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Measuring and Mitigating GHGs:

Salmon

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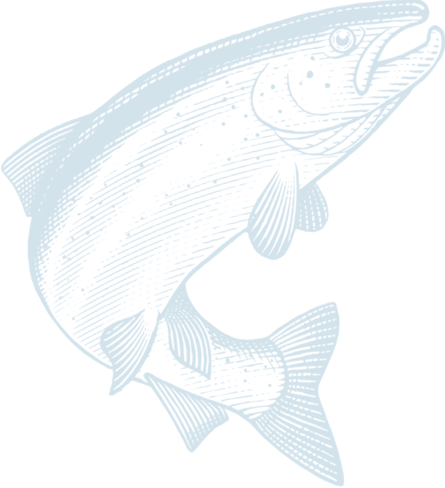
There are millions of farms globally, each using a unique set of practices to cultivate their products in the local climate and soil. Thus, for any commodity, there are many thousands of different production systems and many thousands of different sources of greenhouse gases (GHGs). The relative GHG emissions of producing the same product may differ drastically depending on how and where it is grown. To fully understand how to mitigate emissions and on which farms to focus mitigation efforts, we need a better grasp of the variations and gaps in data.

The authors do not think all the information to quantify GHG emissions from the salmon value chain exists – at the very least, not in one place. This document is our attempt to collate currently available information. This is a working draft; debate, discussion, and comments are welcomed to advance the understanding of this topic. WWF will be producing similar pieces on other key food commodities to stimulate similar discussions. All comments should be justified with evidence and data and sent to Emily Moberg at GHGcommodities@wwfus.org.



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ABOUT SALMON

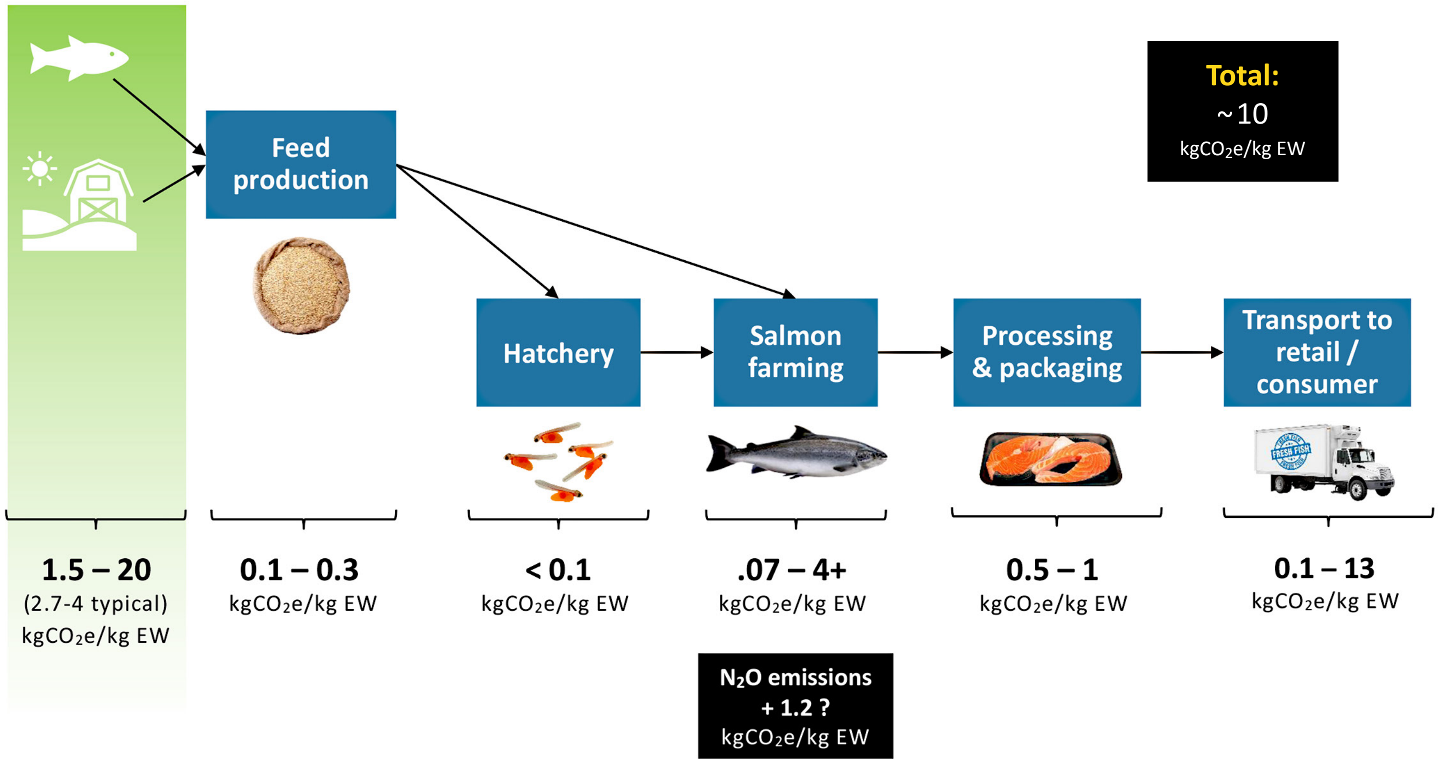
Salmon is a popularly eaten fish that comprises several species. Nearly 5 million tonnes liveweight of salmon are caught or reared each year globally; about 80% of this comes from aquaculture production. Salmon represent only about 3% of global aquaculture production but are economically important in several regions.[1] Salmon aquaculture is typically conducted in ocean net pens, although a few operations on land with recirculating water exist.

AQUACULTURE SALMON SUPPLY CHAINS

Salmon are initially reared in hatchery facilities, which are typically protected, tank-based systems. After reaching a larger size, the fish are moved to ocean net pens, where they are fed until they reach slaughter weight (around 5 kilograms). Feed is typically purchased in salmon-specific formulations, which vary widely in composition. Salmon are then killed, processed, and packaged. Salmon may be sold fresh, frozen, or pre-cooked and shipped around the world.

GHG EMISSIONS FROM AQUACULTURE SALMON SUPPLY CHAINS

Figure 1: Range of GHG emissions from aquaculture salmon supply chains



The emissions from salmon aquaculture are dominated by the emissions embedded in the feed salmon eat. However, on-farm rearing and transport also add to the overall footprint.

To retail, salmon emissions are likely between 7 and 10 $kgCO_2e/kg$ edible weight (EW), although that range could be as low as 2 or higher than 16, depending on how the salmon was produced, packaged, and shipped. To farm gate, emissions are typically around 6 $kgCO_2e/kg$ EW.[2]

This variability arises from variable emissions across each stage of production. The full range of impacts (in $kgCO_2e/kg$ edible meat) is shown below, with the typical range highlighted in darker orange.

Feed

The embedded emissions from salmon feed typically represent a majority of total emissions through retail – sometimes in excess of 90%.

Total feed emissions are a weighted average of embedded emissions per ingredient times the total amount of feed mix used. The total emissions intensity is the weighted average of embedded emissions times the feed conversion ratio.

The embedded emissions in a feed mixture are often between 1.5 and 3 kgCO_2e/kg feed. Feed composition varies, so we have summarized the emissions from four major categories of ingredients: crops, terrestrial livestock, fish, and micro-ingredients.

Terrestrial crop emissions: The cultivation of terrestrial crops releases significant GHGs. These emissions arise largely from the initial clearing of land (deforestation, conversion), production of fertilizer, emission of N_2O from soil, and energy for irrigation and farm vehicle use. The allocation of emissions to the different crop products (e.g., palm oil vs. palm kernel cake) is often done by economic allocation because of differing physical relationships between co-products' end uses.

The difference between the most and least intensive footprints for the same crop is often over 100 times. The highest GHG intensity typically arises from low-yielding production with high levels of LUC.

Table 1: Example crop emissions intensities

Cradle-to-farm-gate emissions for selected common crops
Units of kgCO_2e/kg edible crop. The main number indicates with LUC; parentheses indicate LUC contribution. Data from Poore and Nemecek (2018).

	Low-intensity	Average-intensity	High-intensity
Soybean	0.6 (0)	4.6 (3.2)	15.3 (14.3)
Wheat	0.1 (0)	1.0 (0.1)	48 (0)
Rapeseed oil	1.1 (0)	2.3 (0.03)	5.1 (0)
Maize meal	0.1 (0)	1.6 (0.9)	10.3 (10.1)

Terrestrial livestock product emissions: Terrestrial livestock production typically has higher embedded emissions than crops because the emissions from growing the feed consumed by the animals are added to emissions from manure decomposition, enteric fermentation, and electricity used for rearing the animals. However, the allocation of emissions to the main meat product versus by-products will dramatically lower the emissions embedded in a feed component.

Table 2: Example livestock emissions intensity

Approximate average GHG intensity for various livestock products
Data from MacLeod et al. 2020 in $kgCO_2e/kg$ carcass and the Global Feed LCA Institute (economic allocation) in $kgCO_2e/kg$ meal.

	Carcass emissions	Meal emissions
Beef	47	0.7
Pork	7	0.7
Poultry	3	1.2

Wild-caught fish emissions: The emissions from wild-caught fish originate largely from the fuel used by the harvesting vessel. On average, a kilogram of landed fish is responsible for 2.2 $kgCO_2e$; for fish intended for fish meal and oil, the average is 0.4 $kgCO_2e/kg$ landed.[3] Allocation of emissions to all the fish caught by a vessel in a trip and to processing by-products are both important in assigning emissions to fish meal and fish oil.

Note that emissions of carbon from the seafloor when bottom-trawling occurs may be a globally important source of emissions.[4] Given that forage fish are typically pelagic, we have excluded that emissions source here.

Micro-ingredient emissions: The emissions from these ingredients are poorly characterized, but some may be very emissions-intensive.

The embedded emissions in a feed mixture are often between 1.5 and 3 $kgCO_2e/kg$ feed; when feed conversion ratios are near 1.1 (a low FCR), this translates to 2.6 and 5.3 $kgCO_2e/kg$ EW of salmon. Higher feed conversion ratios push this number upward proportionally.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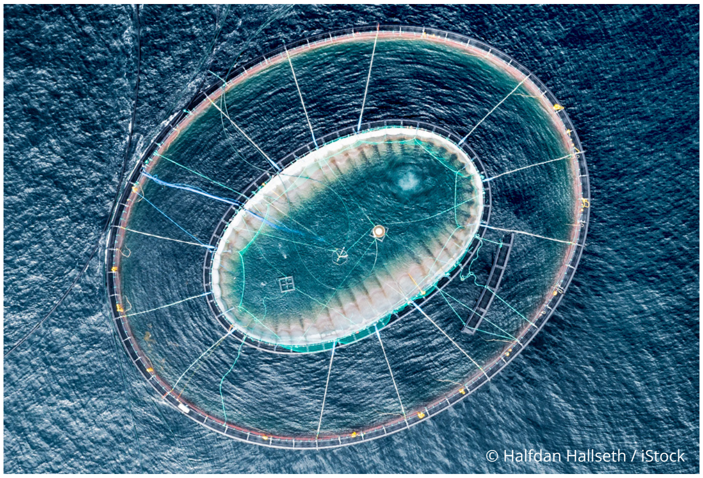
Hatchery

Hatchery emissions are not frequently included in published GHG footprints for salmon, often because emissions are assumed to be small. Ayer and Tyedmers characterized emissions from smolt production and found emissions across four systems well below 0.1 $kgCO_2e/kg$ EW;[5] a study of Canadian hatcheries[6] and life cycle screening for Norway[7] found similar values. Emissions from feed and electricity were the largest contributors.[8]

Farm/Grow-Out

Emissions from salmon grow-out for ocean-based systems come primarily from fuel and electricity use; the range of emissions was about 0.06 to 0.25 $kgCO_2e/kg$ EW.[9] Land-based recirculating systems can have much higher emissions (>3.5 $kgCO_2e/kg$ EW) depending on the yield and electricity mix.

Net pen infrastructure emissions are of similar magnitude to electricity use (0.1– 0.3 $kgCO_2e/kg$ EW);[10] the infrastructure for recirculating systems may be double. Boat infrastructure is rarely quantified.



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There is emerging biogeochemical evidence that aquaculture ponds increase the rate of methane[11] and N_2O emissions.[12] Recent estimates of 0.79 kgCO2e/kg liveweight from N_2O alone[13] suggest that the inclusion of these emissions may be a significant fraction of the total salmon footprint. These studies have not extended to ocean aquaculture. However, better incorporation of these biogeochemical estimates into a life cycle assessment framework to link how production decisions affect the magnitude of these emissions will be required before they can be credibly included. The inclusion of these emissions would be consistent with how waste is treated in terrestrial livestock systems.

Fuel and electricity use on farms add 0.06 – 0.25 $kgCO_2e/kg$ EW in ocean pen systems; the net pens themselves add a similar amount. Emissions of nitrous oxide are likely significant.

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Processing and Packaging

Few estimates of processing and packaging for salmon exist. Poore and Nemecek estimated salmon processing at about 0.1 $kgCO_2e/kg$ EW;[14] Fulton estimated processing at 0.1 – 0.3 $kgCO_2e/kg$ EW (depending on the electrical grid).[15]

Emissions from packaging arise largely from the materials used and are about 0.2 – 0.5 $kgCO_2e/kg$ EW.[16] Cans tend to have higher emissions (about 1.6 $kgCO_2e/kg$ fish),[17] while retort pouches range from about 0.3 – 0.6 $kgCO_2e/kg$ fish.[18]

Processing and packaging together add about 1 $kgCO_2e/kg$ EW to salmon's footprint, with more emissions in packaging.

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Transport to Retail/Consumer

Emissions from transportation depend on the distance traveled and mode of transport; aviation is over 10 times more GHG-intense for the same distance tonnage than trucking or watercraft. Life cycle assessments of transport emissions range from less than 0.1 to over 10 $kgCO_2e/kg$ EW. The low end was within Europe; values near 1 represent non-air travel to Asia, while values near 10 represent air travel to Asia (from Europe).[19] An average or typical value is not calculated, as this value would vary based on the origin of production, destination, and transit mode.


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PRODUCTION SYSTEMS

Most salmon are produced in ocean net pens, and the typical processes and values discussed here reflect that. There are few studies of land-based salmon aquaculture, but electricity use for recirculating water was very high in those studies; high survival and efficient feed use may produce lower GHG contributions from those processes, but the magnitude of impact for each is not available at the moment.

Different species of salmon do have different performance; for example, across salmon, cradle-to-retail emissions averaged 7.6 $kgCO_2e/kg$ EW for salmon and 11.4 $kgCO_2e/kg$ EW for trout species.[20] Differences in feed conversion ratio (FCR) and mortality seem to drive the differences in GHG intensity across species.

REGIONAL VARIATION

Regionally, salmon production varies mostly in the typical feed composition (and sourcing), local electrical grid, and mortality. Given the year-on-year and species level variability in mortality, differences across regions are likely smaller than these other sources. Operations far away from destination markets may also use more air freight than closer operations, which can also strongly influence GHG footprints.

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OUTLIER EMISSIONS SOURCES

The variability in emissions per kilogram of edible salmon highlights the large mitigation potential that exists across current practices. Here we highlight the "low hanging fruit," or practices that drive unusually high emissions intensity. These practices may be good targets for initial screening for improvement.

- **LUC in feed:** Emissions from LUC in feed are a major global source of emissions and contribute to salmon's overall footprint.
- **Optimized diet and feed use:** Improvements in animal health and productivity can have large mitigation potential.
- **Reduced air freight:** While the footprint of salmon tends to come from on-farm activities, when salmon are transported by plane, these emissions can eclipse the upstream emissions. Frozen product traveling by boat is much more GHG-efficient.

MITIGATION

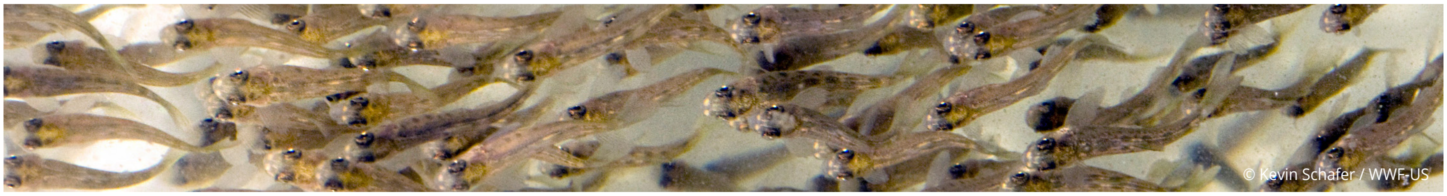
A selection of potential mitigation options is listed below. Mitigation potential is largely a function of current practices, so it was assessed qualitatively.

Table 3: Scope 1 and 2 Mitigation (for salmon farms)

Stage	Mitigation options	Mitigation potential
Salmon hatchery and outgrowing	Transition to renewable energy for electricity	Small — electricity emissions to 0, but current contribution is small
	Alter boat operation (incl. speed) to increase efficiency	Small to medium — lower fuel use can be offset by longer times on the water
	Improved FCR and low mortality	Large — the amount of feed eaten multiplies the GHG embedded in feed, but benefits accrue mostly to Scope 3 since less feed is used
Slaughter/filleting/packaging	Transition to renewable energy for electricity	Small — electricity emissions to 0, but current contribution is small
	Reduce salmon waste (beneficial use for trimmings, etc.)	Small — if trimmings, etc., are currently wasted, the allocation of some production emissions to a by-product could decrease emissions to the fillet

Table 4: Scope 3 Mitigation

Stage	Mitigation options	Mitigation potential
Feed cultivation	Deforestation and conversion-free sourcing	Large — LUC emissions are large for many crops, including soy
	Better cultivation practices	Large — the difference between average footprints and low footprints is often around 50%
	Reduce proportion of product transported by air (e.g., flash freezing)	Large — air freight is much more GHG-intensive than shipping



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TOOLS AND DATA AVAILABILITY

GHG emissions from salmon are relatively poorly characterized relative to terrestrial animal products. In particular, the emissions from decomposition of feces and feed are highly uncertain, and how aquaculture practices influence those emissions is not well studied. Despite most emissions occurring on farms, relatively few tools for on-farm calculations are available.

There are several tools that are in pilot or test versions:

- **FISH-e:** This is the Food and Agriculture Organization's tool for quantifying aquaculture GHG emissions (https://www.fao.org/fishery/affris/affris-home/fish-e-faos-tool-for-quantifying-the-greenhouse-gas-emissions-arising-from-aquaculture/en/). This is an Excel-based tool that uses local feed compositions and on-farm energy use to calculate a footprint.
- **Blonk and IDH tool:** Blonk Consultants has developed a pilot tool for select aquaculture species, including salmon. This tool includes feed, pond off-gassing, and energy use.

There are relatively few studies and tools available for GHG assessment in seafood; there are fewer still focused on salmon specifically. The table below summarizes the contribution of seafood to different categories of GHG emissions. Because seafood is rarely considered, the emissions from seafood are essentially "hidden" in other categories.

Table 4: GHG emissions from selected sectors

	Total emissions ($GtCO_2e/yr$)	Seafood's contribution ($GtCO_2e/yr$)
Agriculture-driven LUC	4.9	**0.13–0.24[21] (aquaculture feed)**
Agriculture	6.2	
Non-agriculture, forestry and other land use (AFOLU) food emissions	2.6–5.2	**?**
Maritime fuel use	1.1[22]	0.18–0.38[23] (capture fisheries' fuel)
Aquatic biogenic	?	**? pond emissions** **1.47 (trawling)[24]**
Global total	52	0.435–0.866 (aq. and w.c. to dock)

The relevant categories for salmon aquaculture are highlighted.

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Seafood is also poorly represented in global food and climate models, so the trade-offs between increased seafood consumption relative to terrestrial foods are not well characterized. However, we do know that the emissions intensity of seafood must decrease regardless of the what proportion of diets it comprises. In 2019, the global emissions intensity of animal & plant source protein was about 75 tCO_2e/t of protein. If the per capita protein consumption stays the same but the population increases, a 30% reduction of GHG intensity will be required to keep overall emissions the same as they are today. Protein production must decline to 14 tCO_2e/t protein to reduce emissions down to about 4 $GtCO_2e/yr$, which is what current modeling[25] suggests the food sector needs to be limited to by 2050. *This suggests the maximum emissions intensity from seafood will be about 14* tCO_2e/t *protein, which is at least triple the current intensity of salmon.*

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CITATIONS / FOOTNOTES

1. FAO FishStat, averaged over 2017–2019.
2. Gephart et al.'s (2021) blue foods analysis calculated this footprint at 5.1 kgCO_2e/kg EW but excluded potential N2O emissions, which are poorly quantified for ocean aquaculture. MacLeod's footprint (2020) was 3.2 kgCO_2e/kg liveweight, or about 6.3 per EW.
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22 Fourth IMO Greenhouse Gas Study. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf.

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