FISH WELFARE INITIATIVE

GUEST REPORT:

THE ENVIRONMENTAL IMPACTS OF FISH FARMING

By Massimo Bedoya, Guest Contributor

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Fish Welfare Initiative thanks Massimo for researching and writing this report. If you are interested in being a guest contributor with Fish Welfare Initiative, we encourage you to contact us.

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Summary

Aquaculture is a burgeoning industry whose historic and projected growth has important consequences for the environment as well as for fish welfare. This paper is intended as a summary of current knowledge on the various methods used to farm finfish and some important ways these practices create environmental harms and risks. The reader should gain a foundational understanding of the various common systems used to farm fishes, the differences between high- and low-intensity systems as well as between inland and offshore aquaculture, their implications for environmental impact, and a bit about the future of the industry and the importance of fish welfare.

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Introduction

Since modern fish farming's inception, the practice has grown at an astounding rate [1]. As of the early 2010s, aquaculture has produced more biomass than capture fisheries (aquatic plants included) [2], and its share of global finfish production is overtaking capture fishery production, contributing over 60% by 2030 [3, 5]. With the industry growing so quickly, it is important to ask what kind of effects it may have on the world around us. Aquaculture can impact the environment in several ways, and this analysis focuses on six important categories:

- Use of wild caught fishes for feed
- Diseases affecting wild fish populations
- Eutrophication
- Farm escapes
- Antibiotic use
- Energy use

Different fish farming techniques impact the environment in different ways. The four main methods are sea cages/pens, raceways, ponds, and recirculatory aquaculture systems (RASs).

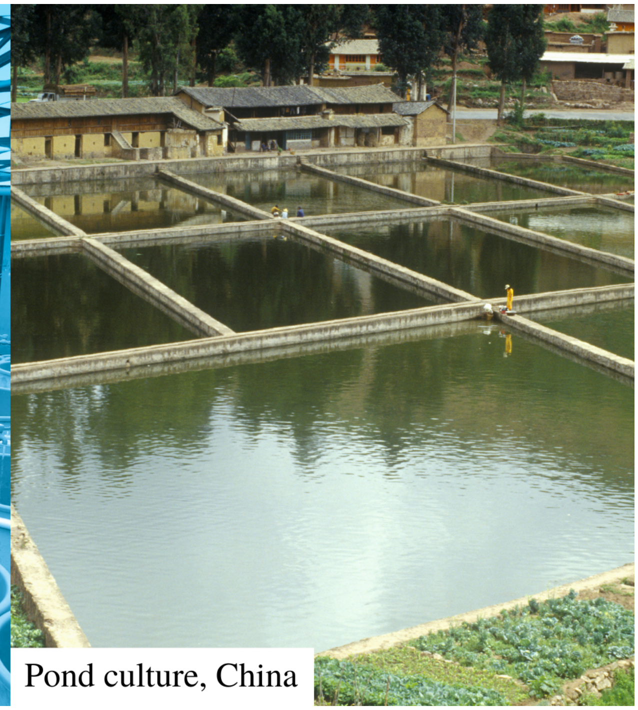
- **Sea cages**: Sea cages involve the use of a cage upheld by buoys in open water, typically for high-density growing operations.

- **Raceways**: Raceways are artificially constructed units, often surrounded by concrete, that receive water on one side and discharge it on the other. The flow of water is induced either naturally due to site inclination or manually through pumping [7].

- **Ponds**: Natural or man-made ponds are used to rear fish, usually in stagnant water [9]. This is likely the most ancient form of fish farming.

- **RAS**: This is a fully closed culture system where runoff water is treated, reoxygenated, and then reused in the culture tank. Pumps move water through the stages, and filters clean the wastewater [10].


RAS, Location Unknown

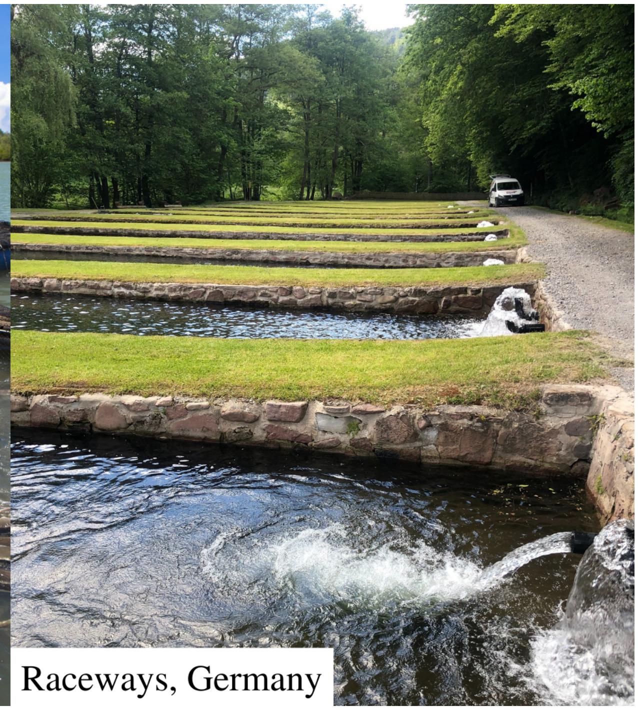

Pond culture, China

It is also important to keep in mind that the intensity of each system will affect its overall environmental impact. Intensity in the context of aquaculture refers to the amount of input (mainly feed, antibiotics, other agrichemicals, and oxygen) that is required to sustain the operation, as well as the stocking density of the culture.

Intensive farms often operate on a large scale with high stocking densities. They will have significant inputs and are entirely dependent on exogenous (i.e., added into their environment) feed to grow their stock. In contrast, extensive operations will use very little to no exogenous feed or oxygen, while a semi-intensive culture may use some feed, but as a supplementary rather than sole source of nutrients for the fishes. RAS cultures are more or less obliged to be intensive because their isolation from any surrounding water necessitates the use of feeds, oxygen, and chemicals. Cage cultures are typically also intensive, especially in western countries, having very high stocking densities within the cages, which require additional feed. Raceways and ponds tend to run more extensively or semi-intensively, especially in Southeast Asia, where the majority of fish farming is made up of smallholder operations and subsistence farms that favor less capital- and resource-intensive cultures.

This report will describe each category of environmental impact and how it flows from the farm to the environment. It will also suggest what configuration of culture type and intensity may result in the most harm and then briefly describe the differences between inland and offshore aquaculture and what unique impacts each might have.

Sea Cages, Vietnam



Raceways, Germany

Use of Wild Caught Fishes for Feed

One of the most important environmental concerns with aquaculture is the quantity of wild caught fishes used to feed captive populations. The environmental harms of capture fisheries have been well-documented and include the depletion of fish stocks, including stocks of ecologically important functional trophic groups [42].

Fish meal and fish oil (FMFO) are products made from the drying, milling, and pressing of whole fish or some by-products. Aquaculture is the largest consumer of FMFO in all sectors of animal husbandry [4] as it is one of the key ingredients of many aquafeeds. De Silva and Hasan (2010) estimated that 44.5% of the 2007 global aquaculture production was dependent on the supply of aquafeeds [16]. On top of this, industrial aquafeed production tripled to 27.1 million tonnes in the period from 1995 to 2007, [17] indicating a rapid trend in growth leading into the 2010s. It is noteworthy that even omnivorous species that can be fed a herbivorous diet are still fed aquafeeds, which adds more pressure to this already strained resource.

As a result of manufacturers innovating to replace animal ingredients in aquafeed and more raw materials being used for human consumption, it is estimated that the amount of FMFO used in aquafeeds will actually reduce in the long run [17]. This trend is likely necessary given that the aquaculture industry is expected to continue growing and capture fishery stocks may not be able to keep up.

When it comes to the use of wild fish for feed, we can expect that the culture system responsible for the production of the largest number of carnivorous fish, which consume the most FMFO, will make the greatest impact. So which system is this?

Although tilapia and carp are the world's most cultivated fish species [23], salmon, who are carnivorous [6], require feeds with a higher proportion of fish oil and meal [25,26,27]. Thus, in 1999, salmon were the highest consumers of both fish meal and fish oil [24]. Today, they remain the highest consumers of fish oil and the second-highest of fish meal (behind shrimp) at 43.2% and 14.8% of aquaculture FMFO supply, respectively [28]. Most salmon are hatched in land-based facilities like RASs before being transferred to sea cages after smolting (just before adulthood).

It should be noted that in RASs, feeding behavior and excess uneaten feed can be monitored and measured more easily by observing how much uneaten feed settles to the bottom of the tank, allowing operators to reduce overfeeding and wastage [18].

Another consideration is the fact that fish convert feed into biomass less efficiently when stressed [30]. **As a result, any system that compromises fishes' welfare leads to an increased need for feed to compensate for the efficiency loss.** This ultimately means that increased stress leads to more FMFO and, thus, more wild-caught fish being needed.

Diseases Affecting Wild Populations

The development, spread, and control of disease is a crucial consideration in all agricultural settings. The primary concerns for farmers are the economic cost of disease and the potential for zoonotic spread, but the environmental harm and risk that these diseases produce are substantial and will be explored in this section.

It is a well studied and documented phenomenon in terrestrial animal agriculture that high stocking densities are conducive to disease outbreaks [13, 14], which can spread to not only wild populations, but also to the humans who interact with the captive animals [49]. High stocking densities can also create selective pressures that favor the increased virulence of pathogens [21]. This same phenomenon occurs in aquaculture too. Of course, stocking density is not the only factor that contributes to the development of disease (we will explore antibiotic use later).

The extremely high density of intensive fish farms facilitates disease outbreaks [17, 21] and these diseases are liable to spread to natural populations, where they can increase mortality and morbidity [8]. In cage aquaculture, there is a constant interface between the captive fishes and the outside waters, meaning that pathogens can travel between captive and wild populations relatively unencumbered. In fact, wild fishes collected near fish farms are 16 times more likely to carry disease and parasites [29]. The constant interaction between wild and farmed fish populations in sea cages can even have a propagating effect wherein the farmed population infects the wild, and then the wild population will reintroduce the pathogen to the farm.

Pond, raceway, and RAS cultures have a theoretical advantage on this front as effluent points are built into these systems and can be designed with treatment systems in place [9, 15]. RASs will expel less water than ponds or raceways, but they are also the most densely-stocked systems, so it is difficult to say whether the net effect of these forces renders RAS more or less impactful on this front. Ultimately, cage aquaculture likely lends itself to disease development and propagation more so than any other culture technique.

It is important to note that having wastewater treatment potential is only an advantage insofar as it is actually practiced, and the extent to which it is practiced is difficult to know. Because the water used in fish farming is a common good, a “tragedy of the commons” phenomenon may occur whereby the shared duty of care for this resource is neglected in favor of greater short-term economic gains (avoiding the cost of establishing and maintaining wastewater treatment facilities frees up resources to invest in, say, pond expansion). Access–or lack thereof–to knowledge, resources, and infrastructure in regards to water testing and treatment will also be a barrier for many farmers.

Eutrophication

Eutrophication is the excessive enrichment of a body of water with nutrients and minerals. It is caused in large part by human activities, such as wastewater runoff from terrestrial agriculture. Many of the feeding mechanisms used for cage culture distribute pellets directly into the cages [11]. When this feed is uneaten, it can leach out of the cages and into the surrounding waters, eventually landing even on the sea floor. The resultant nutrient release can lead to phytoplanktonic or algal blooms, and oxygen depletion [12]. This issue typically persists in intensive or semi-intensive culture systems. As the industry grows, the dominance of the more feed-dependent intensive systems will continue to exacerbate the problem. Other issues such as over-fertilizing and wastewater effluent can also cause eutrophication as they increase the concentrations of nutrients and minerals in the water body.

Any open system, including ponds, sea cages, and raceways, risks this nutrient runoff, and its intensity is a crucial factor in its consequences. An intensive system, regardless of type, will necessarily administer more feed into its culture water and, therefore, may hold an inherent disadvantage in terms of eutrophication risk. While ponds, raceways, and RAS cultures may have the option to treat some of their wastewater, sea cages are practically unable to do so since they are openly situated in their environment.

Furthermore, as mentioned above, fish that are stressed feed less efficiently and leave more feed diffused in the water, thus increasing nutrient accumulation. It stands to reason, then, that one strategy to reduce the environmental risk of eutrophication is to enhance the welfare of the captive animals so that they feed more efficiently, leaving less uneaten feed in the culture and surrounding water as well as requiring less feed to begin with.

A farmed fish feeding on pelleted feed.

Farm Escapes

Escapes are a major issue in global aquaculture. In fact, in Europe from 2007-2009, 255 escape events were reported from sea cages alone, amounting to an estimated 9.2 million escapees [20]. In sea cages, individuals escape directly into the surrounding environment, and pond and raceway escapees may too find themselves in the nearest body of water. In RASs, it is effectively impossible for tank inhabitants to escape. The industry's growing scale makes concerns about farm escapes all the more pertinent. They can occur as major events like, for example, weather events, structural failure, or maritime collisions, or as a more consistent stream of low-volume escapes, also known as "leakage," for example in the form of holes in cages [19].

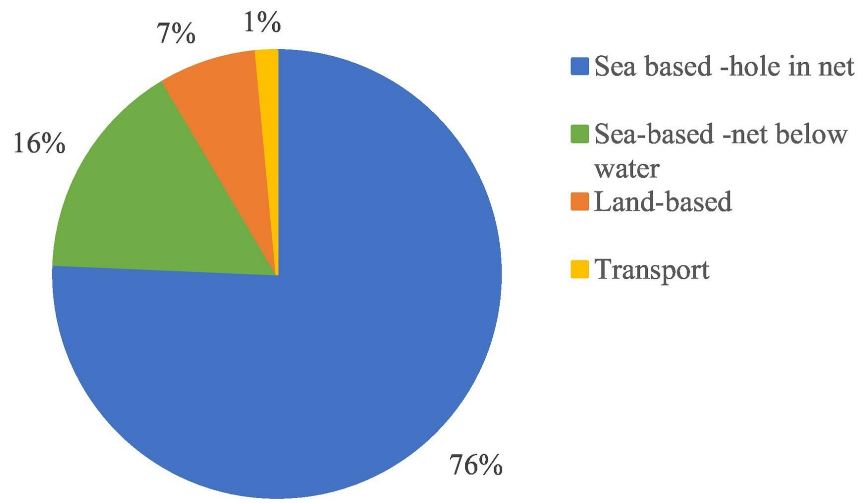
One important aspect of this issue is the potential for the genetic contamination of wild populations by escapees. It is hard to predict the fitness outcomes of such events on wild populations, but where there has been a recorded genetic effect on fitness from escaped Atlantic Salmon (Salmo salar), it appears to have always been negative in comparison to unaffected populations [8].

Where escapees are not native to the region, the risk of genetic contamination is instead replaced with risk of invasiveness [19]. There are many factors determining the invasive potential of a fish species, including the characteristics of the fish themselves and those of the environment in which they are farmed [19]. Invasive fish put excess pressure on native populations in the form of predation and competition for food and spawning grounds [9,19,20].

Finally, escapees also represent a massive potential vector for pathogens. As mentioned earlier, the high stocking densities of fish farms mean that pathogens can readily develop, and escapees can transmit these pathogens to wild populations and even to different species [21].

Thus, the culture system/s that are most at risk of escapes also represent the greatest risk of environmental harm. As it stands, the culture system most at risk of escapes is sea cages. An analysis of salmon and trout escapes in Norway from 2010-2018 found that a total of 92% of reported escapes occurred in sea cages, compared to 7% from land-based systems [50].

In ponds and raceways, escape events can be reduced by the implementation of measures including detention ponds (auxiliary ponds whose purpose is to contain potential escapees), increased distance from streams, fewer effluent points, and the use of control structures [22]. These techniques are impracticable in cage systems simply due to the nature of their construction and location. Furthermore, cages are located in open water where they are exposed to the risk of maritime collisions and predator damage. Double-netting, careful site selection, and frequently checking cages for damage and leaks seem to be the best strategies.



From Føre and Thorvaldsen 2020 [50]. Direct causes and location of fish escapes given as a percentage of the total number of escaped fish in the period 2010–2018. "Net below water" means the top of the net was below the surface of the water, allowing escape.

Antibiotic Use

One of the best-understood risks that antibiotic use poses to the environment is the development of antibiotic resistance (ABR). This phenomenon has been historically observed in other animal farming industries and is the result of antibiotics applying a selective force on the microbial community that favors resistance [32]. For example, there is a positive correlation between antibiotic concentrations in river waters and the number of antibiotic resistant E. coli [34]. One of the most severe environmental dangers of this phenomenon is that resistant strains of pathogens might cause unmanageable disease outbreaks that could leak into the environment and cause mass fish mortality.

Several human activities catalyze the process of ABR development. One of the earliest was the intensification of animal farming by way of increased stocking densities. **Higher stocking densities can necessitate the use of antimicrobials due to the increased risk of disease outbreak and to compensate for poor hygiene and sanitation, so the prophylactic (preventative) use of antibiotics has been a common practice in modern aquaculture since its beginning [40].** This creates an environment with a higher concentration of pathogens and antimicrobials alike, which leads to more pathogen-drug interactions, thus strengthening the selective pressure on the microbial community and the chances that resistant genes will defeat the pharmaceuticals and proliferate. This mechanism has been observed in terrestrial animal farms and also operates in aquaculture [41]. The process of ABR development can be accelerated by enhanced selective pressure from rampant prophylactic use and, in some instances, drug mislabeling [31].

Not only can these pathogens escape the culture system and affect wild populations (of both fishes and pathogens), but the drugs themselves may also leach into surrounding waters, either through uneaten feed or the excretia of treated fishes. It is estimated that 70-80% of the antibiotics administered as medicated pellets end up in the environment [33]. Pharmaceuticals in the surrounding waters can also impart changes to the diversity of the phytoplankton and zooplankton community [31]. Changes to such a foundational level of the food chain may have unpredictable impacts on the rest of the ecosystem.

It follows, then, that the culture systems that 1) use the most veterinary pharmaceuticals and 2) have the greatest exposure to the surrounding environment will generate the highest environmental risk, if not cause the greatest harm. In this way, intensive sea cage cultures may be the riskiest form of aquaculture.

Energy Use

Estimating energy use is a rather difficult task. Many factors contribute to the ultimate energy consumption of any given farm, including not only the culture system used but also its intensity level (intensive, semi-intensive, or extensive), the species being farmed, and the climate (cooler water can hold more dissolved oxygen) [35]. This means that two raceway cultures farming the same species at the same level of intensity but in different regions of the world might consume different amounts of energy. Complicating the matter further is the fact that the same culture systems, even at the same level of intensity and climate, can have different energy input requirements. This is because in low- to middle-income countries, machinery, which is relatively more expensive and less available, is often replaced with cheaper and more abundant human labor [36].

However, the most important factors in energy use are feed and level of intensity. Keep in mind that the energy inputs required to fish or grow the raw ingredients (FMFO or crops) are accounted for in the energetic cost of the feed, not just the energy it takes to transport and distribute it. There is a trend observed in the literature that feed and machinery (pumps, aeration, etc.) comprise the main energetic demands of any fishing operation, and as intensity and dependance on machinery increases (especially pumping), feed becomes a less significant component in the operation's overall energy demand [38, 39].

It is likely that RAS cultures have the highest intrinsic energy demand of any system because of their need for pumping, filtration, oxygenation, aeration, and temperature control [37]. While these features are by no means exclusive to RASs, their isolation from surrounding ecosystems means that any ecosystem service that would benefit a more extensive system, such as natural water flow, requires an alternative, usually one that is more energy-intensive.

Inland And Offshore Aquaculture

So far, we have used the term “aquaculture” to refer to both inland and offshore finfish farming. However, these categories are different and may carry their own unique impacts. offshore aquaculture here refers to aquaculture that takes place primarily in the ocean or estuaries. This includes sea cage aquaculture and the cultivation of aquatic plants and bivalves. inland aquaculture typically takes place more inland in tanks, ponds, freshwater cages, or raceways.

offshore cage aquaculture interfacing more directly with the environment means that feed, waste, antibiotics, other agrichemicals, and escapees can find their way into the environment more readily than from land-based cultures. inland cages can also be located in rivers or lakes, and wastewater from inland cultures may regularly find its way into natural bodies of water. So, the difference here might well be marginal, but the impact offshore cultures have on the surrounding waters may be harder to regulate.

Inland facilities (excluding inland lake cages) may be more removed from the natural water body, but they carry their own unique impacts. Building inland facilities can alter important natural flows of water. One such change is the reduction of the extent of flooding in wetlands [47], effectively reducing the areas’ ecological productivity. Altering environmental flows can also disrupt the life cycles of various species who use changes in flow as cues for life history events such as migration [47,48].

One thing that offshore cultures, like sea cages, and inland cultures, like inland ponds, share is that they both may create an “ecological trap.” [29] This happens when animals become attracted to an ecological niche that actually reduces their overall fitness, meaning they may survive and/or reproduce less successfully [46]. As an example, in 2012, Kloskowski observed that red-necked grebes (a type of predatory bird) who settled in ponds stocked with medium-sized carp in Poland suffered a higher egg-to-hatchling mortality rate than those who nested in unstocked ponds as the carp quickly became too large to eat and began to compete for non-fish prey [51].

Limitations

It is important to note that the environmental impacts considered here are by no means exhaustive. For example, the use of non-antibiotic agrichemicals and their downstream effects was not explored. Another potentially important consideration of fish farms is the amount of land required for each type. Data is not yet available on which culture systems take up the most space on land or at sea either on a per-farm or overall basis. But as the industry matures and intensifies, this could be an important consideration in terms of space usage trade-offs and also in terms of (visual) pollution and habitat destruction.

The four culture methods explored in this paper are also not the only options available to prospective fish farmers. For example, integrated multi-trophic aquaculture (IMTA) systems introduce lower trophic level organisms of commercial value, such as seaweeds and bivalves, into the culture system to utilize the waste products of finfish cultures and transform them into commercially valuable products [43]. Partridge et. al (2006) described a semi-intensive floating tank system (SIFTS) and demonstrated the concept in inland saline ponds in Australia [44]. Finally, aquaculture in China has traditionally been practiced as an integrated pond polyculture system involving other outputs, such as rice crops and other animals, and this is still performed in modernity [45]. IMTA, SIFTS, and integrated pond polycultures were outside the scope of this paper, but their potential environmental performance, especially on a large scale, is certainly an important question.

It is also important to recognize that the above analysis is liable to change as the industry continues to grow and mature. Inevitably, technology and innovation will continue to reduce waste and resource use and improve efficiency, thus ostensibly reducing aquaculture’s impact, at least on a per-unit basis. However, these efficiency gains will likely come as a result of intensification and homogenization. This comes at the cost of fish wellbeing and other externalities which, if internalized, may render these operations economically unsustainable.

Conclusion

It seems apparent that the single most important determiner of environmental harm is the intensity of a system. Intensive systems use multiple inputs in order to artificially increase their carrying capacity, allowing many more individuals to live in a given volume of water than would naturally be able to. When these inputs leak into the natural environment via effluent and wastewater, they can seriously disrupt ecosystems.

Furthermore, the high densities of intensive farming are highly conducive to pathogen development and, specifically, antimicrobial-resistant pathogen development. When cultures interact with surrounding waters, these diseases can then spread to wild populations as pathogens escape, sometimes via infected escapees. Unfortunately, the trajectory of the aquaculture industry points towards greater intensification under the pressure of rising global demand for fish meat.

It seems as though intensive cage cultures currently present the greatest environmental challenges out of the discussed systems. This is partly due to the fact that they are the most exposed to the surrounding environment and controlling what enters and leaves the cages is often not entirely possible. RAS cultures seem to have some environmental advantages but present higher barriers to establishment as well as require higher operating and maintenance costs. This could be a significant barrier to its adoption in many parts of the world until the technology becomes more affordable. RAS cultures are likely the most detrimental to fish welfare as they currently stand, but this is mainly due to pragmatic concerns such as stocking densities and management practices, and not necessarily an inherent feature of RAS cultures.

References

1. Our World In Data, 2020. Fish And Seafood Consumption Per Capita, 1960 to 2017. Online. Available at: <ourworldindata.org/grapher/fish-and-seafood-consumption-per-capita?tab=table&time=earliest..latest&country=~OWID_WRL?

2. The World Bank, 2021. Aquaculture Production. Online. Available at <https://data.worldbank.org/indicator/ER.FSH.PROD.MT>

3. World Bank, 2013. *Fish to 2030: Prospects for Fisheries and Aquaculture*. Washington DC: International Bank for Reconstruction and Development / International Development Association or The World Bank, p.40. Available at: <fao.org/3/i3640e/i3640e.pdf>

4. FAO, 2011. *Aquaculture development. 5. Use of wild fish as feed in aquaculture. FAO Technical Guidelines for Responsible Fisheries. No. 5, Suppl. 5*. Rome, FAO, p.79. Available at : <fao.org/3/i1917e/i1917e00.pdf>

5. FAO. 2020. *The State of World Fisheries and Aquaculture 2020.* Sustainability in action. Rome.

6. Tacon, A.G.J. and Halwart, M, 2015. Cage aquaculture: a global overview. *In* M. Halwart, D. Soto and J.R. Arthur (eds). *Cage aquaculture – Regional reviews and global overview,* pp. 1–16. FAO Fisheries Technical Paper. No. 498. Rome, FAO. pp.241. Available at <http://www.fao.org/3/a1290e/a1290e01.pdf>

7. Fornshell, G., 2019. *Raceways*. Extension [online] Available at <https://freshwater-aquaculture.extension.org/raceways/>

8. Ferguson, A., Fleming, I. A., Hindar, K., Skaala, Ø., McGinnity, P., Cross, T. F., and Prodhl, P. (n.d.), 2007. Farm Escapes. *In* Verspoor, E., Stradmeyer, L. and Nielsen, J,. *The Atlantic Salmon: Genetics, Conservation and Management.* Blackwell Publishing, pp.357–398.

9. Baluyut, E.A., 1989. *Aquaculture Systems and Practices: A Selected Review*. Ch. 4, Aquaculture Methods And Practices: A Selected Review. United Nations Development Programme, FAO, Rome. Available at < http://www.fao.org/3/t8598e/t8598e05.htm>

10. Murray, F., Bostock, J., and Fletcher, D., 2014. *Review of Recirculation Aquaculture System Technologies and their Commercial Application*. Stirling Aquaculture, Institute of Aquaculture, University of Sterling, Sterling.

11. Váradi, L., 1984. Chapter 19: Mechanised Feeding in Aquaculture. In *Inland Aquaculture Engineering*. Aquaculture development and coordination programme. United Nations Development Programme, FAO, Rome.

12. Mente, E., Pierce, G.J., Santos, M.B., Neofitou, C., 2006. *Effect of feed and feeding in the culture of salmonids on the marine aquatic environment: a synthesis for European aquaculture*. Aquaculture International 14, pp.499-522.

13. Tomley, F. and Shirley, M., 2009. *Livestock infectious diseases and zoonoses.* Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1530), pp.2637-2642.

14. Graham, J., Leibler, J., Price, L., Otte, J., Pfeiffer, D., Tiensin, T. and Silbergeld, E., 2008. *The Animal-Human Interface and Infectious Disease in Industrial Food Animal Production: Rethinking Biosecurity and Biocontainment*. Public Health Reports, 123(3), pp.282-299.

15. Natural Resources Conservation Service, 2003. Conservation Practice Standard, Fish Raceway Or Tank. *NRCS, NHCP*. Available at: <freshwater-aquaculture.extension.org/wp-content/uploads/2019/08/Fish_Raceway_or_Tank.pdf>

16. Hasan, M.R., Hecht, T., De Silva, S.S. and Tacon, A.G.J., 2007. *Study and analysis of feeds and fertilizers for sustainable aquaculture development*. FAO Fisheries Technical Paper. No. 497. Rome, FAO. 510p.

17. Tacon, A.G.J., Hasan, M.R., Allan, G., El-Sayed, A.-F., Jackson, A., Kaushik, S.J., Ng, W-K., Suresh, V. & Viana, M.T., 2012. Aquaculture feeds: addressing the long term sustainability of the sector. In R.P. Subasinghe, J.R. Arthur, D.M. Bartley, S.S. De Silva, M. Halwart, N. Hishamunda, C.V. Mohan & P. Sorgeloos, eds. *Farming the Waters for People and Food*. Proceedings of the Global Conference on Aquaculture 2010, Phuket, Thailand. 22–25 September 2010. pp. 193–231. FAO, Rome and NACA, Bangkok.

18. Lee, P.G. and Lawrence A.L., 2001. *Feed Management for RAS, part 2*. Global Aquaculture Alliance [Online}. Available at <aquaculturealliance.org/advocate/feed-management-for-ras-part-2>

19. Atalah, J. and Sanchez-Jerez, P., 2020. *Global assessment of ecological risks associated with farmed fish escapes*. Global Ecology and Conservation, 21, p.e00842.

20. SINTEF Fisheries and Aquaculture, 2013. *Final Report Summary - PREVENT ESCAPE* (Assessing the causes and developing measures to prevent the escape of fish from sea-cage aquaculture). *European Commission final report summary, Cordis*. Available at <cordis.europa.eu/project/id/226885/reporting>

21. Asher, C., 2017. *Does Farming Drive Fish Disease?*. The Scientist [online]. Available at <[the-scientist.com/news-opinion/does-farming-drive-fish-disease-31641>](the-scientist.com/news-opinion/does-farming-drive-fish-disease-31641)

22. Hill, J.E., Tuckett, Q.M., Martinez, C.V., Ritch, J.L., and Lawson, K.M., 2016. *Preventing Escape of Non-Native Species from Aquaculture Facilities in Florida, Part 2: Facility Evaluation Strategies.* Institute of Food and Agriculture Sciences, University of Florida.

23. Cai, J., Zhou, X., Yan, X., Lucente, D., and Lagana, C., 2019. *Top 10 species groups in global aquaculture 2017*. World Aquaculture Performance Indicators (WAPI) factsheet, FAO.

24. New, M.B. and Wijkström, U.N., 2002. *Use of fishmeal and fish oil in aquafeeds: further thoughts on the fishmeal trap*. FAO Fisheries Circular No. 975. Rome. 61 pp.

25. Lall, S.P., 2021. *Atlantic Salmon, Salmo salar.* FAO Fisheries and Aquaculture Department species profile, FAO/FIRA Aquaculture Service, FAO, Rome.

26. FAO, 2021. *Nile tilapia - Oreochromis niloticus*. FAO Fisheries and Aquaculture Department species profile, FAO/FIRA Aquaculture Service, FAO, Rome.

27. FAO, 2021. *Common carp - Cyprinus carpio*. FAO Fisheries and Aquaculture Department species profile, FAO/FIRA Aquaculture Service, FAO, Rome.

28. Tacon, A.G J., and Metian, M., 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. *Aquaculture,* 285(1-4), 146–158p.

29. Barrett, L. T., Swearer, S. E., & Dempster, T, 2018. Impacts of marine and freshwater aquaculture on wildlife: a global meta-analysis. *Reviews in Aquaculture.*

30. Gan, L., Liu, Y.J., Tian, L.X., Yue, Y.R., Yang, H.J., Liu, F.J., and Liang, G.Y., 2013. Effects of dissolved oxygen and dietary lysine levels on growth performance, feed conversion ratio and body composition of grass carp,Ctenopharyngodon idella. *Aquaculture Nutrition*, 19(6), 860–869pp.

31. Lulijwa, R., Rupia, E. J., & Alfaro, A. C., 2019. Antibiotic use in aquaculture, policies and regulation, health and environmental risks: a review of the top 15 major producers. *Reviews in Aquaculture.*

32. Cabello, F. C., 2006. Heavy use of prophylactic antibiotics in aquaculture: a growing problem for human and animal health and for the environment. *Environmental Microbiology*, 8(7), 1137–1144p.

33. Hektoen, H., Berge, J. A., Hormazabal, V., & Yndestad, M., 1995. Persistence of antibacterial agents in marine sediments. *Aquaculture*, 133(3-4), 175–184p.

34. Zhang, Q., Jia, A., Wan, Y., Liu, H., Wang, K., Peng, H., Dong, Z., and Hu, J, 2014. Occurrences of Three Classes of Antibiotics in a Natural River Basin: Association with

Antibiotic-Resistant Escherichia coli. *Environmental Science & Technology*, 48(24), 14317–14325p.

35. Kim, Y., and Zhang, Q., 2018. Modeling of energy intensity in aquaculture: Future energy use of global aquaculture. *Journal of Aquaculture, Fisheries & Fish Science* 2(1) ,p.60-8.

36. Troell, M., Tyedmers, P., Kautsky, N. and Rönnbäck, P., 2004. Aquaculture and energy use. Encyclopedia of energy, 1, p.97-108.

37. Badiola, M., Basurko, O. C., Piedrahita, R., Hundley, P., & Mendiola, D., 2018. Energy use in Recirculating Aquaculture Systems (RAS): A review. *Aquacultural Engineering*, 81, p.57–70.

38. Colt, J., Summerfelt, S., Pfeiffer, T., Fivelstad, S., & Rust, M., 2008. Energy and resource consumption of land-based Atlantic salmon smolt hatcheries in the Pacific Northwest (USA). *Aquaculture*, 280(1-4), p.94–108.

39. Hornborg, S., and Ziegler, F., 2014. Aquaculture and energy use: a desk-top study. *University of Gothenburg*. Available at: <gu.se/sites/default/files/2020-06/1536133_publication---energy-use-in-aquaculture.pdf>

40. Cabello, F. C., 2006. Heavy use of prophylactic antibiotics in aquaculture: a growing problem for human and animal health and for the environment. *Environmental Microbiology*, 8(7), p.1137–1144.

41. Xiong, W., Sun, Y., & Zeng, Z. 2018. Antimicrobial use and antimicrobial resistance in food animals. *Environmental Science and Pollution Research*, 25(19), p.18377–18384.

42. Lam, M. E., 2016. The Ethics and Sustainability of Capture Fisheries and Aquaculture. *Journal of Agricultural and Environmental Ethics*, 29(1), p.35–65.

43. Troell, M., Joyce, A., Chopin, T., Neori, A., Buschmann, A. H., and Fang, J.-G., 2009. Ecological engineering in aquaculture — Potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture*, 297(1-4), p.1–9.

44. Partridge, G. J., Sarre, G. A., Ginbey, B. M., Kay, G. D., and Jenkins, G. I., 2006. Finfish production in a static, inland saline water body using a Semi-Intensive Floating Tank System (SIFTS). *Aquacultural Engineering*, 35(2), p.109–121.

45. Chen, H., Hu, B., and Charles, A. T.,1995. Chinese integrated fish farming: a comparative bioeconomic analysis. *Aquaculture Research*, 26(2), p.81–94.

46. Robertson, B. A., and Hutto, R. L., 2006. A Framework For Understanding Ecological Traps And An Evaluation Of Existing Evidence. *Ecology*, 87(5), p.1075–1085.

47. Dugan, P., Sugunan, V.V., Welcomme, R.L., Bene, C., Brummett, R.E., and Beveridge, C.M., 2007. Inland Fisheries And Aquaculture. *Earthscan*. Online. Available at <https://hdl.handle.net/20.500.12348/1699>

48. Jonsson, N., 1991. Influence Of Water Flow, Water Temperature And Light On Fish Migration In Rivers. *Nordic Journal Of Freshwater Resources*, 66, p. 20-35.

49. Tomley, F. M., and Shirley, M. W., 2009. Livestock infectious diseases and zoonoses. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1530), p. 2637–2642.

50. Føre, H.M, Thorvaldsen, T., 2021. Causal analysis of escape of Atlantic salmon and rainbow trout from Norwegian fish farms during 2010-2018. *Aquaculture*, 532.

51. Kloskowski, J., 2012. Fish stocking creates an ecological trap for an avian predator via effects on prey availability. *Oikos*, 121(10), p. 1567-1576.