should be stored and consumed according to the manufacturer´s recommendations; (3) both staff and visitors should follow biosecurity protocols strictly; (4) foot baths should be installed at entrance points, used by all individuals entering the facility, and changed periodically, and; (5) a quarantine room or facility for newly arrived fish should be constructed. On the other hand, if a pathogen is already present, practices to reduce pathogen spread include: (1) meticulous husbandry, which includes vaccination, optimum nutrition, and the overall reduction of fish stress; (2) culling when necessary, and; (3) the disinfection of equipment (Timmons and Ebeling 2013; Yanong 2012). All the above listed procedures require highly skilled operators who are capable of understanding all the possible biological, chemical, and technological interactions in a RAS and who are able to react rapidly on an unforeseen situation (Badiola et al. 2012).

Biosecurity in RAS, as mentioned in the previous criterion, differs from other aquaculture systems. As such, diseases in RAS mainly occur due to improper quarantine practices during fish introductions (i.e., diseases being introduced from outside the system; Timmons and Ebeling 2013). If good management practices are not followed, i.e., quarantine periods and general health management protocols, the whole system could be impacted. Industry-wide health management practices include (1) quarantine areas physically separated from (i.e., never in close contact with) growing systems, (2) direct employee traffic restricted from the quarantine area to the growing system, (3) quarantine areas in separate buildings, if possible (Timmons and Ebeling 2013).

Historically, few disease issues in RAS have been reported or published; however, some outbreaks have occurred and are outlined below:

1) Shrimp farming in ponds has been highly criticized for negatively impacting coastal environments, and viral pathogens have caused mass shrimp mortalities throughout the world. This prompted shrimp farmers and researchers to develop biosecure technologies to mitigate these diseases and RAS was successfully proven to be a potential solution (Otoshi, et al. 2003).

2) Noble and Summerfelt (1996) published a list of diseases encountered in rainbow trout cultured in RAS, concluding that disease concerns for each farm are unique due to different protocols and management practices.

3) Masser et al. (1999) listed particularly problematic diseases in RAS in general: (1) protozoal diseases Ich (*Ichthyophthirius*) and *Trichodina*, (2) bacterial diseases columnaris, *Aeromonas, Streptococcus,* and *Mycobacterium*, (3) *Trichodina* and *Streptococcus* diseases especially with tilapia, and (4) *Mycobacterium* with hybrid striped bass.

4) The author of this report facilitated an open request for information on disease outbreaks in RAS on a professional social network, which yielded the following additional examples: (1) salmon RAS systems in Chile have suffered from both IPN (2005) and ISA virus diseases, (2) complete shutdown of a striped bass production system in Florida due to disease, (3) a koi farm was shut down by the Aquaculture Disease Committee for a koi herpes virus (KHV). All respondents who provided information note that the majority of disease cases in RAS were due to external pathogen introduction from the incoming fish, which is consistent with the conclusions of Timmons and Ebeling (2013), who note that most disease issues in RAS are a result of improper quarantine procedures during the introduction of fish.

Despite the practical production challenges of disease in RAS, there is a low risk of transmission to wild populations due to the physical separation, the limited volumes of water discharged, and the ability to treat or otherwise control those discharges. Therefore, even though disease may be a production issue within RAS, there is a low environmental concern and a high score-the numerical score for Criterion 7–Disease is 8 out of 10.

# Criterion 8: Source of Stock–Independence from Wild Fisheries

***Impact, unit of sustainability, and principle***

- *Impact: The removal of fish from wild populations for ongrowing to harvest size in farms.*
- *Sustainability unit: Wild fish populations*
- *Principle: Aquaculture operations use eggs, larvae, or juvenile fish produced from farm-raised broodstocks, use minimal numbers, or source them from demonstrably sustainable fisheries.*

**Criterion 8 Summary**

| | | |
|---|---|---|
| C8 % of production from hatchery-raised broodstock, natural (passive) settlement, or sourced from sustainable fisheries | 100 | |
| **C8 Source of stock Final Score** | **10.00** | **GREEN** |

For the overwhelming 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 10 out of 10 has been applied as a universal score.

However, there are some select examples of wild-caught juveniles being reared to market size in RAS. One notable example is RAS eel aquaculture in Europe and Asia. Therefore,, if a species-specific Seafood Watch assessment is available with a red source of stock criterion score, the species-specific score will supersede this global recommendation and Criterion 8–Source of Stock will be considered to be red for the ranking of this species in RAS. If this is the only red criterion, the final overall ranking for this species in RAS will be “Yellow–Good Alternative” instead of “Green–Best Choice.”

# Criterion 9X: Wildlife and Predator Mortalities

*A measure of the effects of deliberate or accidental mortality on the populations of affected species of predators or other wildlife.*

*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**

| | | |
|---|---|---|
| **C9X Wildlife and predator mortality Final Score** | **-2.00** | **GREEN** |

**Brief Summary**

Tank-based RAS facilities provide physical separation of the culture area from the natural environment. While indoor RAS do not present any risk of wildlife interactions, outdoor facilities may present minor concerns in exceptional cases. As such, the score for Criterion 9X–Wildlife Interactions is -2 out of -10.

**Justification of Ranking**

Most RAS facilities around the world are fully enclosed buildings, although some may be constructed outdoors. For indoor systems, the interaction with wildlife is of no concern as all operations are physically separated from the surrounding environment, which completely eliminates any risk of wildlife and predator interactions. In contrast, in outdoor systems some predator-interaction issues may occur. To avoid these interactions outdoor tanks are usually covered by nets; water shooting mechanisms or acoustic deterrents may also be put in place.

Overall, while indoor RAS do not present any risk of wildlife interactions, outdoor facilities may present minor concerns in exceptional cases. As such, the score for Criterion 9X–Wildlife Interactions is -2 out of -10.

# Criterion 10X: Escape of Unintentionally Introduced Species

*A measure of the escape risk (introduction to the wild) of alien species other than the principle farmed species unintentionally transported during live animal shipments.*

*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 10X Summary**

| | | |
|---|---|---|
| **C10X Escape of intentionally introduced species** | **-2.00** | **GREEN** |

**Brief Summary**

International shipment of animals is common in the RAS industry—this represents a significant biosecurity risk and has been the cause of several disease outbreaks in RAS. However, these outbreaks are shown to be caused by lack of adherence to proper biosecurity and quarantine practices. Additionally, as all effluents have the capacity to be treated and sterilized prior to discharge, the risk of unintentionally introducing a live organism into the surrounding environment is low. As such, Exceptional Criterion 10X–Escape of Unintentionally Introduced Species is -2 out of -10.

**Justification of Ranking**

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 is a significant biosecurity risk (Timmons and Ebeling 2013). RAS are therefore considered to be 100% reliant on the movement of animals. While the appropriate quarantine of these animals prior to entering the system is essential, there remains some risk of the transfer of unintentionally introduced species.

In contrast to other aquaculture production systems, the technology-biology interaction and complex engineering designs of RAS indicate that several stringent biosecurity levels are present in a given facility, and as such these systems lower the risk of any unexpected species introduction. Thus, although most of the RAS production systems depend on external animal sources, this is compensated for by good biosecurity protocols for both origin (i.e., hatcheries) and destination (i.e., RAS facility where growout occurs). As such, the score for Criterion 10X–Unintentionally Introduced Species is -2 out of -10.

# Conclusion

Several years ago recirculating aquaculture systems were presented as one of the potential solutions to reducing many of the environmental impacts associated with other aquaculture production systems (i.e., net pens, ponds, and flow-through systems). As such, and as shown through the presented report, RAS represent a promising model for mitigating many of the direct environmental concerns associated with commercial aquaculture production.

For example, in RAS the majority of water is treated and reused as opposed to being discharged. These systems have the capability to treat and sterilize the relatively small volumes of effluents that are discharged. Therefore, these effluents present less environmental concern than large volumes released untreated. Additionally, the physical separation of the culture area and the surrounding environment mitigates many of the concerns over escapes and interactions with wildlife. The inherent isolation of the system from the surrounding environment, coupled with strict biosecurity protocols, decreases the risk of outbreak of disease and the subsequent need for chemical use. Feed remains an area of concern; however, these impacts are not specific to RAS but rather all aquaculture production, and the global trends toward decreased inclusion of raw marine ingredients, increased use of processing byproducts and crop proteins, and improvements in feed conversion ratios are expected to continue to reduce the concerns associated with feed use in aquaculture.

Energy use is identified as the single greatest environmental and economic cost associated with RAS, and future research and development should focus on reducing these costs and their subsequent environmental concerns. However, overall RAS are shown to be a promising method for reducing many of the environmental impacts associated with aquaculture worldwide, and as such, recirculating aquaculture systems should be further developed and supported by both the aquaculture industry as well as the global sustainable seafood movement.

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# Appendix 1 - Data points and all scoring calculations

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

## Criterion 1: Data quality and availability

| Data Category | Relevance (Y/N) | Data Quality | Score (0-10) |
|---|---|---|---|
| Industry or production statistics | *Yes* | 5 | 5 |
| Effluent | Yes | 7.5 | 7.5 |
| Locations/habitats | Yes | 10 | 10 |
| Chemical use | Yes | 5 | 5 |
| Feed | Yes | 5 | 5 |
| Escapes, animal movements | Yes | 10 | 10 |
| Disease | Yes | 5 | 5 |
| Source of stock | Yes | 10 | 10 |
| Predators and wildlife | Yes | 5 | 5 |
| Other–(e.g., GHG emissions) | Yes | 7.5 | 7.5 |
| **Total** | | | **70** |

| | | |
|---|---|---|
| **C1 Data Final Score** | **7.00** | **GREEN** |

## Criterion 2: Effluents

Effluent Evidence-Based Assessment

| | | |
|---|---|---|
| **C2 Effluent Final Score** | **9.00** | **GREEN** |

## Criterion 3: Habitats

**3.1. Habitat conversion and function**

| | |
|---|---|
| F3.1 Score | **9** |

**3.2 Habitat and farm siting management effectiveness (appropriate to the scale of the industry)**

**Factor 3.2a - Regulatory or management effectiveness**

| Question | Scoring | Score |
|---|---|---|
| 1 - Is the farm location, siting and/or licensing process based on ecological principles, | Moderately | 0.5 |

| | | |
|---|---|---|
| including an EIAs requirement for new sites? | | |
| 2 - Is the industry's total size and concentration based on its cumulative impacts and the maintenance of ecosystem function? | Moderately | 0.5 |
| 3 – Is the industry's ongoing and future expansion appropriate locations, and thereby preventing the future loss of ecosystem services? | Moderately | 0.5 |
| 4 - Are high-value habitats being avoided for aquaculture siting? (i.e., avoidance of areas critical to vulnerable wild populations; effective zoning, or compliance with international agreements such as the Ramsar treaty) | Moderately | 0.5 |
| 5 - Do control measures include requirements for the restoration of important or critical habitats or ecosystem services? | Moderately | 0.5 |
| | | 2.5 |

**Factor 3.2b - Siting regulatory or management enforcement**

| Question | Scoring | Score |
|---|---|---|
| 1 - Are enforcement organizations or individuals identifiable and contactable, and are they appropriate to the scale of the industry? | Moderately | 0.5 |
| 2 - Does the farm siting or permitting process function according to the zoning or other ecosystem-based management plans articulated in the control measures? | Moderately | 0.5 |
| 3 - Does the farm siting or permitting process take account of other farms and their cumulative impacts? | Moderately | 0.5 |
| 4 - Is the enforcement process transparent - e.g., public availability of farm locations and sizes, EIA reports, zoning plans, etc? | Moderately | 0.5 |
| 5 - Is there evidence that the restrictions or limits defined in the control measures are being achieved? | Moderately | 0.5 |
| | | 2.5 |

| | |
|---|---|
| **F3.2 Score (2.2a*2.2b/2.5)** | **2.50** |

| | | |
|---|---|---|
| **C3 Habitat Final Score** | **6.83** | **GREEN** |
| | Critical? | NO |

# Criterion 4: Evidence or Risk of Chemical Use

| Chemical Use parameters | Score | |
|---|---|---|
| C4 Chemical Use Score | **6.00** | |
| **C4 Chemical Use Final Score** | **6.00** | **YELLOW** |
| Critical? | NO | |

# Criterion 5: Feed

| | | |
|---|---|---|
| **C5 Feed Final Score** | **4.00** | **YELLOW** |

# Criterion 6: Escapes

### 6.1a. Escape Risk

| | |
|---|---|
| Escape Risk | **8** |

| Recapture & Mortality Score (RMS) | |
|---|---|
| Estimated % recapture rate or direct mortality at the escape site | 0 |
| Recapture & Mortality Score | 0 |
| **Factor 6.1a Escape Risk Score** | **8** |

### 6.1b. Invasiveness

**Part A – Native species**

| | |
|---|---|
| **Score** | 0 |

**Part B – Non-native species**

| | |
|---|---|
| **Score** | **2** |

**Part C – Native and Non-native species**

| Question | Score |
|---|---|
| Do escapees compete with wild native populations for food or habitat? | To some extent |
| Do escapees act as additional predation pressure on wild native populations? | To some extent |
| Do escapees compete with wild native populations for breeding partners or disturb breeding behavior of the same or other species? | No |
| Do escapees modify habitats to the detriment of other species (e.g., by feeding, foraging, settlement, or other)? | No |
| Do escapees have some other impact on other native species or habitats? | No |
| | 4 |

| | |
|---|---|
| **F 6.1b Score** | **6** |

| | | |
|---|---|---|
| **Final C6 Score** | **7.00** | **GREEN** |
| | Critical? | **NO** |

# Criterion 7: Diseases

| Pathogen and parasite parameters | Score |
|---|---|

| | | |
|---|---|---|
| C7 Biosecurity | 8.00 | |
| **C7 Disease; pathogen and parasite Final Score** | **8.00** | **GREEN** |
| Critical? | NO | |

## Criterion 8: Source of Stock

| Source of stock parameters | Score | |
|---|---|---|
| C8 % of production from hatchery-raised broodstock or natural (passive) settlement | 100 | |
| **C8 Source of stock Final Score** | **10** | **GREEN** |

## Exceptional Criterion 9X: Wildlife and predator mortalities

| Wildlife and predator mortality parameters | Score | |
|---|---|---|
| **C9X Wildlife and Predator Final Score** | **-2.00** | **GREEN** |
| Critical? | NO | |

## Exceptional Criterion 10X: Escape of unintentionally introduced species

| Escape of unintentionally introduced species parameters | Score | |
|---|---|---|
| F10Xa International or trans-waterbody live animal shipments (%) | 0.00 | |
| F10Xb Biosecurity of source/destination | 8.00 | |
| **C10X Escape of unintentionally introduced species Final Score** | **-2.00** | **GREEN** |