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Environmental footprints of farmed chicken and salmon bridge the land and sea

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Summary

Food production, particularly of fed animals, is a leading cause of environmental degradation globally. Understanding where and how much environmental pressure different fed animal products exert, is critical to designing effective food policies that promote sustainability. Here we assess and compare the environmental footprint of farming industrial broiler chickens and farmed salmonids (salmon, marine trout, Arctic char) to identify opportunities to reduce environmental pressures. We map cumulative environmental pressures (greenhouse gas emissions, nutrient pollution, freshwater use, and spatial disturbance), with particular focus on dynamics across the land and sea. We found broiler chicken production disturbs nine times more area than salmon production (~924,000 km^2 vs. ~103,500 km^2) but yields 55 times greater production. The footprints of both sectors are extensive, but 95% of cumulative pressures are concentrated into <5% of total area. Surprisingly, the location of these pressures is similar (85.5% spatial overlap between chicken and salmon pressures), primarily due to shared feed ingredients. Environmental pressures from feed account for >78% and >69% of cumulative pressures of broiler chicken and farmed salmon production, respectively, and could represent a key leverage point to reduce environmental footprints. The environmental efficiency (cumulative pressures per tonne of production) also differs geographically, with areas of high efficiency revealing further potential to promote sustainability. The propagation of environmental pressures across the land-sea underscores the importance of integrating food policies across realms and sectors to advance food system sustainability.

Results and Discussion

Mapping cumulative pressures of farmed chicken and salmon

We spatially assess cumulative environmental pressures of broiler chicken and farmed salmonids (salmon, marine trout, Arctic char, hereafter referred to as salmon) based on data from Halpern et al. (2022)[1]. Industrial production of broiler chickens and farmed salmon represent two of the largest animal-sourced food sectors in their respective realms (land and sea), offering a compelling case study of production trajectories and environmental footprints. Chicken and salmon are also similar in lean protein quality[2 3] and are relatively environmentally efficient[2,4,5] with low feed conversion ratios (FCRs)[6–8] due to intensive selective breeding, feed specialization, and improved production technologies (i.e., combined domestication).

We calculate the cumulative pressures index (CPI), which represents the proportional contribution of each cell to the total global pressures from chicken and salmon production (maximum CPI for a cell: 0.00035 for chicken; 0.00016 for salmon; with the sum of all cells equaling one, Fig. 1A and B). Both chicken and salmon have vast spatial footprints (Fig. 1), however, 95% of total CPI is concentrated within <5% of cells for both sectors. Areas with high CPI occur across terrestrial regions of the Midwest of the United States, Brazil, Europe, India, and China for chicken (Fig. 1A). For salmon, these areas are found across most coastal areas (particularly the east coast of South America, western Africa, India, China, and Southeast Asia), the North Sea, and large areas of the Pacific Ocean, with terrestrial areas across Europe and the Americas (Fig. 1B). In fact, just 20 countries account for 75% of CPI and 68% of production across both salmon and chicken sectors (Fig. 2), with only the United States having high CPI in both sectors. Determining the drivers of these spatial distributions can help determine patterns and leverage points for reducing and managing these pressures, as well as assing their impacts on nature and people.

Feed drives overlap of cumulative pressures

Feed composition drives the geographic distribution and displacement of pressures and CPI from both sectors across jurisdictional and ecosystem boundaries (Figs. 1 and 2). While nearly all of chicken CPI occurs on land (>99%), the majority of countries (N = 171 of 244) produce CPI from chicken on both land and sea due to the 527,300 tonnes of fishmeal and fish oil (FMFO) used in commercial chicken feed[13]. Total CPI from chicken production is highest in the United States, China, and Brazil for land CPI, and off the coasts of Chile, Mexico, and China for marine CPI. Salmon pressures are more varied, with 14% of CPI on land due to salmon aquaculture currently consuming 2.3 million tonnes of crops for feed[14–17]. This largely consists of oil crops, soybean, and wheat[18]. Norway has by far the largest marine CPI for salmon production while Chile and Canada have the largest land CPI.

Land-sea feed interdependencies result in substantial CPI overlap for chicken and salmon (85.5% of cells with chicken or salmon CPI>0, Figure 1C). Overlap is greatest in areas where both chicken and salmon CPI are at low (0-45th quantile) or medium levels (45-90th quantile) (43.7% of overlapping cells, Fig. 2). Feed accounts for >78% of broiler chicken's CPI and >67% of farmed salmon CPI, highlighting the significance of off-farm pressures embedded in fed animal production. Nearly all pressure from spatial disturbance and freshwater use are driven by feed production for both sectors. Indeed, 100% of freshwater use of salmon is from feed given that on-farm water is assumed to be released back into the catchment. Both sectors show similar patterns for GHG emissions, with >55% of emissions originating from feed activities. Notably, only 8% of salmon nutrient pressures result from feed practices (i.e., 92% originate from on-farm production) compared to 60% for chickens. In the future, pressures from feed are likely to continue to become more terrestrially based as the price of fish meal increases, raising the question of whether the demand for land or marine feed resources are more sustainable, particularly given shifting diets and consumer preferences[17,18].

Comparing environmental efficiency of production

Global chicken production is over 55 times greater than salmon (130.8 vs. 2.4 million tonnes slaughter weight, respectively), logically leading to higher pressures and CPI. However, compared to these levels of production, for three of four pressures, chicken production is more efficient, resulting in only 8.9 times more spatial disturbance than salmon, 20 times higher nutrient pollution, and 38 times greater GHG emissions. Freshwater use, however, was considerably less efficient (135 times greater), again due to the assumption that on-farm water use for salmon production is released back into the catchment[19]. One factor contributing to these efficiencies is the very fast reproductive cycle of chickens compared to salmon: 6-7 chickens can typically be produced in the same location in a given year, taking 6-8 weeks to reach slaughter weight[20,21]; whereas salmon take 12-24 months to reach slaughter size, excluding the land-based, freshwater period[22].

Looking at feed efficiency, our metric shows that feed production from crops is more environmentally efficient than for FMFO for both chicken and salmon. This pattern is driven by disturbance and GHG emissions as FMFO has zero pressures for nutrients and water. We believe this unintuitive result is driven by several factors including the inclusion of ocean disturbance in our analysis and the diffuse nature of FMFO compared to crops. There is a great deal of uncertainty in estimating disturbance in fisheries due to a lack of knowledge about underlying biomass and how to scale fishing practices into a metric of disturbance. Finally, this metric doesn't account for the quality of the feed, which is likely much higher for FMFO.

Notably, other life-cycle synthesis studies have found that salmon outperforms chicken across these pressures[23–25], due to varying assumptions and model parameters. There are several major differences to consider that we briefly describe here. We estimate that salmon have somewhat higher GHG estimates, which is largely because we include on-farm N_2O emissions produced by microbial nitrification and denitrification of faecal matter in our estimates. For salmon, N_2O emissions are likely substantial, and, in our estimates, account for over 80% of on-farm GHG emissions. This input is often not included in aquaculture GHG estimates because it is very uncertain and extremely variable across farms[78]. Second, for chicken nutrient estimates, we only consider "excess" nutrients that we define as the proportion of the nutrient load that leaches, runs-off, or volatilizes into the system whereas other studies consider total nutrient loading (i.e., all nutrients excreted by the animal). Finally, as mentioned above, our measure of disturbance estimates both land and sea use, which accounts for the large footprint of capture fisheries in FMFO production, making it difficult to compare to studies that only measure land use. Further work to reduce uncertainty, particularly in GHG emission estimates, would help to better understand differences between these sectors, which are both highly efficient compared to other animal protein sources.

On-farm and feed-production efficiencies vary geographically for both chicken and salmon production (Fig 3). On-farm environmental efficiency of chickens in the United States (the largest producer of chicken) and Brazil (2nd largest) are more efficient than China (3rd largest). While Brazil and the U.S. are similar for each pressure relative to production, Brazil has slightly lower spatial disturbance, GHG emissions and water use, while the U.S. has lower nutrient pollution, likely due to manure management and/or differences in dietary composition. China, on the other hand, has substantially lower efficiencies for on-farm water use and nutrient pollution – highlighting key improvement areas that could increase overall efficiency of production. For salmon, the top five producers have similar on-farm efficiencies despite large differences in production amounts (Norway produces nearly 15 times more than Faroe Islands, the 5th largest producer). Chile has the highest on-farm CPI per tonne production, while the U.S. has the lowest – a 2-fold difference, despite Chile producing nearly 40 times more salmon. It appears that salmon production can scale very efficiently relative to on-farm environmental pressures.

The United States, Brazil and China are also the largest producers of chicken feed, with production almost entirely (>99%) made up of crops. Feed efficiency (CPI per tonne feed production) trends in these top-producing countries follow the same pattern as on-farm efficiency. The largest producers of salmon feed are Peru, Norway, and Chile, with Peru and Norway producing mostly FMFO and Chile producing predominantly crops. Interestingly, Norway's feed production efficiency is 1.8 times that of Peru, despite similar production levels. This is because in Peru <1% of salmon feed production is crops, compared to ~24% in Norway.

High total CPI in a country can result from low pressure over a larger area, or higher pressures within a more concentrated area. To disentangle this, we compared total CPI with CPI footprint (# of pixels) within each country (Fig. 4). We removed the bottom 5th percentile of pixels with CPI in each country to compensate for likely area overestimation, as it is difficult to determine area used to produce feed specifically for chicken and salmon (as opposed for other fed production types). Russia is ranked 7th globally for chicken CPI and 4th for chicken production, which is spread across 78% of all pixels in Russia (~360,000 pixels), while the CPIs of the United States and China (the two highest CPIs) account for 79% (~217,000 pixels) and 92% (~183,000 pixels) of all pixels, respectively. For salmon, Brazil, the United States, and Russia have lower CPI across a larger area compared to Norway, Chile, and the United Kingdom. Notably, the U.S., Brazil, Norway, and Chile have salmon CPI across ~70% of cells within the country while Russia is only 30% and the United Kingdom is 95%. Determining the conditions that lead to different production practices and higher efficiencies in some locations over others, both between and within countries, can be leveraged to improve efficiencies – benefiting both production levels and the environment.

Developing sustainable food policies

The small overlap of high and medium-high CPI values for both chicken and salmon present two options for reducing environmental impacts of these sectors: 1) strategic mitigation in high pressure areas from both sectors, or 2) designating areas as high-pressure zones in order to focus mitigation efforts in places where pressures may be easier to alleviate. Additionally, overlaps in environmental footprint demonstrate the potential for resource competition between sectors that could have inequitable and perverse outcomes if left unregulated[26]. For instance, there are few guidelines on how water rights should be distributed among food production sectors as limited water resources become scarcer (e.g., the food-energy-water nexus)[26–28], even leading to large scale land acquisitions to secure water resource rights for agriculture production (i.e., 'water grabbing')[29,30]. Currently, agriculture, aquaculture, and fisheries remain in separate policy, regulatory and research silos, meaning that these often complex and unintuitive overlaps are not explicitly considered by decision makers or consumers. Our analysis reveals these areas of overlap and can be used to further examine resource use and guide these policy decisions.

Feed offers a key leverage point for reducing CPI of these food sectors. For example, closing yield gaps of feed crops can reduce per-unit pressures, most obviously for disturbance, but also for GHG emissions and nutrient use[31]. Other site-specific interventions, like optimized application of irrigation water and/or location of feed production, can also reduce CPI, often while maintaining or increasing yields (e.g.,[32]). Feed composition and FCRs are important factors in this equation. For industrial broiler chickens, it is unlikely that FCR and reliance on crops for feed will shift dramatically in the coming years, since diet optimization has been a strong focus of increasing efficiency and sustainability of poultry production for decades[33]. However, salmon aquaculture diets are continuing to evolve, with a strong push to reduce the inclusion of wild-caught fish products due to increasing prices and poor social acceptance[34–36]. Shifts to more crop-based feed would increase the overlap, and thus potential for resource competition of chicken and salmon by increasing shared feed inputs such as soy and corn, but will be mediated by both technological innovations (e.g., protein concentrates, scaling of recirculating systems) and market forces (e.g., shifts towards pescatarian diets, crop shortfalls)[17,18]. Continued advances in aquafeed manufacturing and novel circular feed ingredients (e.g., from waste streams and trimmings), will help lower salmon CPI, improve feed efficiency, and reduce intersectoral competition[17,37,38]. Indeed, CPI estimates for forage fish here likely overestimate current pressures from FMFO use due to an increasing proportion coming from fish trimmings rather than wild capture. Greater support for and adoption of certification schemes that account for environmental context of pressures embedded in feed production will also help. In terms of on-farm pressures, minimizing on-farm nutrient leaching through manure management and optimized stocking rates and feeding regimes, as well as reducing GHG emissions, would result in the greatest reduction to CPI for chicken and salmon.

When assessing ways to reduce CPI and improve environmental sustainability, policies should also consider leverage points that can benefit people and organisms. A One Health approach, which recognizes the links between human health and the health of farmed animals and the environment, could help assess and balance environmental and socio-economic outcomes from management decisions and improve consumer trust when implementation is properly measured and communicated[39–41]. This holistic view could help salmon aquaculture contribute to human nutrition, while minimising pathogen spill over, and environmental degradation[41]. For chickens, such an approach may provide innovative solutions to pollution concerns (soil, water, air, and noise) that can impact organism, worker, and environmental health[39,40]. Additional work is urgently needed to translate CPI into assessments of on-the-ground environmental impacts on nature and people[42,43] to better account for trade-offs.

Spatially mapping the CPI of these two food sectors represents an important step towards sustainable food policies that, ultimately, need information about the location, magnitude, and drivers of CPI for any given food production sector. Future consideration of additional pressure categories (e.g., acidification potential, plastic pollution), pressure sources (e.g., packaging and processing, post-consumer waste), and potential production trajectories will further understanding of how and where different environmental pressures to identify potential solutions. Future work should explore the implications of the relative magnitude of individual pressures on environmental outcomes, as we consider all pressures in this analysis to be of equal importance. This is particularly important given that the realized impacts from CPI may be more reliant on spatial context than pressure magnitude due to underlying environmental and social vulnerabilities[43]. We urge researchers, consumers, and policy makers to shift the thinking around fed animal production as being “terrestrial” and “aquatic”, but rather as fitting on a continuum, exhibiting both reliance and pressure on a huge number of environments and production systems. Integrating food policy across realms and across sectors will be critical for optimizing and achieving sustainability across the global food system now and in the future.

Author Contributions :

Conceptualization: all authors contributed to the conceptualization of the project.

Methodology: MF, JV, PER, CDK, BSH with feedback from all authors

Software: MF, JV, PER, CDK

Validation: MF, JV, PER

Formal analysis: MF, JV, PER, CDK

Investigation: MF, JV, PER, CDK

Data Curation: MF, JV, PER

Writing – Original Draft: CDK

Writing – Methods: MRF, JV, PER, CDK

Writing – Review and Editing: BSH, RSC, HEF, DRW, MF, KLN, JAG, PBM, JT provided substantial revisions, with final approval from all authors

Visualization: MF, CDK, JV, PER with feedback from all authors

Supervision: BSH

Project administration: MF and BSH

Funding acquisition: BSH

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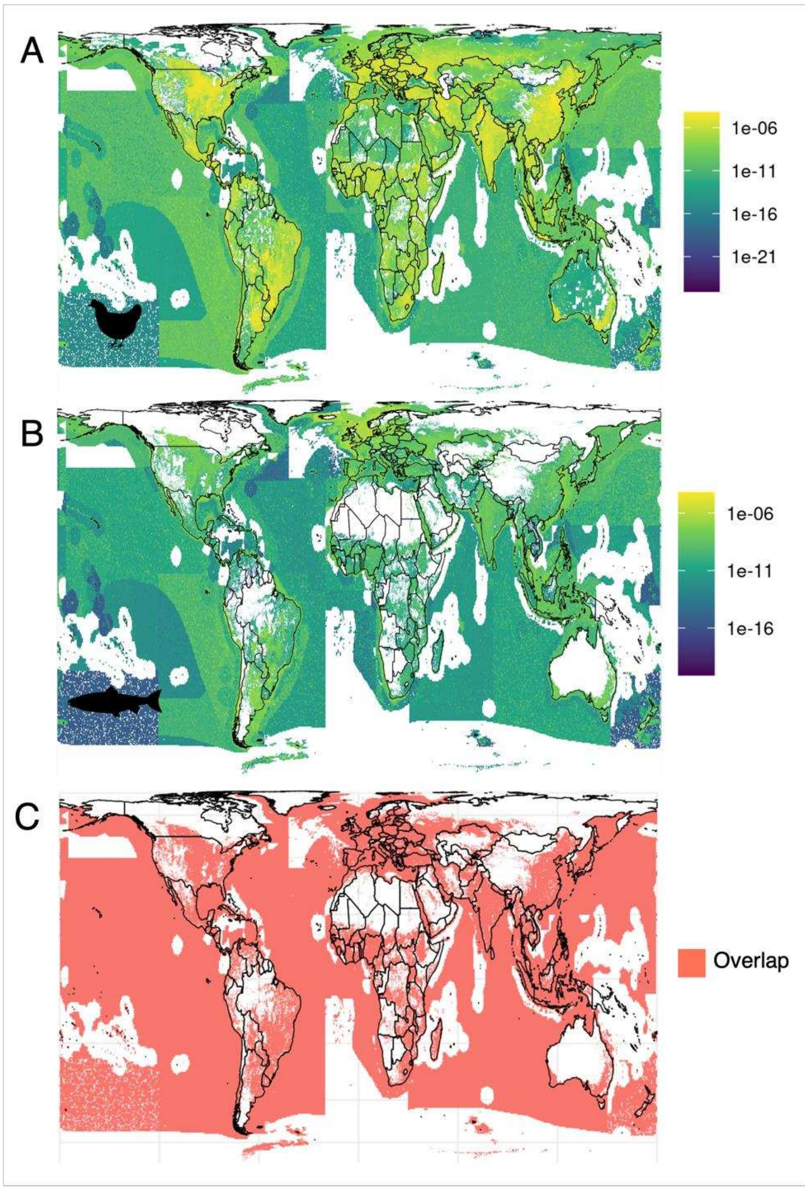
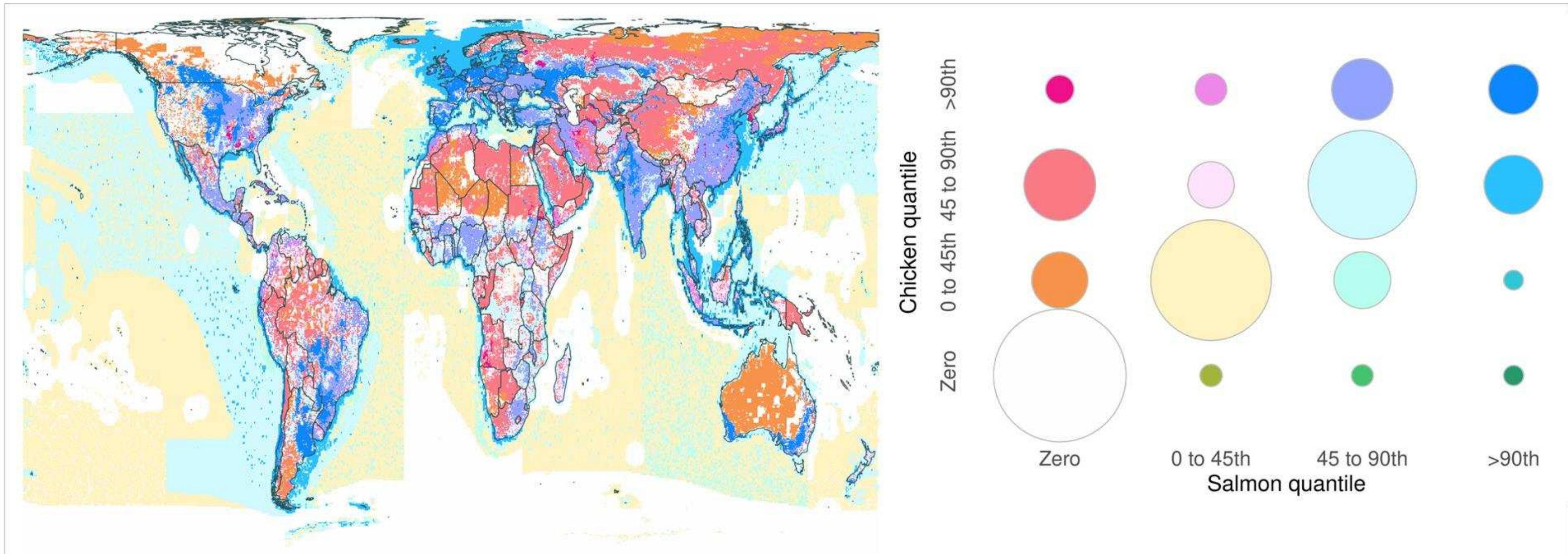
Figures

Figure 1.



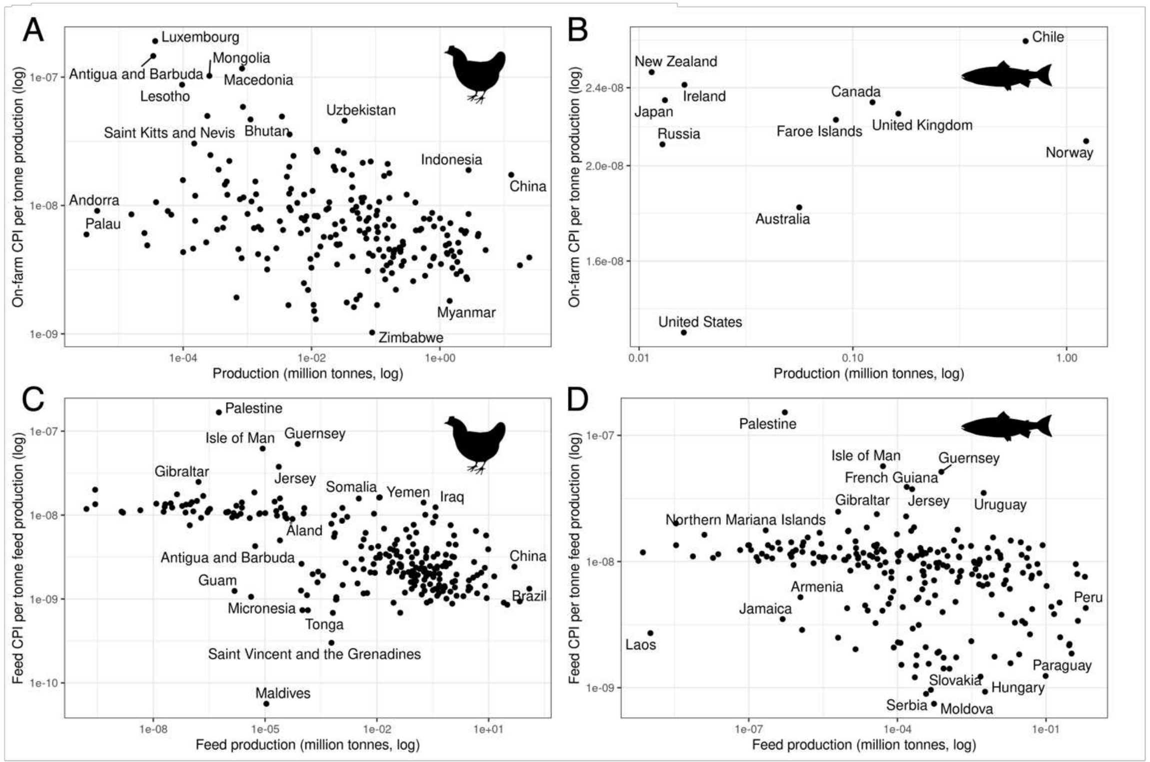
Cumulative environmental pressure index (CPI) for (A) broiler chicken production and (B) farmed salmon production globally and (C) areas of overlap of chicken and salmon pressures. CPI represents the sum of the proportional contribution of each cell or country to global pressures from chicken and salmon production. Data is log transformed.

Figure 2



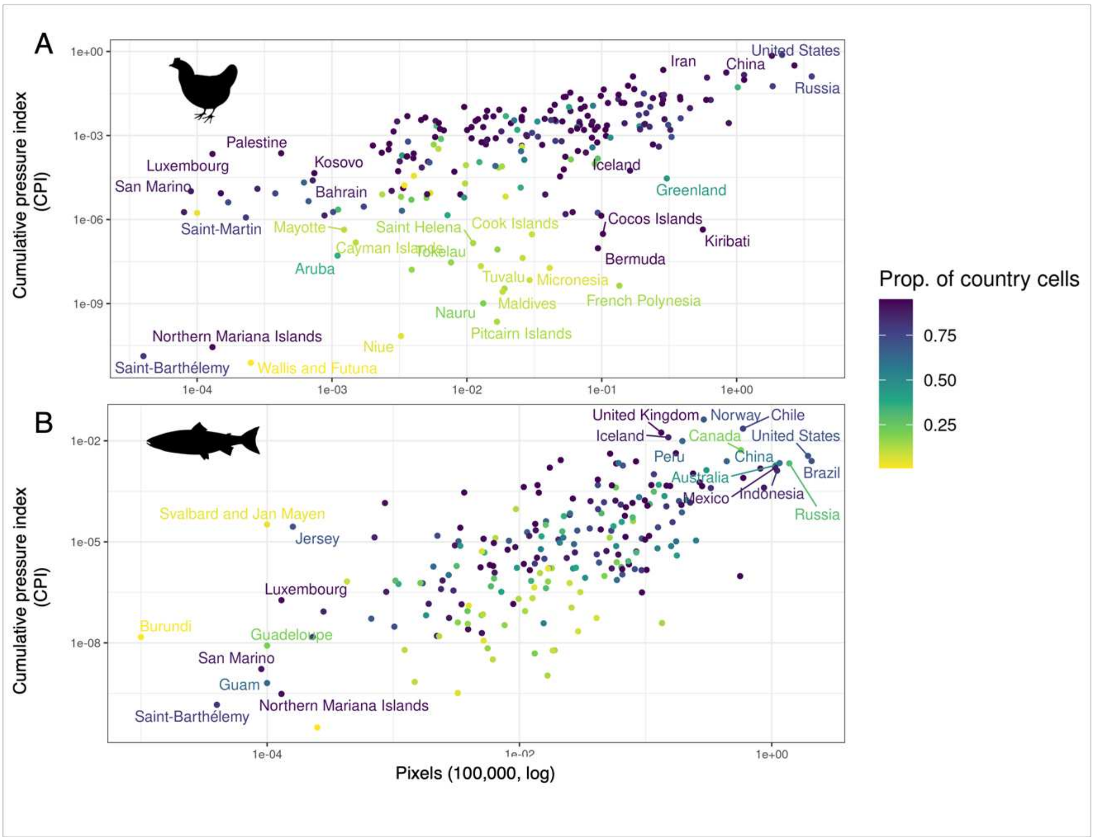
Overlap of the cumulative environmental footprint (CPI) of broiler chicken and farmed salmon production. Legend circle size indicates the number of overlapping cells across quantiles of CPI for farmed chicken and salmon.

Figure 3.



The efficiency (CPI/tonnes production) for on-farm (A and B) and feed (C and D) pressures relate to tonnes of animal or feed production for chicken (A and C) and salmon (B and D). Axes are log transformed.

Figure 4.



Cumulative pressure index (on-farm and feed) relative to produce area (number of pixels) in each country for (A) broiler chicken and (B) farmed salmon productive. Left panels show zoomed in area designated in gray on right panels. Countries with no cells with CPI were removed from the figure.

STAR methods

Data

This paper analyzes existing, publicly available data. These accession numbers for the datasets are listed in the key resources table.

Code

All original code has been deposited at [github.com/OHI-Science/chicken_salmon_v2] and is publicly available as of the date of publication. DOIs are listed in the key resources table.

Method details

We compared the environmental pressures caused by the production of broiler chickens and aquaculture salmon, which are important and highly industrialized[6] sources of human food. Using publicly available datasets[44] we determined the pressures resulting from on-farm activities (i.e., at the production site) and off-farm activities (i.e., at location of feed production), including both the crops and marine fish components of feed. We included four pressures: spatial disturbance (km^2), blue water withdrawal (m^3), nutrient pollution (tonnes PO_4^{3-}eq), and greenhouse gas (GHG) emissions (tonnes CO_2eq). Production and pressure data reflect 2017 values. Code to reproduce all analyses is available on Github (https://github.com/cdkuempel/food_chicken_salmon - **to be made public upon acceptance**). All analyses were conducted using R version 3.6.3 [45]. Complete details of the methods can be found in Halpern et al. 2022[44].

Mapping animal heads and production

The location of broiler chickens and aquaculture salmon (number of heads and production per raster cell in 2017) was based on a variety of data sources. For broiler chickens, the proportional distribution of chickens in each country raster cell was from the FAO Gridded Livestock of the World [46,47] data. These raster values were then multiplied by the FAO estimates of the total number of broiler chickens for each country in 2017 [48].

One complication was that FAO gridded livestock maps[46,47] do not differentiate between industrial chickens (combining layers and broilers), but do provide counts for backyard systems. However, the FAOSTAT data[48] we use for the 2017 counts reports chickens as layers and broilers, but lumps backyard chickens into these categories. To estimate the number of backyard chickens, we used the FAO gridded livestock maps to calculate the proportion of backyard (i.e., "extensive") chickens in each country. We then multiplied the FAO broiler and layer counts by the proportion of backyard chickens to estimate the number of backyard chickens and to adjust the broiler and layer counts to exclude backyard chickens.

We mapped industrial broilers and layers to the same locations (although the counts vary), which fails to capture the actual relative distribution of these food sectors within a country.

The location of salmon aquaculture is from Clawson et al. (2022)[49].

We report production in tonnes at slaughter. For broiler chickens we obtained meat production from FAO Primary Livestock data[50] and converted to slaughter weight by multiplying this value by 1.35[51]. For salmon, production values are 2017 FAO reported salmon aquaculture production[52].

1. *On-farm pressures*

1.1 Broiler chickens

1.1.1 Spatial disturbance

The area of disturbance from broiler chicken farms was estimated using data describing standard rearing densities, reported in kg per m^2. Heads of chickens in a raster cell was converted to kg of live weight using country specific GLEAM data[53]. Based on a variety of sources, broilers are reared at densities of about 35 kg/m^2 [ref[44]]. From aerial photos and blueprints we estimated that about 10% additional building area and about 60% additional farm area is required beyond the chicken living quarters. Based on these additional space requirements, we estimated total farm chicken densities of about 13 kg per m^2. We assume 100% land use change when habitat is replaced by a chicken farm. We divided the kg living broiler chickens in each cell by the adjusted chicken density to estimate the total area required by broiler farms, capping total area to not exceed the total area of the raster cell.

1.1.2 Freshwater use

Freshwater use for broiler chickens included both service water use and drinking water consumption. We used a service water value of 0.09 l/day/individual across all countries [54]. Drinking water consumption per broiler chicken was estimated based on the relationship between temperature and consumption [55] (see Supplementary methods). Total water consumption per raster cell was calculated by multiplying the number of chickens in each cell by the predicted water consumption (drinking + service water per chicken).

1.1.3 Nutrient pollution

We estimated excess nitrogen and phosphorus from manure as the tonnes likely to runoff/leach, and for nitrogen we also included the tonnes that volatilizes as NH_3 based on supernational volatilization estimates[56]. The amount estimated to leach/runoff was mapped as:

$TN_{leach} = PN_{leach} \times N_{ex} \times N_{animals}$

where,

PN_{leach} = raster data describing total proportion of N runoff/leaching for broiler chickens based on how the manure is likely managed[53] and regional differences in withdrawal[57], nitrification/denitrification[58,59], and volatilization[56].

N_{ex} = raster describing annual N excretion, tonnes N animal^{-1} year^{-1} (country specific values from FAOSTAT (2020)[60].

$N_{animals}$ = raster describing number of broiler chickens

To calculate the total P in manure excreted from livestock, we used the total N excreted rasters we created and applied an animal system specific N:P conversion calculated from ref. [61]. To account for phosphorus leaching we assumed that 0.065 of deposited P runoff/leached[62]. Excess N and P were mapped separately and, at the last step, added together to obtain a general indicator of excess nutrients

1.1.4 Greenhouse gas emissions

We calculate GHG emissions from direct energy use on farm (CO_2), and manure.

Emissions from direct energy use were obtained from GLEAM[53]. GHG emissions from manure consist of CH_4 and N_2O gases from aerobic and anaerobic manure decomposition processes. For emissions related to managed manure (CH_4) we used GLEAM models and parameters[53]. For manure left on field and applied to soils we used FAOSTAT manure emissions data[63,64]. Notably, we attribute GHG emissions from manure left on fields and applied to soils to the livestock (as opposed to crop production) because our primary concern is mapping the location where the pressures are generated, which is generally located near the chicken farms due to the large volumes and weight that make transportation difficult [65].

To map the total tonnes of CO_2eq emissions for each livestock system, we multiplied the emission rates for each GHG input by the raster map describing the heads of animals in each cell and summed all the input rasters.

1.2 Salmon Aquaculture

1.2.1 Spatial disturbance

We calculated the area disturbance from salmon aquaculture given pen size and stocking density, buffer areas around pens, and extra area for associated infrastructure. First, we calculated the total number of pens required to rear the salmon in each raster cell by dividing the kg living salmon by pen capacity (kg/pen). We assume cages are circular with 9000 m^3 area [66] and 10 m depth. Based on stocking density of 20kg/m^3 [67], we estimated a capacity of 180,000 kg of salmon at harvest weight per cage. We converted this to heads of salmon per cage by dividing by an average harvest weight of 4.9 kg per salmon which was estimated from Norway harvest data (tonnes harvested/number harvested) from 2010 to 2018[68,69]. Converting yearly tonnes of production within a raster cell to living heads of animals is complicated by the fact that salmon require more than one year to mature, and consequently, the average number of salmon on a farm will be greater than the number produced during the year. Using Norway data[69], we estimated that a farm will have an average of 1.45 heads of salmon for every salmon produced during the year.

To get total area requirements, we calculated the total number of pens required to rear the salmon in each raster cell by dividing the live number of salmon by pen capacity. We increased the number of cages by 30% to account for fallowing. We then estimated total disturbance given the surface area of the cages plus an additional 5 m area surrounding each cage. To account for farming infrastructure such as docks and other facilities, we increased the total area (within cage plus buffer areas) by 50%. Due to variability in cages and infrastructure for each country (and farm), the buffer and additional infrastructure area estimates are based on our best professional judgement after assessing farm diagram schematics in Cardia and Lovatelli[70].

1.2.2 Freshwater use

We estimate freshwater consumption to be zero because such a negligible amount of freshwater is consumed by on-farm processes [14,71]. Water used in hatcheries, brood stock and for cleaning is assumed to have been returned to the catchment area, although there is some loss through evaporation. We do not consider freshwater loss during the transport of smolt from freshwater to seawater, estimated at 0.42 m^3/tonne [72].

1.2.3 Nutrient pollution

We quantified the nitrogen and phosphorus (dissolved and particulate) from salmon farm feces using models and parameters from [73]. We assumed a uniform global feed conversion ratio (FCR) due to the similarity in the feed. The model was applied to each raster cell, which assumes that nutrients remain in the same cell as the salmon and ignores diffusion and ocean current systems. Notably, we do not quantify excess nutrients from uneaten feed which are hard to verify and appear low.

1.2.4 Greenhouse gas emissions

Estimates of GHG emissions for salmon include on-farm energy use and N_2O from microbial nitrification and denitrification of waste. For on-farm energy use, we used global emissions value of 0.159 kg CO2eq/kg live weight [74] and multiplied this values by the percent of on-farm energy use reported in the Seafood Carbon Emissions Tool dataset[75]. For emissions due to N_2O, which is produced by microbial nitrification and denitrification of faecal matter in aquatic farms[76], we used a flat rate of 0.791 tonnes of CO_2eq per tonnes of live weight production for all species groups[77]. However, estimates of aquatic N_2O are uncertain and highly variable across farm types[78]. To obtain the final emissions, the emission rates were multiplied by the raster describing live weight tonnes.

2. Off-farm pressures

Feed used to produce broiler chickens and salmon aquaculture largely come from crops and forage fish. For feed components, pressures were mapped to the location where the crops are grown, or fish are captured (vs. where they are fed to animals).

To get at this, we first estimated the amount of each crop or fish product consumed by each country and animal system based on feed consumption rates and feed composition.

For broiler chickens and salmon, we calculated for each country, *c*, and feed product (crop or forage fish), *f*, the total tonnes consumed, $F_{c,f}$, given the heads of animals (livestock) or tonnes of production (salmon, weight at slaughter), *Ssw*; consumption, *C,* based on consumption rate for broilers (tonnes head^{-1} year^{-1}, FAO (2018)[53]) and economic feed conversion rate of 1.3 for salmon[79] (tonnes feed/tonnes product); and feed composition (broilers[53] and salmon[79]), adjusted for loss during processing[80–82].

FCadj:

$$F_{c,f} = Ssw_c \;\; X \;\; C_c \;\; X \;\; FCadj_{c,f}$$

Economic food conversion rates, eFCRs, account for the food consumption by animals that are critical to food production (e.g., breed stock, mortality) but don't directly contribute to production.

For broilers, the GLEAM estimates of percent composition fish meal/fish oil overestimated global fish consumption, so we adjusted these values so final forage fish consumption was consistent with reported values[83].

Identifying the likely location where feed is grown or captured is complicated by the fact that the country where the product is consumed is often not the country of origin. For crops, we determined the country where the feed was likely grown using FAO global trade data[44,84,85].

We determined the likely country of origin for fish used in animal feed by comparing domestic landings to imported and exported fish meal (under the HS Code 230120), converted to the live weight equivalent. Trade data come from the UN Comtrade for the year 2015. Since this method only traces sourcing back one country step (i.e., does not consider re-exportation or foreign processing), we treated both imports and landings minus exports as being consumed within a given country. This then allowed us to calculate the proportion of forage fish sourced domestically versus from each exporting country. Finally, we multiplied each country-production system pair's forage fish use by the proportion coming from each exporter and domestic landings. This then allowed us to compute the total forage fish coming from each country's landings that go to feed for each animal food system.

For feed crops, after determining the tonnes of each feed product produced for each animal sector in each country, we divided this value by the total tonnes of production of the given crop in the country[86,87] to estimate the proportion going to each food system. For each country, the proportion of FMFO fish going to animal food systems was estimated by dividing the tonnes of forage fish fed to each animal food system by each country's total landings calculated using the country of the fishing vessel[88], which we then traced to location of catch.

For both crops and FMFO, we multiplied the raster describing the proportion of production going to broiler or salmon feed by each of the pressures associated with growing/capturing the source of food.

2.1 Feed crop pressures

To determine the pressures from feed production, we first calculated the total pressures associated with the production of each crop based on the Spatial Production Allocation Model, SPAM v2.0[87], which provides 2010 crop production and harvest area data for 42 crops at 5 arc minutes resolution. For each crop category, SPAM identifies four production systems based on inputs (e.g., fertilizer, pesticide, herbicides) and irrigation. We adjusted SPAM production values for each raster cell, *r*, to the year 2017 based on the proportional change in FAOSTAT[86] production from 2010 to 2017 for each country and crop.

Spatial disturbance was measured for each crop using the physical area of cropland in a given cell based on SPAM's[87] physical area spatial layer. This assumes that crops fully replace natural habitats.

For the crop water pressure, we report the total blue water footprint (WF, m^3 $tonne^{-1}$) which results in aquifer and surface water depletion for each SPAM crop category using subnational-scale data[89]. Total water consumption for each crop was calculated by multiplying the WF raster cells by the tonnes of crop produced in the respective cells.

For nutrient pollution, excess nutrient inputs were from N and P_2O_5 synthetic fertilizers applied to crops. Many studies include organic (i.e., manure) fertilizers as well, however, we account for this at the site of the livestock farm. We distributed the N and P quantities described at the country scale[90] among raster cells according to: the national fertilizer use by crop rates[91,92]; the total hectares of harvested area for each crop, and the intensity of the agriculture sector as described by SPAM[87]. We estimated excess nitrogen and phosphorus as the tonnes likely to runoff/leach[57–59,62], and for nitrogen we also included the tonnes that volatilizes as NH_3 based on supernational volatilization estimates[56].

For the GHG pressures, emissions were based on crop residue burning, crop residue N_2O metabolization, synthetic fertilizer N_2O metabolization, irrigation pumping, field maintenance machinery operations emission from production and transportation of fertilizers, and emissions from production and transportation of pesticides[44].

2.2 Feed fish

To determine the location of FMFO capture, we used data from Watson and Tidd[88] (v5.0, provided by request), which describe tonnes of global catch in 2017 at 0.5 degree resolution. Watson and Tidd allocated country scale FAO catch data to gridded areas based on the spatial distribution of fished taxa and the location of country fleets given fishing access agreements[93]. Tonnes of catch are reported by species (or, larger taxonomic groups) for "Reported", "IUU", and

“Discarded” categories, as well as the country of the fishing vessel, and fishing gear type. Catch in the FMFO category was based on the 238 taxa identified by Froehlich *et al.*[83] that accounted for >99% of FMFO catch in 2012.

Spatial disturbance caused by marine fisheries is fundamentally different from spatial disturbance from land-based crops. Marine fisheries can cause disturbance by destroying seafloor habitat when certain gear types are used (e.g., bottom trawls) as well as through biomass removal throughout the water column and from the seafloor. We estimate the degree of seafloor destruction based on total fishing effort[94,95] (hours) using demersal destructive gear types. For biomass removal, we would ideally measure the total proportion of fish biomass removed, but because these data do not exist, we standardize total catch by dividing the tonnes of catch[96] by NPP to produce an impact metric relative to natural production. This assumes that the higher the biomass removal (relative to NPP) the higher the pressure. The raster maps describing both forms of marine fisheries disturbance (i.e., seafloor destruction and biomass removal) are rescaled to values between 0 to 1 by determining, for each map, the value across all the raster cells corresponding to the 99.9th quantile and dividing all the raster cells by this value. The two rescaled rasters are then averaged to get total marine fisheries disturbance. To make this measure comparable to land disturbance (measured in km^2), we multiply this rescaled score by the 2-dimensional area of the ocean cell. Our decision to rescale fisheries disturbance by the 99.9th quantile assumes 0.1% of ocean area is highly disturbed by fishing (e.g., has a fully disturbed value of 1).

We estimated zero water consumption and nutrient pollution from wild-caught fisheries. Water is used and nutrient pollution likely occurs during processing; however, we did not generally include pressures associated with processing of product in this assessment due to challenges of mapping processing locations.

We estimated GHG emissions based on tonnes of catch. We used data describing emissions for the FMFO fishing sector [97]. We adjusted values from Parker et al. (2018)[97] to include only direct costs and arrived at an estimate of 0.3 kg CO_2eq per kg catch. We multiplied this value by our raster describing the tonnes of fish used for FMFO feed for broilers and salmon.

3. Calculating cumulative pressures

Combining different pressures requires that all pressures share the same units [98]. To achieve this, we first converted the latitude/longitude rasters used for the initial calculations to the Gall-Peter’s equal area coordinate reference system, with 36 km^2 grid size. Each pressure raster was rescaled to unitless values by dividing each raster cell value by the total global pressure intensity from all inputs from both aquaculture salmon and broiler chickens, such that each raster cell describes the proportion of its contribution to the global pressure. The cumulative pressure raster was calculated by summing the four rescaled pressure rasters.

Quantification and statistical analysis

All analyses were conducted in the R programming language (version 4.1.3).

Key resources table

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited Data		
Halpern, B.S., Frazier, M., Verstaen, J., Rayner, P.-E., Clawson, G., Blanchard, J.L., Cottrell, R.S., Froehlich, H.E., Gephart, J.A., Jacobsen, N.S., et al. (2022). The	Github repository	https:// github.com/OHI-Science/global_food_pressures

environmental footprint of global food production. Nat Sustain. 10.1038/s41893-022-00965-x.		
Software and Algorithms		
R programming software version 4.1.3	https://cran.r-project.org/	

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KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited Data		
Halpern, B.S., Frazier, M., Verstaen, J., Rayner, P.-E., Clawson, G., Blanchard, J.L., Cottrell, R.S., Froehlich, H.E., Gephart, J.A., Jacobsen, N.S., et al. (2022). The environmental footprint of global food production. Nat Sustain. 10.1038/s41893-022-00965-x.	Github repository	https:// github.com/OHI-Science/global_food_pressures
Software and Algorithms		
R programming software version 4.1.3	https://cran.r-project.org/	